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SYSTEMS ANALYSIS FOR SUSTAINABILITY ASSESSMENT OF BIOGAS AND
BIO-CH₄ PRODUCTION FROM FOOD WASTE AND DAIRY MANURE MIXTURES
IN THE US

By

Sharath K. Ankathi

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Chemical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2020

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Chemical Engineering.

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Table of Contents

List of figures.....	viii
List of tables.....	xiv
Preface.....	xxvi
Acknowledgements.....	xxx
List of abbreviations	xxxii
Abstract	xxxiii
1 Review of sustainability issues for future biogas and biomethane production in the US from anaerobic digestion of mixtures of food waste and animal manure.....	1
1.1 Introduction	1
1.1.1 Biogas process performance criteria.....	1
1.1.2 Chemical characterization of feedstock	2
1.1.3 Protein-rich substrate	2
1.1.4 Carbohydrate-rich substrate	3
1.1.5 Fat-rich substrate.....	4
1.1.6 Temperature	4
1.1.7 pH.....	5
1.2 Two stage anaerobic co-digestion (AcoD) process	5
1.3 State of the practice for biogas production in the U.S.....	6
1.4 Introduction to biomethane modeling and production in the US	11
1.5 Current federal and state policies on biogas in the US.....	14
1.6 Social factors with biogas applications in the US	16
1.7 Economic costs and benefits	17
1.8 Environmental issues of biogas production.....	28
1.9 Review of existing frameworks on sustainability assessment of bioenergy systems.....	40
1.10 Research objectives for this dissertation	42
1.11 References	44
2 Carbon footprint and energy analysis of Bio-CH ₄ from a mixture of food waste and dairy manure in Denver, Colorado.....	54
2.1 Introduction	54
2.1.1 Food waste generation	54

2.1.2	Landfills and GHG emissions.....	55
2.1.3	Manure generation and management.....	55
2.1.4	Composting for management of food waste	56
2.1.5	LCA Literature review.....	56
2.1.6	Research Objectives.....	57
2.2	Materials and Methods	57
2.2.1	Goal and Scope	57
2.2.2	Functional Unit	57
2.2.3	System boundary.....	58
2.2.4	Allocation.....	62
2.2.5	Inventory Analysis	62
2.2.6	Impact Assessment.....	67
2.3	Results and discussion.....	68
2.3.1	Case 1 BAU composting versus Bio-CH ₄	68
2.3.2	Case 2 Scenario steady state analyses.....	70
2.3.3	Case 2 transient analysis	71
2.3.4	Fossil Energy Consumption for Case 2	73
2.3.5	Broader impacts of AD in the US	73
2.4	Summary and Conclusions	74
2.5	Acknowledgements	74
2.6	References	75
3	Life cycle assessment of oilseed crops produced in rotation with dryland cereals in the inland Pacific Northwest.....	78
3.1	Introduction	79
3.2	Methods.....	81
3.2.1	LCA goal and scope.....	81
3.2.2	LCA system boundaries.....	81
3.2.3	Functional unit and crop rotations	82
3.2.4	Allocation.....	83
3.2.5	LCA inputs.....	83
3.2.6	Inventory analysis	88
3.2.7	Impact assessment.....	89
3.2.8	Field experiment description and input data.....	89
3.2.9	Measurement of soil gas emissions.....	90
3.3	Results and discussion.....	92
3.3.1	Greenhouse gas emissions	93
3.3.2	Cumulative energy demand (CED).....	95
3.3.3	Comparison of crop rotations.....	98
3.4	Conclusions	101

3.5	Acknowledgements	102
3.6	Funding.....	102
3.7	References	103
4	Synergistic Effects Between Hydrolysis Time and Microporous Structure in Poplar 106	
4.1	Introduction	106
4.2	Materials and methods.....	109
4.2.1	Dilute acid pretreatment.....	109
4.2.2	HPLC Analysis	110
4.2.3	Enzymatic Hydrolysis.....	111
4.2.4	NMR Cryoporometry Protocol	112
4.2.5	Temperature control and Measurement	112
4.3	Results and discussion.....	113
4.3.1	Pretreatment	113
4.3.2	Cryoporometry	115
4.4	Acknowledgements	123
4.5	References	124
5	GIS-integrated optimization for locating food waste and manure anaerobic co- digestion facilities	129
5.1	Introduction	129
5.1.1	Review of biogas systems analysis	132
5.2	Methods.....	133
5.2.1	Proposed systems analysis framework.....	133
5.2.2	Identification of potential biogas plant locations in Wisconsin.....	134
5.2.3	Process simulation using Aspen +	136
5.2.4	LCA methodology	136
5.2.5	Optimization model and formulations	137
5.2.6	Economic optimization equations.....	138
5.3	Results and discussion.....	138
5.4	Acknowledgements	145
5.5	References	146
6	Summary, Conclusions and Recommendations for Future Work	149
A	Supporting Information for Chapter 2	152
A.1	AD Bio-CH ₄ Pathway Calculations and Eco-profiles	152
A.1.1	Landfill pathway eco-profiles	154

A.1.2	Peat pathway	164
A.1.3	Composting pathway	164
A.1.4	Synthetic fertilizer pathway	165
A.1.5	Manure pathway.....	167
A.1.6	Natural gas pathway.....	168
A.2	170	
A.2.1	Model derivation for the transient calculations of landfill anaerobic digestion (AD) emissions	170
A.3	Calculations of inputs into SimaPro	175
A.3.1	Case 1: AD Bio-CH ₄ pathway	176
A.3.2	Case 2: Avoided pathways to AD Bio-CH ₄ pathway	182
A.4	Nationwide resource assessment	186
A.4.1	Calculation for estimating GHG emission savings nationwide in United States.....	187
A.5	References	189
B	Supporting Information for Chapter 3	190
B.1	Yields and prices of spring and winter crops	190
B.1.1	Crop prices and allocation factors (economic and energy).....	190
B.1.2	Input field activities	196
B.1.3	Pesticides conversion	257
B.2	Eco profiles in SimaPro.....	291
B.2.1	Inventory of materials and processes to SimaPro on an acre basis.....	291
B.2.2	Eco profiles for field emissions in SimaPro	336
B.3	GHG emissions of 3-year and 2-year crop rotations	341
B.3.1	Gives information on market value allocation (MVA) of different 2-yr and 3-yr cropping systems:	341
B.4	References	344
C	Supporting Information for Chapter 4	345
C.1	Cryoporometry Materials and Methods:	345
C.2	HPLC standards calibration figures:	348
C.3	Compositional Analysis Method for Pretreated Biomass ⁶ :.....	350
C.3.1	Composition Analysis Calculations:.....	350
C.4	Calculations of % yields for dilute acid pretreated and enzyme hydrolyzed DN34 Hybrid Poplar:.....	354
C.4.1	Dilute Acid Pretreatment % Yield (Glucan, Xylan) Calculations:.....	354
C.4.2	Enzymatic Hydrolysis % Yield of Glucan Calculations:.....	356
C.5	Conversion of porosity for normalized pore volume	359

C.6	Calculations used for determining the initial rate of hydrolysis	399
C.7	References	402
D	Supporting Information for Chapter 5	403
D.1	Introduction to food waste and circular economy	403
D.2	Mathematical formulation of optimization model:	407
D.2.1	Revenues include:	409
D.2.2	Costs include:	410
D.3	System boundary and process simulation for AD	412
D.3.1	Emission savings calculation:	414
D.4	Results from optimization model	415
D.5	AMPL script for optimization model	431
D.5.1	MOD file:	431
D.5.2	DATA file:	433
D.5.3	RUN file: solving using cplex	480
D.5.4	Google script for calculating distances:	481
D.6	References:	483
E	Copyright documentation	484

List of figures

Figure 1-1 Reaction scheme for AD process	1
Figure 1-2 Different types of biogas plants by country in Europe [44].....	11
Figure 1-3 Biogas Potential for different substrates [80-84]	13
Figure 2-1 System boundaries for the case 1 Business-as-Usual (BAU) system	59
Figure 2-2 System boundaries for the case 1 Bio-CH ₄ system	60
Figure 2-3 System boundaries for the case 2 Bio-CH ₄ scenario avoided BAU with different landfill systems.....	61
Figure 2-4 Case 2 Bio-CH ₄ avoided BAU with different landfill scenarios pathways.....	61
Figure 2-5 Fossil energy demand for BAU composting system and Bio-CH ₄ system in units of MJ/day	70
Figure 2-6 Case 2, Bio-CH ₄ emissions avoiding different BAU steady-state landfill scenarios.....	71
Figure 2-7 Case 2, Bio-CH ₄ emissions avoiding the BAU landfilling a) uncontrolled Scenario-1, b) gas collection system (GCS) & flaring scenario-2, and c) landfill gas collection with electricity generation (LFGE) scenario-3.	72
Figure 2-8 Fossil energy demand for case 2, scenario-1, scenario-2, and scenario-3.	73
Figure 3-1 Cradle-to-gate lifecycle system boundary for cereal and oilseed crops.....	82
Figure 3-2 Static gas chambers for the CO ₂ , N ₂ O and CH ₄ measurements	91
Figure 3-3 Greenhouse gas emissions of winter wheat (WW) and spring wheat (SW) in seven different crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms	92
Figure 3-4 Greenhouse gas emissions of spring oilseeds (SO) and winter oilseeds (WO) in different crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms	93
Figure 3-5 Greenhouse gas emissions of spring barley (SB), spring triticale (ST), and winter triticale (WT) in other crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms	93

Figure 3-6 Cumulative energy demand for different wheat crop rotations (MA: mass allocation; MVA: market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ	96
Figure 3-7 Cumulative energy demand for different oilseed crop rotations (MA: mass allocation; MVA: market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ	96
Figure 3-8 Cumulative energy demand for other crop rotations (using both mass and market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ	97
Figure 3-9 Intensity of energy demand for different oilseed crop rotations; numbers enclosed in white boxes indicate the total value	98
Figure 3-10 Overall greenhouse gas emissions of all the rotations over 6 years in tons of CO ₂ eq. ha ⁻¹ ; numbers enclosed in white boxes indicate the total value of emissions	99
Figure 3-11 The total sales value of all the rotations over 6 years in dollars/hectare. Variability bars demonstrating the observed range in crop yields obtained from standard deviations of the means (n = 11–14 varies with rotation); numbers enclosed in white boxes	100
Figure 3-12 The total sales value against total emissions of nine dryland crop rotations over 6 years; entries enclosed in white boxes indicate the rotation name	101
Figure 4-1 Dilute acid pretreatment of poplar with acid concentration (0.5% wt.) and temperature (160 °C) as a function of pretreatment time. *Hemicellulose and cellulose content of raw dry poplar biomass (see paragraph 1 of materials and methods).....	113
Figure 4-2 The enzymatic hydrolysis of dilute acid pretreatment time samples as a function of hydrolysis time. Most error bars are within the size of the symbols. *cellulose content of pretreated poplar biomass (see glucan in Table 1).	115
Figure 4-3 Porosity distribution of dilute acid pretreatment over time (acid concentration (0.5% wt.) and temperature (160 °C)).....	116
Figure 4-4 Absolute pore volume of acid pretreated poplar biomass over time.....	117
Figure 4-5 Normalized pore volume fraction of dilute acid pretreatment poplar biomass over time (acid concentration (0.5% wt.) and temperature (160 °C)).....	118
Figure 4-6 Porosity distribution of enzymatic hydrolyzed 8 min pretreated poplar biomass sample over time.	119

Figure 4-7 Absolute pore volume of enzymatic hydrolysis poplar biomass over time a) 8 min of dilute acid pretreatment (DAP), b) 15 min DAP, c) 21 min DAP, d) 40 min DAP.	120
Figure 4-8 Correlation of rate of hydrolysis with the absolute pore volume >51 Å in pore size.	122
Figure 5-1 Framework for the sustainability of AD co-digestion from food waste and manure mixture.	134
Figure 5-2 Capacities and locations of the optimal biopower plants in Wisconsin (left: scenario-1 and right: scenario-2)	139
Figure 5-3(A) Sensitivity analysis for the coefficients of objective function (manure acquisition cost and foodwaste (FW) tipping fee) with capacity of biogas facilities at varying carbon credits a) \$0 carbon credits	140
Figure 5-4 Sensitivity analysis for the coefficients of objective function with objective function value (profits). MAC is manure acquisition cost (\$/ton), CC is carbon credits (\$/ton CO ₂)	143
Figure. A-1 Flow diagram of landfill emissions with gas collection system and flaring	172
Figure. A-2 Flow diagram of landfill emissions without gas collection system	175
Figure. B-1. Greenhouse gas emissions of winter wheat (WW) and spring wheat (SW) in different crop rotations based on market value allocation.	342
Figure. B-2. Greenhouse gas emissions of different oilseed crop rotation based on market value allocation.	343
Figure. B-3. Greenhouse gas emissions of spring barley (SB), spring triticale (ST), and winter triticale (WT) in other crop rotations based on market value allocation. .	343
Figure. C-1. NMR Cryoporometer – v2b NMR RF hardware, which has recently been developed by Lab-Tools.	345
Figure. C-2. Melting point depressions, for different pore geometries: Sol-Gel (spherical), SBA-15 (hexagonal) and MCM-41 (hexagonal), plotted against inverse pore diameter, as determined by gas adsorption. ⁴	346
Figure. C-3. The 3 screens show the multitasking and cooperating AplX programs generating and controlling Graphical User Interfaces (GUIs) controlling the	

firmware in the red pitaya and the AplX software in the 2 windows PCs, and generating the output graphs and di	347
Figure. C-4. Ch1: RF pulse output by red pitaya and input to NMR linear amplifier. Ch2: RF pulse across NMR probe, as monitored at a 1/100 attenuator followed by 1/10 Scope Probe. Ch4: transmitter enable pulse generated by the red pitaya.	347
Figure. C-5. HPLC glucose calibration standards	349
Figure. C-6. HPLC xylose calibration standards	349
Figure. C-7. HPLC furfural calibration standards	350
Figure. C-8. Porosity distribution of dilute acid pretreatment of 8 min sample (acid concentration (0.5% wt.) and temperature (160°C))	374
Figure. C-9. Normalized Fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 0-hours of EH	389
Figure. C-10. Normalized fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 4-hours of EH	389
Figure. C-11. Normalized fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 24-hours of EH	390
Figure. C-12. Normalized fraction of pore volume distribution of poplar biomass sample with 13 Min of DAH and 0-hours of EH	390
Figure. C-13. Normalized fraction of pore volume distribution of poplar biomass sample with 13 Min of DAH and 24-hours of EH	391
Figure. C-14. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 0-hours of EH	391
Figure. C-15. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 4-hours of EH	392
Figure. C-16. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 24-hours of EH	392
Figure. C-17. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 0-hours of EH	393
Figure. C-18. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 4-hours of EH	393

Figure. C-19. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 24-hours of EH	393
Figure. C-20. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAH and 0-hours of EH	394
Figure. C-21. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAH and 4-hours of EH	394
Figure. C-22. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAH and 24-hours of EH	395
Figure. C-23. Porosity distribution of enzymatic hydrolyzed 13-min pretreated poplar biomass sample over time	395
Figure. C-24. Porosity distribution of enzymatic hydrolyzed 15-min pretreated poplar biomass sample over time	396
Figure. C-25. Porosity distribution of enzymatic hydrolyzed 21-min pretreated poplar biomass sample over time	396
Figure. C-26. Porosity distribution of enzymatic hydrolyzed 40-min pretreated poplar biomass sample over time	397
Figure. C-27. Absolute pore volume of enzymatic hydrolysis poplar biomass over time (with 13-min of acid pretreatment)	397
Figure. C-28. Absolute pore volume of enzymatic hydrolysis poplar biomass over time (with 8 min of acid pretreatment)	398
Figure. C-29. Normalized pore volume fraction of enzymatic hydrolysis poplar biomass over time a) 13 min of dilute acid pretreatment (DAP), b) 15 min DAP, c) 21 min DAP, d) 40 min DAP.	398
Figure. C-30. Initial rate of hydrolysis for 8-min dilute acid pretreated poplar biomass samples.....	399
Figure. C-31. Initial rate of hydrolysis for 13-min dilute acid pretreated poplar biomass samples.....	400
Figure. C-32. Initial rate of hydrolysis for 15-min dilute acid pretreated poplar biomass samples.....	400
Figure. C-33. Initial rate of hydrolysis for 21-min dilute acid pretreated poplar biomass samples.....	401

Figure. C-34. Initial rate of hydrolysis for 40-min dilute acid pretreated poplar biomass samples.....	401
Figure. D-1 . Circular flow diagram of food and food waste using AD.	403
Figure. D-2 2017 US total MSW generation by material in percentage.....	404
Figure. D-3 Availability of dairy manure at each farm in Wisconsin (in dry tons/day)..<	405
Figure. D-4 Availability of food waste at each courthouse in Wisconsin (in dry tons/day)	406
Figure. D-5 Transportation network for scenario-2 from potential biogas facilities (mapping feedstock location and plant locations) [X- potential plants, ▲- courthouses, ●- dairy farms, ---- network, X – potential plants with no capacities)	407
Figure. D-6 ASPEN + two stage co-digestion biopower facility	413
Figure. D-7 Cradle-gate system boundary for biopower system.	413

List of tables

Table 1.1 Carbon/nitrogen (C/N) ratios of different substrates [5].	3
Table 1.2 Theoretical biogas yields and methane content of substrates [20].	4
Table 1.3 Advantages and disadvantages of two-stage over single-stage AcoD.	5
Table 1.4 Sources of substrates for biogas production in U.S.	7
Table 1.5 Operating biogas plants in the US.	9
Table 1.6 Different anaerobic digestion models.	12
Table 1.7 Policy/Programs initiated by agencies.	14
Table 1.8 Summary of 14 different techno-economic articles on AD.	18
Table 1.9 Summary of 14 different techno-economic articles on AD (continued).	21
Table 1.10 Summary of 14 different techno-economic articles on AD (continued).	24
Table 1.11 Summary of 13 different LCA articles on AD (emphasize GHG emissions).	29
Table 1.12 Summary of 13 different LCA review articles on AD (continued-emphasize GHG emissions).	32
Table 1.13 Summary of 13 different LCA articles on AD (continued-emphasize GHG emissions).	34
Table 1.14 Bioenergy sustainability framework review.	40
Table 2.1 Inputs to AD Bio-CH ₄ pathway (basis of 1 day): case 1 and case 2.	62
Table 2.2 Inputs to compost pathway (basis of 1 day): case 1 BAU.	63
Table 2.3 Inputs to natural gas pathway: case 1 BAU.	64
Table 2.4 Inputs to synthetic fertilizer pathway: case 1 BAU.	64
Table 2.5 Inputs to peat pathway: case 1 Bio-CH ₄ .	65
Table 2.6 Inputs to avoided landfill without gas collection pathway: case 2 scenario-1...	65
Table 2.7 Inputs to avoided landfill with gas collection and flaring: case 2 scenario-2....	65

Table 2.8 Inputs to avoided landfill with gas collection & electricity pathway: case 2 scenario-3.....	66
Table 2.9 Inputs to avoided synthetic fertilizer pathway: case 2.....	66
Table 2.10 Inputs to avoided peat moss pathway: case 2.	66
Table 2.11 Inputs to avoided manure pathway: case 2.	67
Table 2.12 GHG emissions for peat manufacturing, packaging transport and use.....	67
Table 2.13 Case 1: Business as usual composting system (basis of 1 day).....	68
Table 2.14 Case 1: Bio-CH ₄ system (basis of 1 day).....	68
Table 3.1 Nine crop rotations used in the cropping systems study, Echo, OR.....	82
Table 3.2 Annual inputs for two-year rotations includes both tillage and cropping; per ha.	84
Table 3.3 Weighted average annual inputs for spring barley, spring triticale, winter triticale; per ha.	85
Table 3.4 Weighted average annual inputs for winter wheat and spring wheat crops; per ha.....	86
Table 3.5 Weighted average annual inputs for 3-year reduced tillage fallow; per ha.	87
Table 3.6 Weighted average annual inputs for winter oilseed and spring oilseed crops; per ha.....	87
Table 4.1 Carbohydrate composition analysis of pretreated DN34 hybrid poplar samples.	114
Table 5.1 Criteria for identifying suitable areas for AD in Wisconsin.....	134
Table 5.2 Input parameters from simulation values at different capacity levels.	136
Table. A-1. Eco profile for CH ₄ emissions Bio-CH ₄ combustion (basis 1kg Bio-CH ₄)..	152
Table. A-2. Eco profile CO ₂ emissions from AD process (basis 1kg Bio-CH ₄)	152
Table. A-3. Density calculations.....	153

Table. A-4. Eco-profile for the AD (anaerobic digestion) process electricity use is taken from “Colorado grid” basis 1kWh energy. Renewable is assumed to be equal portion of hydro, biomass, wind, and solar.....	153
Table. A-5. Eco-profile for CO ₂ emissions from AD compost soil application: basis 1kg wet compost.	154
Table. A-6. Liquid digestate N ₂ O emissions on field application: basis 1kg N in liquid digestate	154
Table. A-7. Landfill emissions without gas collection system (uncontrolled) steady state (basis: 1 kg of dry waste)	155
Table. A-8. Landfill emissions Gas Collection System (GCS) steady state (basis: 1 kg of dry food waste)	155
Table. A-9. Landfill emissions Gas Collection System and Electricity generation (GCSE) steady state (basis: 1 kg of dry food waste)	155
Table. A-10. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 1 (basis: 1 kg of dry waste)	156
Table. A-11. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 5 (basis: 1 kg of dry waste)	156
Table. A-12. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 10 (basis: 1 kg of dry waste)	156
Table. A-13. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 20 (basis: 1 kg of dry waste)	157
Table. A-14. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 30 (basis: 1 kg of dry waste)	157
Table. A-15. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 40 (basis: 1 kg of dry waste)	158
Table. A-16. CH ₄ and CO ₂ emissions from landfill without gas collection (uncontrolled) year 50 (basis: 1 kg of dry waste)	158
Table. A-17. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 1 (basis: 1 kg of dry waste)	158
Table. A-18. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 5 (basis: 1 kg of dry waste)	159

Table. A-19. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 10 (basis: 1 kg of dry waste).....	159
Table. A-20. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 20 (basis: 1 kg of dry waste).....	159
Table. A-21. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 30 (basis: 1 kg of dry waste).....	160
Table. A-22. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 40 (basis: 1 kg of dry waste).....	160
Table. A-23. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring year 50 (basis: 1 kg of dry waste).....	160
Table. A-24. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity generation year 1 (basis: 1 kg of dry waste)	161
Table. A-25. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 5 (basis: 1 kg of dry waste).....	161
Table. A-26. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 10 (basis: 1 kg of dry waste).....	162
Table. A-27. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 20 (basis: 1 kg of dry waste).....	162
Table. A-28. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 30 (basis: 1 kg of dry waste).....	163
Table. A-29. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 40 (basis: 1 kg of dry waste).....	163
Table. A-30. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity year 50 (basis: 1 kg of dry waste).....	164
Table. A-31. Emissions from peat moss manufacturing, transport and use (basis 1 m ³ peat-moss).....	164
Table. A-32. Eco-profile for composting decomposition emissions (CH ₄ & N ₂ O). These factors are taken from IPCC biogenic report 3	165
Table. A-33. Eco-profile for composting decomposition emissions (CO ₂). This factor is taken from IPCC biogenic report 3.....	165
Table. A-34. Eco-profile for CO ₂ emissions from compost land application.....	165

Table. A-35. Diesel used in tractor for heartland LCA composting (basis: 0.0435 kg diesel).....	165
Table. A-36. Eco-profile for US mix fertilizer is” US_Mix_ecoprofile” basis 1kg nitrogen fertilizers, as N US Mix (heartland project), S	166
Table. A-37. Emissions of N ₂ O from synthetic N fertilizer applied to field: (basis: 1kg synthetic N fertilizer)	167
Table. A-38. Manure lagoon emissions (N ₂ O, CH ₄ and CO ₂) (basis: 1kg dry manure)..	167
Table. A-39. Manure slurry storage emissions (N ₂ O, CH ₄ and CO ₂) (basis: 1kg dry manure)	167
Table. A-40. Manure lagoon emissions (N ₂ O, CH ₄ and CO ₂) (basis: 1kg dry manure)	167
Table. A-41.Heartland phase 1B water balance in AD Bio-CH ₄ pathway	168
Table. A-42. Wood composition (percentage).....	168
Table. A-43. Calculation for carbon, CH ₄ , CO ₂ potential in landfill.....	169
Table. A-44. Landfill emissions with gas collection system and flaring.....	172
Table. A-45. Landfill emissions with gas collection system and electricity generation..	173
Table. A-46. Calculation for electricity generation from a landfill with gas collection system and electricity generation.....	173
Table. A-47. Year wise electricity generation from a landfill with gas collection system and electricity generation.	174
Table. A-48. Landfill emissions without gas collection system	175
Table. A-49. All the input data for AD Bio-CH ₄ pathway provided by Jim Potter, Ag energy LLC.	176
Table. A-50 Case 1: peat pathway:	178
Table. A-51. Case 1: BAU composting pathway.....	178
Table. A-52. Case 1: BAU synthetic fertilizer pathway:	180
Table. A-53 Case 1: BAU natural gas pathway	182
Table. A-54. Avoided landfill pathway without gas collection system (uncontrolled) ...	182

Table. A-55. Avoided landfill pathway with gas collection system and flaring.....	183
Table. A-56. Avoided landfill pathway with gas collection system and electricity generation.....	183
Table. A-57. Avoided synthetic fertilizer pathway.....	184
Table. A-58. Avoided peat pathway	185
Table. A-59. Avoided manure pathway	186
Table. A-60. Calculation of overall nationwide resource assessment on diversion of food waste and manure to Bio-CH ₄ system.	186
Table. B-1. Crop prices of different cereal and oilseeds (spring and winter).....	190
Table. B-2. Average yields different rotation crops over 5 years including the standard deviation (SD) values.....	191
Table. B-3. Total average sales values of individual rotation with SD and allocation factors based on price.....	192
Table. B-4. Total average yield values of individual rotation with SD and allocation factors based on yield.....	194
Table. B-5. Lower heating values for oil and oilseed meal.	195
Table. B-6. Total average oil concentrations in oilseed of individual oilseed rotation and energy allocation factors based on LHV of oil and oil meal	195
Table. B-7. Intensity of energy demand (return on investment) for different oilseed crop rotations (using both mass and market value allocation).....	196
Table. B-8. Average input field activities for rotation SF-WW on the basis of per acre per year.....	197
Table. B-9. Average input field activities for rotation RTF-WW on the basis of per acre per year.....	201
Table. B-10. Average input field activities for rotation RTF-WO (RTF-WO-RTF-WW) on the basis of per acre per year.....	206
Table. B-11. Average input field activities for rotation RTF-WW (RTF-WW-RTF-WO) on the basis of per acre per year.....	210
Table. B-12. Average input field activities for rotation RTF-WW-SB on the basis of per acre per year	215

Table. B-13. Average input field activities for rotation RTF-WW-SO on the basis of per acre per year	222
Table. B-14. Average input field activities for rotation RTF-WO-SW on the basis of per acre per year	229
Table. B-15. Average input field activities for rotation RTF-SO-SW on the basis of per acre per year	236
Table. B-16. Average input field activities for rotation RTF-WO-ST on the basis of per acre per year	243
Table. B-17. Average input field activities for rotation RTF-SO-WT on the basis of per acre per year	251
Table. B-18. SF-WW rotation conversions of pesticides from fluid ounce to grams.....	258
Table. B-19. RTF-WW rotation conversions of pesticides from fluid ounce to grams...	259
Table. B-20. RTF-WO (RTF-WO-RTF-WW) rotation conversions of pesticides from fluid ounce to grams.....	261
Table. B-21. RTF-WW (RTF-WW-RTF-WO) rotation conversions of pesticides from fluid ounce to grams.....	263
Table. B-22. RTF-WW-SB rotation conversions of pesticides from fluid ounce to grams	265
Table. B-23. RTF-WW-SO rotation conversions of pesticides from fluid ounce to grams	269
Table. B-24. RTF-WO-SW rotation conversions of pesticides from fluid ounce to grams	273
Table. B-25. RTF-SW-SO rotation conversions of pesticides from fluid ounce to grams	277
Table. B-26. RTF-WO-ST rotation conversions of pesticides from fluid ounce to grams	281
Table. B-27. RTF-SO-WT rotation conversions of pesticides from fluid ounce to grams	285
Table. B-28. Inputs to Simapro for the rotation SF-WW based on per acre.....	291
Table. B-29. Inputs to Simapro for the rotation RTF-WW based on per acre.....	293

Table. B-30. Inputs to Simapro for the rotation RTF-WW (RTF-WW-RTF-WO) based on per acre.....	296
Table. B-31. Inputs to Simapro for the rotation RTF-WO (RTF-WO-RTF-WW) based on per acre.....	299
Table. B-32. Inputs to Simapro for reduced tillage fallow (RTF-WW-SB) based on per acre.....	301
Table. B-33. Inputs to Simapro for spring barley (RTF-WW-SB) based on per acre	303
Table. B-34. Inputs to Simapro for winter wheat (RTF-WW-SB) based on per acre	305
Table. B-35. Inputs to Simapro for reduced tillage fallow based on per acre	307
Table. B-36. Inputs to Simapro for spring oilseed (RTF-WW-SO) based on per acre....	308
Table. B-37. Inputs to Simapro for winter wheat (RTF-WW-SO) based on per acre	310
Table. B-38. Inputs to Simapro for reduced tillage fallow (RTF-WO-SW) based on per acre.....	312
Table. B-39. Inputs to Simapro for spring wheat (RTF-WO-SW) based on per acre	314
Table. B-40. Inputs to Simapro for winter oilseed (RTF-WO-SW) based on per acre ...	316
Table. B-41. Inputs to Simapro for reduced tillage fallow (RTF-SO-SW) based on per acre.....	317
Table. B-42. Inputs to Simapro for spring oilseed (RTF-SO-SW) based on per acre	319
Table. B-43. Inputs to Simapro for spring wheat (RTF-SO-SW) based on per acre.....	321
Table. B-44. Inputs to Simapro for reduced tillage fallow (RTF-WO-ST) based on per acre.....	323
Table. B-45. Inputs to Simapro for spring triticale (RTF-WO-ST) based on per acre	325
Table. B-46. Inputs to Simapro for winter oilseed (RTF-WO-ST) based on per acre.....	327
Table. B-47. Inputs to Simapro for reduced tillage fallow (RTF-WT-SO) based on per acre.....	329
Table. B-48. Inputs to Simapro for spring oilseed (RTF-WT-SO) based on per acre.....	330
Table. B-49. Inputs to Simapro for winter triticale (RTF-WT-SO) based on per acre....	333

Table. B-50. Dry_land_field_emissions_CH ₄ -SF-WW (1 lb. N applied)	336
Table. B-51. Dry_land_field_emissions_N ₂ O- SF-WW (1 lb. N applied)	336
Table. B-52. Dry_land_field_emissions_CH ₄ - RTF-WW (1 lb. N applied)	336
Table. B-53. Dry_land_field_emissions_N ₂ O- RTF-WW (1 lb. N applied)	336
Table. B-54. Dry_land_field_emissions_CH ₄ - RTF-WW -WO-RTF (1 lb. N applied)..	336
Table. B-55. Dry_land_field_emissions_N ₂ O- RTF-WW -WO-RTF (1 lb. N applied) .	337
Table. B-56. Dry_land_field_emissions_CH ₄ - RTF-WO -WW-RTF (1 lb. N applied)..	337
Table. B-57. Dry_land_field_emissions_N ₂ O- RTF-WO- WW-RTF (1 lb. N applied) .	337
Table. B-58. Dry_land_field_emissions-RTF (RTF-WW-SB) _CH ₄ & N ₂ O (1 lb. N applied)	337
Table. B-59. Dry_land_field_emissions-SB (RTF-WW-SB) CH ₄ & N ₂ O (1 lb. N applied)	337
Table. B-60. Dry_land_field_emissions--WW (RTF-WW-SB) CH ₄ & N ₂ O (1 lb. N applied)	338
Table. B-61. Dry_land_field_emissions-SO (RTF-WW-SO) CH ₄ & N ₂ O (1 lb. N applied)	338
Table. B-62. Dry_land_field_emissions--WW (RTF-WW-SO) CH ₄ & N ₂ O (1 lb. N applied)	338
Table. B-63. Dry_land_field_emissions--RTF (RTF-WW-SO) CH ₄ & N ₂ O (1 lb. N applied)	338
Table. B-64. Dry_land_field_emissions--RTF (RTF-WO-SW) CH ₄ & N ₂ O (1 lb. N applied)	338
Table. B-65. Dry_land_field_emissions--SW (RTF-WO-SW) CH ₄ & N ₂ O (1 lb. N applied)	339
Table. B-66. Dry_land_field_emissions--WO (RTF-WO-SW) CH ₄ & N ₂ O (1 lb. N applied)	339
Table. B-67. Dry_land_field_emissions-3D-RTF (RTF-SO-SW) CH ₄ & N ₂ O (1 lb. N applied)	339

Table. B-68. Dry_land_field_emissions--SO (RTF-SO-SW) CH ₄ & N ₂ O (1 lb. N applied)	339
Table. B-69. Dry_land_field_emissions--SW (RTF-SO-SW) CH ₄ & N ₂ O (1 lb. N applied)	339
Table. B-70. Dry_land_field_emissions--RTF (RTF-WO-ST) CH ₄ & N ₂ O (1 lb. N applied)	340
Table. B-71. Dry_land_field_emissions--ST (RTF-WO-ST) CH ₄ & N ₂ O (1 lb. N applied)	340
Table. B-72. Dry_land_field_emissions--WO (RTF-WO-ST) CH ₄ & N ₂ O (1 lb. N applied)	340
Table. B-73. Dry_land_field_emissions-RTF (RTF-WT-SO) CH ₄ & N ₂ O (1 lb. N applied)	340
Table. B-74. Dry_land_field_emissions--SO (RTF-WT-SO) CH ₄ & N ₂ O (1 lb. N applied)	340
Table. B-75. Dry_land_field_emissions--WT (RTF-WT-SO) CH ₄ & N ₂ O (1 lb. N applied)	341
Table. B-76. Dry_land_field_emissions_CO ₂ (1 kg Urea)	341
Table. B-77. Gasoline combustion_emissions (1 kg gasoline)	341
Table. B-78. Diesel combustion_emissions (1 kg diesel)	341
Table. C-1. Weights of the severity pretreatment and enzyme hydrolysis poplar biomass samples after wetting (in grams)	348
Table. C-2. Peak area of sugars in pretreated DN34 hybrid poplar samples	351
Table. C-3. Concentration (g/L) of sugars in pretreated DN34 hybrid poplar samples	351
Table. C-4. Mass (g) of sugars in pretreated DN34 hybrid poplar samples	352
Table. C-5. Mass of xylan (xylose, galactose, mannose), glucan (glucose, cellobiose), and arabinan (arabinose) in pretreated DN34 hybrid poplar samples	353
Table. C-6. Percent composition of xylan and glucan in pretreated DN34 hybrid poplar samples	354
Table. C-7. Compositions by weight of DN34 hybrid poplar samples before dilute acid pretreatment (in 0.5 g dry biomass) ⁷	354

Table. C-8. Concentrations of DN34 hybrid poplar samples after dilute acid pretreatment	355
Table. C-9. Mass of sugars in pretreated DN34 hybrid poplar samples	355
Table. C-10. Mass of glucan and xylan in pretreated DN34 hybrid poplar samples (accounting the effect of hydrolysis of water)	355
Table. C-11. Percent yield of xylan and glucan with respect to hemicellulose and cellulose in dried DN34 hybrid poplar samples.....	356
Table. C-12. Carbohydrate composition of pretreated DN34 hybrid poplar samples	356
Table. C-13. Formulae used for calculating the % yields of glucan.....	356
Table. C-14. Percent glucan yield with respect to cellulose in 8 Min pretreated DN34 hybrid poplar samples	357
Table. C-15. Percent glucan yield with respect to cellulose in 13 min pretreated DN34 hybrid poplar samples	357
Table. C-16. Percent glucan yield with respect to cellulose in 15 min pretreated DN34 hybrid poplar samples	358
Table. C-17. Percent glucan yield with respect to cellulose in 21 min pretreated DN34 hybrid poplar samples	358
Table. C-18. Percent glucan yield with respect to cellulose in 40 min pretreated DN34 hybrid poplar samples	359
Table. C-19. Raw measurement data of 8 min acid pretreatment and 0-hour enzymatic hydrolysis from NMR cryoporometry.	360
Table. C-20. Integrated porosity data of 8 min of acid pretreatment and 0-hour enzymatic hydrolysis.....	375
Table. D-1 The volume and energy flows were obtained from ASPEN+	414
Table. D-2 LCA emission factors for biopower systems analysis 4.....	414
Table. D-3 The amount of manure and supply chain distances from farm to plant in scenario 2	415
Table. D-4 The amount of food waste and supply chain distances from courthouse to plant in scenario 2	417

Table. D-5 Capacities of potential plant locations in WI with \$0 CO ₂ credits, \$0 tipping fee, and \$40 per ton of manure	420
Table. D-6 Scenario 1 monthly income and costs of the entire supply chain.....	421
Table. D-7 Capacity levels of potential plant location with \$15 CO ₂ credits, \$20 tipping fee, and \$40 per ton of manure	422
Table. D-8 Scenario-2 monthly costs and incomes of the entire supply chain.....	424
Table. D-9 Calculation of overall emission savings in WI considering scenario 2	424
Table. D-10 The locations specific cost and incomes on a monthly basis for scenario 1	426
Table. D-11 The locations specific cost and incomes on a monthly basis for Scenario 2	427

Preface

Individual chapters presented here support the objective to perform systems analysis of biopower production from conversion of food waste and manure in WI (Chapter 5). In chapter 1, sustainability issues for future biogas and biomethane production in the US from anaerobic digestion of mixtures of food waste and animal manure helps to find the gaps in the existing sustainability frameworks and to understand different sustainability issues. The second paper was a carbon footprint and energy analysis of bio-CH₄ from anaerobic digestion (AD) of a mixture of food waste and dairy manure in Denver, Colorado. This study discusses the advantages of avoiding landfilling of food waste (FW) and conventional dairy manure (DM) management, and the need to perform a consequential analysis in order to understand the change in emissions where the FW and DM are not managed in a conventional way but sent to AD to produce biomethane.

Life cycle assessment skills are further developed in the assessment of oilseed bioenergy crops produced in rotation with dryland cereals in the inland Pacific Northwest (chapter 3). In this study I learn more about multiple allocation methods (mass and market value) when multiple products are present in the system. Whereas Chapter 4 stands separately from the sustainability and LCA research, this study helped me to develop experimental skills in woody biomass conversion and made more me familiar with different bioenergy and biofuel pathways through experimental procedures. With the LCA and experimental knowledge, both play a key role in the systems analysis of bioenergy and biofuel systems.

These chapters together provide a unified PhD in achieving the final goal of performing systems analysis of biopower production in WI. In this final chapter (5), the systems analysis integrated GIS data with AD biopower process simulations, LCA results, and transportation logistics into a holistic analysis of biopower production economic feasibility in a specific region, the state of Wisconsin, USA.

This doctoral dissertation contains material previously peer-reviewed and published in scientific journals along with material currently submitted to scientific journals. Full citations of these are as follows:

Chapter 1

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Robert M. Handler	Review and editing of the paper.
Shonnard	Design of the study, analysis and interpretation of data, paper review and editing.

Chapter 2

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Chapter 3

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David R. Shonnard Design of the study, experimental planning, analysis and interpretation of data, paper writing, review and editing.

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Chapter 5

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Jacob Zuhlke	Process modeling and data inputs to the model
David Shonnard	Design of the study, analysis and interpretation of data, paper review and editing.

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List of abbreviations

AcoD: Anaerobic co-digestions

AD: Anaerobic Digestions

CHP: Combined Heat and Power

FW: Food Waste

GHG: Greenhouse gas

GIS: Geographic Information Systems

GWP: Global Warming Potential

LCA: Life cycle assessment

TEA: Techno Economic Analysis

MILP: Mixed Integer Linear Programming

NMR: Nuclear Magnetic Resonance

RTF: Reduced tillage fallow

SB: Spring barley

SF: Summer fallow

SO: Spring oilseed

SW: Spring wheat

WO: Winter oilseed

WW: Winter wheat

Abstract

The purpose of the dissertation is to relate systems analysis for bioenergy to identify optimum configurations for improved scenarios and to make better decisions in a systems perspective.

Chapter 1 is a review of the literature to identify the state of the knowledge in terms of systems analysis for anaerobic digestion (AD) bioenergy systems. The key outcomes from this review showed that anaerobic digestion of mixtures of food waste and animal manure has great potential to achieve economic and environmental benefits compared to other treatments of organic waste materials, such as landfilling or conventional manure management.

Chapter 2 focuses on carbon footprint of one particular bio-CH₄ production facility. This study developed consequential methodology to address the environmental impacts of system parameters such as avoiding landfilling and manure management. The key results from this LCA show that the AD Bio-CH₄ pathway has 15.5% lower greenhouse gas (GHG) emissions compared to the prior practice of composting of food waste and manure in Denver, CO.

Then chapter 3 provides opportunities for additional studies in bioenergy environmental and economic performance. The objective of this chapter is to gain a system level understanding of the integration of bioenergy crops into rotations with food grains. This study combines both environmental and economic impacts into a single decision assessment. The key results in this chapter show the system parameter yield is the deciding parameter in finding the most optimum crop rotations with integration of bioenergy crops.

In Chapter 4 the objective is to understand enzyme accessibility inside woody biomass and its role in controlling the rate of conversion of cellulose to glucose. The goal of this study was to measure the cellulose accessibility due to the effect of dilute acid pretreatment (DAP) and enzymatic hydrolysis (EH) time of *Populus* biomass.

The last chapter of the dissertation presents a novel systems sustainability analysis framework that evaluates the optimum locations, sizes, and the number of plants for AD biogas power production in Wisconsin accounting for both the profits from the biopower supply chain and carbon credits. This dissertation ends with overall conclusions and recommendations for future research.

1 Review of sustainability issues for future biogas and biomethane production in the US from anaerobic digestion of mixtures of food waste and animal manure

1.1 Introduction

1.1.1 Biogas process performance criteria

According to some researchers, AD is the most environmentally favorable and energy-saving process for the generation of bioenergy from food waste and manure compared to other waste management processes such as composting, landfilling and incineration [1-4]. The AD process is a complex physio-chemical-biochemical process involving 4 stages with multiple reactions in series, such as hydrolysis, acidogenesis, acetogenesis/dehydrogenation, and methanogenesis, involving a consortium of bacteria at each stage [5-8]. The overall anaerobic digestion reaction schema is shown in Figure 1.1 [9,10].

Figure 1-1 Reaction scheme for AD process

The first stage in the AD process is hydrolysis, involving the breaking of complex organic material containing carbohydrates, proteins, fats, and lignin into long chain fatty acids, monosaccharides, and amino acids as water soluble fragments using hydrolytic bacteria and enzymes. The second stage is acidogenesis, in which the water-soluble monomers from the hydrolysis stage are converted into volatile fatty acids (VFAs) such as propionate, butyrate, and valerate, plus alcohols along with hydrogen, carbon dioxide and NH_3 gases using acidogenic bacteria. Acetogenesis is the third stage, where VFAs are converted into H_2 , CO_2 , and acetate by acetogenic bacteria. Both acidogenic and acetogenic reactions produce H_2 and acetate, which act as substrates for methanogenic bacteria [5,6,9,11]. The methanogenic reaction is exothermic and needs strictly anaerobic conditions to produce methane. Methane bacteria (hydrogenophilic) and acetoclastic methane bacteria (acetophilic) are two groups of methane-producing bacteria [5,6,9]. In the methanogenesis stage, methanogenic archaea convert acetate and H_2 or CO_2 into CH_4 and CO_2 .

There is a wide range of parameters that affect the biogas yield in an AD process, such as chemical composition of feedstock, and process parameters such as pH, temperature, and hydraulic retention time [12,13]. It is important to understand these parameters to optimize yields and incorporate them into mathematical models and applications on an industrial scale.

1.1.2 Chemical characterization of feedstock

Feedstock characterization and management plays a significant part in the overall supply chain of biomethane. It is difficult to estimate the exact composition of feedstock, as the content of organic matter in each source varies (simple to complex) based on the source type (food waste, agricultural biomass, manure etc.). There are four important concepts to understand in selecting the AD substrate: 1. Bioavailability, 2. Bioaccessibility, 3. Biodegradability, and 4. Carbon/Nitrogen (C/N) ratios [5]. Bioavailability is defined as the fraction of ingested nutrient available for utilization, bioaccessibility is the fraction of food waste available for microorganisms to absorb, and biodegradability is the ability to breakdown organic material into simpler molecules. Bioaccessibility and biodegradability depend on the digestion time and hydrolytic activity of the material. However, chemical analysis of the substrate helps to understand the biochemical composition of specific substrates.

1.1.3 Protein-rich substrate

Proteins play an important role in AD substrates producing biogas and can be found in nearly all organic substrates. Pig and chicken manure, and slaughterhouse waste are some examples of protein-rich substrates. Food waste and domestic wastewater have low protein concentration. Many previous studies proved that the protein-rich substrates help to increase the production of biomethane by AD [14,15]. Proteins are made of amino acid sequences, and each amino acid sequence has an amine ($-\text{NH}_2$ -) group. Processing protein-rich substrates in AD is a very complex task because it tends to produce ammonium ions

and disease-causing proteins like prions, also known as PrP^{Sc} [16]. The high ammonium ion concentration in AD inhibits methanogenic bacteria, responsible for producing methane. However, this can be prevented by optimizing the C/N ratios. Table 1.1 presents the C/N ratio of different substrates. Many studies have identified varying C/N optimum values, but the most acceptable values to avoid ammonium accumulation is 25-30:1 [17]. Ahiring's study reported that chemical treatment methods could also eliminate prions before getting inside the anaerobic reactor [16].

Table 1.1 Carbon/nitrogen (C/N) ratios of different substrates [5].

Substrate	Carbon/nitrogen (C/N) ratio
Cow dung	16-25
Poultry manure	5-15
Pig manure	6-14
Fruits and vegetable waste	7-35
Food waste	3-17
Mixed food waste	15-32
Sugar cane bagasse	140-150
Corn straw	50-56
Sawdust	200-500

1.1.4 Carbohydrate-rich substrate

Carbohydrates are the most common organic material present in all types of substrates in different proportions. Carbohydrates are most common in regular diets like rice, potatoes, pasta, bread, and other food wastes in the form of starch. The carbohydrates are generally hydrolyzed in a few hours, depending upon the operational parameters like enzyme loading, pH, and temperature. The carbohydrate-rich substrate is often used as a supplement when there is a shortage of substrate sources, and it helps in increasing the rate of protein conversion and protease activity. Maintaining a balanced C/N ratio is important in selecting substrates for AD as it is necessary to provide required nutrient balance to the bacteria [18]. Co-digestion of agricultural wastes with other livestock waste without prior mixing or pretreatment increases the lignin content and C/N ratio, thereby decreasing the biogas yields. The decomposition of carbohydrates leads to the formation of volatile fatty acids (VFA's). Substrates with high concentrations of simple sugars may accumulate VFA's in the reactor and thereby lower the pH and inhibit methanogenesis. So, an AD reactor

must be designed in such a way that it could prevent the over-production of VFA's. However, this can be avoided by mixing carbohydrate-rich substrates with proteins and fats, which helps in the digestion of the hemicelluloses, cellulose and also improves the buffering effect of NH₃ and VFAs [16,19].

1.1.5 Fat-rich substrate

Fats are easily degraded and commonly found in oil mills, dairy industries, and wastewater from slaughterhouses. AD substrates with high fat content are used to increase biogas yields. The disintegration of fats (triglycerides) produces glycerol and long-chain fatty acids (LCFA's). Glycerol is then converted to biogas, while the disintegration of LCFA's in high concentration leads to malfunction of microbes in AD. LCFAs can cause foaming and are responsible for the inhibition of biological function, which can be measured with the half-maximal inhibitory concentration (IC₅₀). To avoid this problem, the fat-rich substrate should be mixed with a carbohydrate-rich substrate, which also helps in achieving high efficiency of biogas production [5,16]. The yield from manure or digested sewage sludge is reported to be 70.62 cubic foot biogas per cubic foot reactor volume per day. In comparison, the reactors would yield in the range of 141 to 353 cubic feet biogas per cubic foot reactor volume per day after adding 20% fatty waste. Adding fats and oil waste to the already existing food waste or household waste, even in small amounts, could increase the production of biogas extensively [16,19]. Table 1.2 represents theoretical AD yields and methane content for different categories of substrate [20].

Table 1.2 Theoretical biogas yields and methane content of substrates [20].

Substrate	Biogas yield (Nm ³ /t TS - cubic meters/ ton of total solids)	Methane	Carbon dioxide
Raw Protein	700	70-71 %	29-30 %
Carbohydrates	790-800	50 %	50 %
Raw Fat	1200-1250	67-68 %	32-33 %

1.1.6 Temperature

An anaerobic digester is operated mainly in three temperature ranges, 1) Psychrophilic (25 °C), 2) Mesophilic (35°C), and 3) Thermophilic (55°C). Mesophilic and thermophilic temperatures are considered as the best suitable for the growth of AD microbes. It is crucial to maintain a steady temperature range from 45-60°C (thermophilic) during the digestion process. Generally, thermophilic temperatures require more energy to heat and it is more difficult to maintain the constant temperature of the AD. The temperature variations have negative impacts on microorganisms, which in turn significantly impact biogas production [21-23]. Optimum temperature range also helps methanogenic bacteria to generate more

methane, but at elevated temperatures outside the optimum range has been found to increase the ammonia concentration and inhibit the microbial population, causing a decrease in biogas production [13,24]. The Mesophilic temperatures are also suitable for thermophilic bacteria, but the growth rate is slower [25].

1.1.7 pH

pH has a significant effect on the AD process. In general, most of the microorganisms prefer neutral pH; however, in the AD process, there exists a wide range of microbes that require different pH conditions. Some studies reported that maximum biogas yields are achieved at a pH range of 6.8-7.2 [25] where the microbes are most active. The acidogenic bacteria are less sensitive to pH compared to methanogenic bacteria. The acidogenic bacteria prefer a pH range of 4-8.5, whereas methanogens favor a pH of 7.0. The optimum pH for hydrolysis and acidogenic bacteria is 5.5-6.5 [15,26]. One of the significant factors to separate digester in two stages is to maintain optimum pH values by separating two phases in two reactors acidogenesis and methanogenesis, respectively [26,27]. The co-digestion of substrates is used for maintaining stable pH values and, to avoid acidification in the reactor. The pH is easy to control with mixed substrates than with one substrate as a change of pH is more stable in a mixture compared to a single substrate [28].

1.2 Two stage anaerobic co-digestion (AcoD) process

Two-stage AcoD was first developed and designed by Pohland and Ghosh [29]. In this setup, co-digestion happens in two reactors in a semi-continuous mode. In semi-continuous feeding, the liquid slurry from the first reactor is removed after regular HRT (hydraulic retention time) intervals and an equal volume of substrate is added to each reactor [29,30]. The first reactor is operated at 30-40°C and at a pH of 5.5-6.5 to facilitate the acidogenic reactions, and the second reactor is operated at 45-60 °C and at a pH of around 7 to facilitate the methanogenic reactions [31,32]. The two-stage AcoD helps to achieve stability by controlling acidification in the first reactor and enhanced methanogenesis in the second reactor [5]. The methanogenesis is carried in two pathways, 1) acetate pathway, and 2) hydrogen pathway. About 70% of methane is produced through the acetate pathway with the help of acetogenic bacteria at a slow growth rate, and the remaining 30% of methane is produced through the hydrogen pathway at a fast growth rate using the methanogenic bacteria [5].

Table 1.3 Advantages and disadvantages of two-stage over single-stage AcoD.

Advantages [33-36]	Disadvantages [37,38]
<ul style="list-style-type: none"> Increased stability and pH control Higher organic loading rates compared with single stage AcoD Efficient control of pathogens 	<ul style="list-style-type: none"> Inhibits acid forming bacteria due to hydrogen buildup It needs higher investments in terms of capital

<ul style="list-style-type: none"> • Volatile solids to chemical oxygen demand ratio (VS/COD) could be reduced efficiently. • Production of methane increases with increase in specific activity of methanogens. 	<ul style="list-style-type: none"> • Interdependent nutrients elimination is possible for methanogenic bacterial • It involves complex technicalities
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Table 1.3 lists the advantages of the two-stage AcoD. Advantages include maintenance of good culture stability and pH, high organic loading rate (OLR), and efficient control of pathogens. These features help to generate more methane despite limitations that affect the microbial activity and high capital costs [5]. Fluctuations in the concentration of substrates may lead to process instability; this is observed mostly in large-scale biogas plants treating different ratios of different types of wastes. Detecting the process problems is a challenging task in anaerobic digestion plants. However, this could be countered by installing sensors, which would make it easier to detect process upsets. Many studies proved that the two-stage AcoD process has stable pH control and high methane yields compared to a single stage. The two-stage system allows increased stability by controlling acidification in the first reactor, thereby avoiding the inhibition of methanogenic bacteria in the second reactor. The acidogenesis stage can be optimized to generate bio-hydrogen to enhance methane production in the second stage. The two-stage system may solve the VFA inhibition problem and help to study the microbial populations and variations in the system. Microbial process and their efficiency could be increased by bio-augmentation, i.e., by employing microbial populations having advanced degradation abilities, for example, xylanolytic microbes (thermophilic) [16].

1.3 State of the practice for biogas production in the U.S.

Biogas production has been encouraged in the U.S. through policies such as the Clean Air Act and as an alternative to natural gas for vehicles through transportation policies such as the national Renewable Fuel Standard (RFS2). Additionally, some of the US policies that banned food waste disposal indirectly influenced the production and the application of biogas [39]. This measure led to a decrease in GHG emissions from landfills. Additionally, from a performance criterion, there is no difference between biogas and natural gas after separating CH₄ from the biogas and the elimination of pollutants like siloxanes, CO₂, and H₂S. The use of biogas would be more prominent if it is economically produced, which in turn depends upon factors such as availability of feedstock and production cost, equipment costs, and demand. Table 1.4 discusses available resources for biogas production in different states of the US [40] .

Table 1.4 Sources of substrates for biogas production in U.S.

State	Total food waste generated (Million tons/yr.)	Total manure (Million tons/yr.)	Total wastewater (Million gallons/day.)
California	12.3	44.8	3235
Colorado	1.79	5.80	291
Connecticut	1.1	0.50	191
Florida	6.70	3.4	1050
Georgia	3.29	12	456
Illinois	3.93	11.4	1951
Iowa	0.98	46.7	256
Maryland	1.88	3.2	537
Massachusetts	2.15	0.28	571
Michigan	3.1	13	1133
Minnesota	1.75	29	371
Missouri	1.9	11.1	637
Nevada	0.96	0.85	188
New Jersey	2.76	0.15	996
New York	6.03	16	2617
North Carolina	3.25	24.3	471

North Dakota	0.24	0.63	19
Ohio	3.63	11.9	1534
Oregon	1.31	3.2	360
Pennsylvania	3.96	16.9	1324
Rhode Island	0.33	0.021	25
Texas	9	20.6	1772
Utah	1	3.8	254
Vermont	0.19	3.2	28
Washington	2.37	7.2	163
Wisconsin	1.8	33.4	433

Hypothetically, the availability of feedstock should directly correspond to the number of operating biogas plants. However, the data from the American Biogas Council (2018) [40] shows that this is not always the case. Table 1.5 describes the operating biogas plants in each U.S. state for different feedstock sources in alphabetical order. In total, the U.S. has just over 2,000 biogas plants in different locations converting a wide range of feedstock; 250 on farms, 1,269 operating at wastewater treatment plants, and 652 landfill gas projects [40]. The potential for future growth of biogas in the US total over 11,000 additional facilities, mostly on farms processing animal manure (75%), at wastewater treatment plants (20%), and recovery of biogas at untapped landfills (5%). Other developed regions of the world have installed a much greater number of biogas facilities. Germany currently has over 9,000 biogas facilities [40,41]. To show biomethane potential in the US, Ankathi et al [8] estimated that producing biomethane from co-digestion of food waste currently landfilled with dairy manure could displace 0.74% of current US natural gas consumption while reducing US annual GHG emissions by 0.41%.

Table 1.5 Operating biogas plants in the US.

State	Food waste to biogas plants	Agriculture waste to biogas plants	Wastewater to biogas plants	Landfill to biogas plants
California	30	38	156	77
Colorado	1	1	20	4
Connecticut	1	1	10	2
Florida	5	4	40	21
Georgia	4	2	20	24
Illinois	3	3	87	27
Iowa	7	5	53	5
Maryland	1	2	11	10
Massachusetts	8	8	6	15
Michigan	2	8	65	72
Minnesota	3	3	25	7
Missouri	N/A	4	2	6
Nevada	N/A	N/A	5	2
New Jersey	5	N/A	32	22
New York	13	30	118	49
N. Carolina	1	14	26	41
North Dakota	2	N/A	2	2
Ohio	13	7	58	29
Oregon	4	6	34	11
Pennsylvania	9	33	81	58
Rhode Island	N/A	N/A	1	3

Texas	3	2	45	36
Utah	N/A	4	15	5
Vermont	5	17	13	5
Washington	1	9	33	6
Wisconsin	17	40	62	34

The mentioned advantages have led to the widespread adoption of biogas internationally. This is especially true in Europe, which houses 17,376 biogas plants in 2015 [42]. European countries are shifting towards renewable energy sources from the existing fossil-fuel based sources and biogas is a primary focus apart from solar and wind-based energy sources. The policy enables supporting schemes and tariffs for biogas production plants. Additionally, a key inference is that there is a diverse variation in the sources used to produce biogas among the European countries. Based on the source, the biogas production plants are classified as landfill-based, sewage-based, agriculture-based and industrial food, beverage and bio-waste-based plants. Agriculture-based sources predominantly exist in Germany (87% of biogas plants), Italy (80% of biogas plants), Czech Republic (69% of biogas plants) and Austria (46% of biogas plants) while a mix of landfill, sewage sludge, and agriculture-based sources are used in other European countries [43]. The different types of biogas plants, utilizing different feedstocks, by country in Europe are indicated in Figure 1.2 [44]. In addition, the application of biogas is gaining popularity among developing countries as they move forward to sustainable electricity production.

Figure 1-2 Different types of biogas plants by country in Europe [44]

1.4 Introduction to biomethane modeling and production in the US

There are many different processes to generate biogas which includes landfilling, AD of organic feedstock like wastewater sludge, food waste or manure, and thermal gasification of residual or biomass feedstock (lignocellulosic) [45]. The early applications of biogas dates to late 10th century BC in Assyria for heating water through a septic tank that acted as an anaerobic digester. Later in the 17th Century, Jan Baptista van Helmont discovered that the flammable gases could be produced from the microbial decay. The first ever-anaerobic digestion plant was established in 1859 in India, then, in 1895, England built AD plants in Exeter to produce the biogas for streetlamps.

In 1997, the first mathematical AD model involving the biochemical and physio-chemical reactions was proposed by researchers through the International Water Association (IWA). IWA extended the MATLAB model by modeling two-stage digestion which is then created a base simulation for wastewater treatments. The AD process modeling has been improving since then; for example, Peris Serrano, 2010 [46] modeled biogas simulation using calculation block coded in FORTRAN and then incorporated in the process simulation software Aspen Plus. However, this model can simulate only the acidogenic, acetogenic and methanogenic stages of AD process using two reactor sets but not the hydrolysis. Additionally, that model is incomplete as feed is assumed to be already hydrolyzed and hence, not suitable for wide applications. This model was further developed by Rajendran et.al., 2014 [47] and Al-Rubaye et al., 2019 [48] who proposed a two-stage model including

the hydrolysis step and, an AD simulation model that predicts the effect of H₂ in feed stream with the biogas production in the product stream, respectively. The former study had challenges with mass balances in the proposed simulation that rendered the model inconsistent whereas the later did not address biogas downstream processing. Recently Flores-Alsina et al. 2016 [49] further developed the MATLAB model by including the interactions of sulphur, iron, and phosphorous in a dynamic simulation environment. All the references of these AD models are presented in Table 1.6. There are other software tools in the market such as Aquasim, Biowin, and Simba; all used to predict the biogas yield and composition by varying different process and feed parameters.

Table 1.6 Different anaerobic digestion models.

Model	Software used	Reference
Single stage AD model (IWA 2002)	MATLAB	[11]
Two-stage AD using the IWA Anaerobic Digestion Model No. 1 (ADM1)	MATLAB	[30]
ASM/ADM model interface for dynamic plant-wide simulation	MATLAB	[50]
Benchmark simulation model no 2:	MATLAB	[51]
Extension of anaerobic digestion model no.1 with processes of sulfate reduction	MATLAB	[52]
An extension of the Anaerobic Digestion Model No.1 to include the effect of nitrate reduction processes	MATLAB	[53]
Modelling phosphorus (P), sulfur (S) and iron (Fe) interactions for dynamic simulations of anaerobic digestion processes.	MATLAB	[49]
Modelling of food waste digestion using ADM1 integrated with Aspen Plus	MATLAB, ASPEN PLUS	[54]

Novel Process simulation model for AD	Fortran, Aspen Plus	[47]
Two stage AD for methane production	Fortran, Aspen Plus	[48]
Biogas Process simulation using aspen plus	Fortran, Aspen Plus	[46]

As mentioned earlier, biogas can be produced using different feedstocks. These sources have different potential to produce biogas. Figure 1.3 indicates these potentials [55-59]. Fats and greases have the highest potential to produce biogas followed by bakery wastes and food scraps. Manure from pigs and cow have very low potential to produce biogas as compared to the above-mentioned wastes. The results from Figure 1.3 are experimental biomethane potentials (BMP's) seem to be misleading because they were completely carried out under perfect laboratory conditions. The results from BMP do not give broader information on application in actual digesters. A co-digestion product might be favorable at lab scale but can be toxic in high loading rates at commercial scale [59]. The biogas obtained from these sources can then be used for producing pipeline biomethane or electricity. However, the extent of this diverse application depends upon the geographic, social, economic, environmental benefits and policies at hand.

Figure 1-3 Biogas Potential for different substrates [80-84]

1.5 Current federal and state policies on biogas in the US

Although the above-stated potentials, trends, and characteristics present an optimistic view about the application of biogas, the existence of relevant policies and legislation plays a crucial part in turning these potentials into reality. Most of the policies that incentivize or encourage the use of biogas are indirect i.e., the policies holistically cover all renewable energy sources. The following paragraphs discuss such direct and indirect policies and programs. Agencies like the US EPA (Environmental Protection Agency), USDA (United States Department of Agriculture), and DOE (Department of Energy) have passed several policies/programs at the national level to enhance the application of biogas [60]. Table 1.7 lists these policies and programs in detail.

Table 1.7 Policy/Programs initiated by agencies.

Agency	Policy/Program	Details
USDA	(REAP) Rural Energy for America Program	Financing for anaerobic digester projects
	Renewable Chemical, 9003 biorefinery and biobased product manufacturing assistance program	Funding for commercial, municipal, and industrial biogas plant formation
	Rural Utilities Services (RUS)	Federal Financing Bank Loan
	NRCS (National Resources Conservation Service) and EQIP (Environmental Quality Incentives Program)	Financial and technical assistance to agricultural producers through contracts.
	Program Coordination (Stacking)	Deliver USDA services to producers
EPA	Renewable Fuel Standard (RFS)	Generates credits or Renewable Identification Numbers (RINs) for biofuels
DOE	Renewable Hydrogen Potential resource assessment from Biogas in the US	Determines overall potential and net accessibility of methane in raw biogas
	Bioenergy Technologies Office (BETO) and Multi-Year Program Plan (MYPP)	Identifies potential of high-impact resources for domestic manufacturing of bio-product

		precursors, biogas, biofuels, electricity and heat.
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The RFS program provides financial incentives for biogas-derived electricity used for transportation and approved biogas as an RFS qualifying feedstock in 2014. Some of the complementary state programs to the federal RFS include California's Low Carbon Fuel Standard (LCFS) and Oregon's Clean Fuels incentive programs [61]. The Farm Bill program provides grants and loan guarantees to agricultural producers and rural small businesses to produce renewable energy and improve energy efficiency. The AgSTAR program is jointly supported by EPA, DOE, and USDA to produce biogas at livestock operations as a means to reduce methane emissions.

The federal electricity Production Tax Credit (PTC) policy provides per kWh tax credits for qualified energy resources such as biogas. Currently, the PTC is valued at about 2.3 cents/kWh [61]. Under this policy a modification of facility can also receive investment credits but should be an electricity generation facility. New market tax credits is another policy which allocates credits for the projects located in low-income regions. Apart from these policies and acts of legislation, numerous policies such as National Gas Act, Clean Air Act, Clean Energy Standard, Carbon Pricing, and Renewable Portfolio Standards directly or indirectly aid the application of biogas at the national level [40].

Similarly, there are many direct/indirect policies initiated at the state level. Most of the states in the U.S. have Renewable Portfolio Standards (RPS) that indirectly influence the generation and application of biogas through AD. There is a wide disparity for motivation to generate and use biogas among states. This may be because of a lack of policies benchmarking the application of biogas [60]. Through the 2012 Bioenergy Action Plan, California plans to utilize and implement diverse biomass resources to produce low-carbon biofuel, biogas, and renewable electricity. Additionally, other California policies such as the Western Climate Initiative, Greenhouse Cap and Trade Market aim to reduce GHG levels indirectly aid the utilization of biogas. According to the Iowa's House Bill 544, a facility employing waste conversion technologies, including anaerobic digestion, shall obtain an annual permit from the department and the annual fee for such permits shall be sufficient to cover the costs of the permit program. The state of Maryland has many indirect policies such as the GHG Reduction Plan and Maryland's Source Reduction Credit System, with goals for waste diversion and recycling rates that boost the application of biogas [62].

New York is also one of the forefront states in the generation and application of biogas. There are several policies, such as the Clean Energy Fund, Greenhouse Gas Bans and Reforming the Energy Vision (REV) proposal, that aid the application of biogas. Wisconsin has also pioneered the application of biogas through its conversion into CNG fuel from the Dane County landfill and the Janesville wastewater treatment plant. Similar policies exist in North Carolina, namely, the Renewable Energy Investment Tax Credit and House Bill 681 [40]. The Database of State Incentives for Renewable Energy (DSIRE®)

provides a U.S. map that can be used to find various renewable energy policies, including those related to anaerobic digestion [63].

1.6 Social factors with biogas applications in the US

Only a few U.S. studies [64,65] have highlighted social barriers to biogas applications, while others [66] highlighted social benefits and/or issues in Germany [67], Denmark [68], Africa [69-71], Malaysia [72], China [73], India [74], Nepal [75,76], Latin America [77], and Bangladesh [78,79]. Some of the noted common social benefits include employment opportunities, improved health of communities, and local source of renewable energy, while common barriers include lack of public/stakeholder participation in decisions about biogas adoption, public acceptance, inadequate knowledge, and a desire to maintain the status quo.

Some of the major social barriers identified to the use of biogas as renewable energy in the US include odor complaints, difficulties in coordination with local power and gas utilities, and following business-as-usual (BAU) (maintaining status quo), but also include human factors such as lack of knowledge and experience, breakdown in decision making, poor communication, lack of interest in green power, political support (difficulties in gaining projects approval, time delay in getting permissions from regulators for air permitting) [65], and poor siting [80] (remote location of facility and nature of road infrastructure). Also, the cheap price of fossil fuels such as natural gas, is another factor affecting the lack of increased implementation of biogas production and use in the US [81]. Odors at an AD facility may arise from waste receiving, biogas storage bladder vents, in-vessel and outdoor composting sections, and transportation of feedstock or processed waste to and from the facility [82]. For example, the Heartland biogas facility near La Salle, Colorado, which converted food waste and cattle manure into biogas, has suspended operations due to neighbor complaints about the unpleasant odor [83].

According to a US study [65], some biogas producing facilities face difficulties in coordinating with outside agents such as power and gas utilities. Many power companies may not accept biogas produced electricity due to concerns, justified or not, over the consistency of power production. In order to overcome such difficulties with outside agents, some strategies were suggested: to leverage current relationships with third parties to discuss potential of combined heat and power (CHP), public education on benefits of CHP, and to classify biogas as a renewable energy source (some of the jurisdiction may not classify the same). Their study also highlighted that some facilities may not be willing to adapt to new technologies / changes and may restrict their focus only on their core objectives such as complying with National Pollutant Discharge Elimination (NPDES) permits to produce clean water and not on CHP to produce electricity. This barrier of maintaining status quo could be overcome by highlighting the risk of status quo to decision makers and advocate for beneficial use of biogas.

The lack of knowledge or awareness about the benefits of biogas hinders achieving a robust biogas industry in the US. Gaining deep understanding of the overall biogas systems and

value of investing in biogas systems in the US could be beneficial for different stakeholders such as investors, the public, policy makers [84]. The biogas producing facilities in small villages face the barrier of lack of skilled workers [65]. The barrier of human factors such as decision-making, communication, lack of experience and knowledge can be overcome by decision theory and analysis, and innovation diffusion theory, which is further discussed in detail elsewhere [65].

1.7 Economic costs and benefits

Techno-economic analyses of biogas energy technologies determine their profitability, typically using a discounted cash flow methodology. Many prior techno-economic analyses focused on biogas in combined heat and power applications, but very few studies for cooking and as a vehicle fuel. Tables 1.8 – 1.10 contain a summary of techno-economic analyses including different feedstocks, operating conditions such as capacity, utilization, organic loading rate (OLR), hydraulic retention time (HRT), and determined different profitability indicators such as net present value (NPV), payback period (PBP), internal rate of return (IRR), discount rate (DR), capital expenditure (CAPEX) and operational expenditure (OPEX). This review is based on 14 articles from diverse geographic locations. Some of these studies use discounted cash flow analysis while others are limited to cost-benefit analysis

Table 1.8 Summary of 14 different techno-economic articles on AD.

Location	Italy [85]	Egypt [86]	Turkey [87]	India [88]	USA (IA, MD, CT, NY, VT, MN) [89]
System	Converting a biopower plant to biomethane plant	Household biogas production	Farm scale biogas plant	Novel biogas digester for replacing LPG and Kerosene	Economic analysis of small-scale Ag digesters
Feedstock	Cattle/ buffalo manure co-digested with energy crop and whey	Dairy manure co-digested with crop residues (7:3)	Dairy manure co-digested with sheep dung	OFMSW, manure and water	Cow manure
LCA				X	
TEA	X	X	X	X	X
GIS		X			
Capacity	4.4 MWh d ⁻¹		289 kW		Average 0.8 MWh/cow/year
Digester volume(m³)	D1-270, D2-750	2-6	2713	1.5-4	Based on # cows range from 100-250

CAPEX	€ 1,205,000	€582.28 - €1151.31	€2500 to €7500 per kWh/h	200-300 USD	\$12000-\$61000 per annum
OPEX		€283.99 -€851.96	€0.019/kWh	5% of capital costs	25% to 50% of annual capital costs
ESP	0.093€ kW/h instead of 0.28 € kW/h ^a and BM sold at 0.23/m ³	€0.55 per m ³ of biogas	€0.1/kWh		Heat and electricity \$47- \$100/cow/year and CO ₂ credits (\$7/cow/year)
DSP		€50.3–€60.4 per m ³	Solid - €120/t, Liquid- €32/t		\$100/cow/year for solids
HRT (days)	D1-10, D2-20	30	25-40	75	
OLR			2.29 and 0.44 kg ODM/m ³ d	0.1-1 gVS/L/day	
GHG emissions			7506 t CO ₂		
NPV	– €903,473.18	€10649 - €32543.2	€9.88 million	\$250-\$3500	8 of 16 digesters showed positive NPV at 50% cost share
PBT (years)	35.3	3.2 – 4.8	3.4	1.3-3	

IRR (%)		30.8 - 39.6		12-108	
TR (%)					
IR (%)		15			
DR (%)		12	14	8±5	8
Used for Cooking		X		X	
Used as BioCH₄	X				
Used as electricity			X		X
Used as heat			X		X
Key outcomes	Upgrading to biomethane is not economically feasible even under incentives. Due to the high investment cost for upgrading	The household small scale biogas in rural Egypt is profitable and the profitability indicators increased with increase in the size of biogas	The biogas produced in a CHP unit is more profitable than the utilizing biogas in a combustion unit that produces only heat.	This novel system is economically feasible for replacing LPG and kerosene in both subsidized and non-subsidized scenarios, reducing the fossil needs	Economically viable on 250 cow dairies but additional revenues such as tipping fee from food waste may reduce the size to 100 cow dairies

Table 1.9 Summary of 14 different techno-economic articles on AD (continued).

Location	Italy [90]	Sweden [91]	Canada* [92]	Colombia [93]	USA (Louisiana) {Co-EAT} [94]
System	Regional biogas power generation	Biogas CHP plant from manure under mesophilic and thermophilic cond.	Utilization of Food Processing Waste for Production of Energy and Chemicals	Co-digestion of Milk whey and potato	AD of food waste
Feedstock	Citrus pulp, Olive pomace, Cattle manure, Whey, Poultry manure, Silage	Manure	food waste and water	1000 m ³ /day for MW and 300 t/day for PS	Food waste
LCA					
TEA	X	X	X	X	X
GIS	X		X		
Capacity	3.6 MW-e (0.9-1.2 MW-e)	1-6 GWh/annum	Variable	13,277 kW of power	1,739,866-3,717,514 kWh/year

Digester volume(m³)		500-2900			2600- 5800
CAPEX	€2690000- €3156000	Meso: 17000€/year to 90000€/year	38142439 Canadian dollars	\$5.49 M.- \$34.28 M.	\$561/ton of FW
OPEX	4% for digester 3% for CHP unit	2.5-4% of investment costs	1,970,400 Canadian Dollars	\$7.96 M.- \$15.35M. per year,	\$48/ton of FW
ESP	0.16 €/kWh	20–50 €/MWh	\$0.035/kWh*	0.14 USD/kWh	\$0.078/kWh and \$2.67/mcf. for heat
DSP	0.02 €/wet kg	0.5 to 3.2€/ton		10-30 USD/ton	Assumes no revenues
HRT (days)	20	Meso:25 and Themo:18		30	
OLR				0.04 & 0.45 m3/kg VS	
GHG emissions					
NPV				-\$21.15 to -\$45.21 M. at \$10/ton digestate sale price	-\$6,762,992

PBT (years)	< 6.5 years				
IRR (%)			10		
TR (%)				25	
IR (%)	2	5		17	7
DR (%)					10
Used for Cooking					
Used as BioCH₄					
Used as electricity	X	X	X	X	X
Used as heat	X	X	X	X	X
Key outcomes	This system can satisfy 27% of Italy electricity needs	1. CHP from biogas based on manure is not profitable under current market conditions in Sweden, 2. Biogas process operated under thermophilic conditions is profitable than	With C.C: - Economically viable at 10% IRR with a tipping fee of \$81/t for S.S(500 t/yr.), \$64/t for M.S(10000 t/yr.) and \$57/t, for L.S(2000 t/yr.), By	High organic load has the best economic feasibility, and raw material cost is the most important factor in the economics	Poor financial performance includes low area tipping fees and energy prices as well as high capital costs for the technology.

		mesophilic conditions.	keeping gate fee at \$65/t the IRR varies from 3.6,10.5,17.8 for S.S, M.S and L.S respectively.		Additionally, there is no state policy requiring renewable energy generation
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Table 1.10 Summary of 14 different techno-economic articles on AD (continued).

Location	Canada* [95]	USA (Iowa) [96]	Palestine [97]	Spain (Barcelona) [98]
System	Electricity Production from Anaerobic Digestion of Household waste	Farm scale AD	Biogas energy from animal wastes	Co-digestion of animal manure and cheese whey
Feedstock	78% kitchen organic waste and 22% nondegradable material	Biomass, manure and glycerin	Cow, Sheep, Goat, and Chicken manure	livestock manure (Cow, Goat & Sheep) and cheese whey
LCA	X	X		
TEA	X	X	X	X
GIS				
Capacity	0.5-10 MW	950 kW	7 MW	

Digester volume (m³)			3000-8000 (12 Digesters)	1174
CAPEX		\$0.44-\$0.55 /kWh	\$21600000	
OPEX		Glycerin reduces the operating cost by 32%.	\$5108000	7200 €/year.
ESP	\$0.147/kWh	\$0.064/kWh and \$(0.015)/kWh-e renewable tax		0.14 ± 0.03 €/kWh.
DSP	at no cost to farmers	liquid- \$2.64/t; Solid: \$35.25/t		
HRT (days)	22		50	28
OLR				2.0 kg COD·m ⁻³ ·d ⁻¹
GHG emissions	0.7 to 1 t CO ₂ eq/t HSSOW	358-400 g CO ₂ e/kWh for glycerin scenario		
NPV		Greater NPV for Glycerin case	\$7392000	>0
PBT (years)			8	<10
IRR (%)	11	3.51 and 5.57		5-10

TR (%)		39		
IR (%)		7.5		
DR (%)				
Used for Cooking				
Used as BioCH₄				
Used as electricity	X	X	X	X
Used as heat	X	X	X	X
Key outcomes	Current FiT rate (\$0.147/kWh), a 200 kt/yr facility requires a \$50/t fee to attain an 11% IRREQUITY, while a 50 kt/yr facility requires a \$95/t fee to reach an 11% IRREQUITY	Increased the ROI by 27% with glycerin addition	Economically feasible with a ROI of 15%	Co-digestion of manure with cheese whey found to be economical compared to mono digestion of animal manure. NPV is negative and the IRR ranges from 0.97 to 5.88% for low Cheese whey % ratio

TEA: techno economic analysis; GIS: geographic information systems; CAPEX: capital expenditure; OPEX: operating expenditure; ESP: estimated selling price; DSP: digestate selling price; HRT: hydraulic retention time; OLR: organic loading rate; NPV: net present value; IRR: internal rate of returns; TR: tax rate; IR: interest rate; DR: discount rate; FiT: feed in tariff; ROI: return on investment; Canada* indicates the values in Canadian dollars, kt/yr: kilo tons/year

Feedstocks reported in the techno-economic analyses could be categorized into the conventional substrates such as the organic fraction of MSW [88], animal manure [85-91, 96-98], or food waste/kitchen waste [90, 92-94] and the other feedstocks such as milk whey, and energy crops [85, 86, 90, 93, 96, 98]. Capacities reported in techno-economic analysis varied between 20,000 and 200,000 tons of annual processing capacity, while the CAPEX ranged between 25 and 165 M\$. The IRR, DR, and PBP ranged between 7-20%, 8%-15% and 35.3-1.3 years for the small-scale and commercial-scale facilities, respectively.

These studies showed that co-digestion of feedstock showed a positive impact on the economic feasibility compared to mono-digestion. A study from Seyed Mostafa [98] showed that co-digestion of cheese whey and raw dairy manure to produce electricity and heat has a positive NPV for all sizes of herds (minimum 115 head) at high cheese whey ratios ($> 30\%$) compared to mono-digestion of animal manure. The IRR and PBP for Mostafa study were found to be 10% and < 9 years respectively at a co-digestion ratio of 70:30 of manure: cheese whey [98]. The microbial conditions affect the economics of biogas plants. For example, a study by Mikael [91] on CHP generated from biogas based on AD of manure alone illustrated that with a capacity of 1-6 GWh/annum at a 5% interest rate is not profitable under the market conditions in Sweden, whereas biogas processes operated under thermophilic conditions showed higher profitability compared to mesophilic conditions. Martínez-Ruano studied co-digestion of milk whey and potato to generate electricity with a 14 MW capacity showed that with higher organic loadings, NPV decreased from \$-45M. to \$-21M. but still negative due to high raw material costs [93]. Additionally, Alvina's study [96] on co-digestion with glycerin increases the profitability of biogas CHP plants (increased ROI by 27%). Moreover, profitability increases with increasing size of the biogas plant [86].

Most of the studies reported that lack of incentivizing policies, high capital cost and low tipping fee are the critical barriers in the biogas-to-energy or biogas-to-fuel technologies [85, 89, 93-95]. A study by Sanscartier [95] from Canada showed that with current feed in tariff (FiT) rate (\$0.147/kWh), a 200 kt/yr co-digestion facility requires a \$50/t tipping fee to attain an 11% IRR, while a 50 kt/yr facility requires a \$95/t fee not accounting the revenue from digestate sales. Ullah [92] studied the effect of carbon credits by varying the tipping fee and including carbon credits to attain a 10% IRR. The results from that study showed that the facility requires a tipping fee of \$81/t for small scale (500 t/yr.), \$64/t for medium scale (1000 t/yr.) and \$57/t, for large scale (2000 t/yr.) for 10% IRR. Keeping the gate fee at \$65/t and with carbon credits, the IRR varies 3.6, 10.5, 17.8 for SS, MS, and LS, respectively.

Studies also showed that biogas produced in a CHP unit is more profitable than the utilizing of biogas in a combustion unit that produces only heat [87]. Upgrading from CHP to biomethane for an existing plant is not economically feasible without incentives due to high upfront costs for biomethane separation [85] but producing biogas for cooking and to

replace LPG and kerosene is economically and environmentally feasible in both subsidized and non-subsidized scenarios [88].

1.8 Environmental issues of biogas production

There are many reviews focused on environmental life cycle assessment (LCA) of AD, some emphasizing different feedstocks such as food waste co-digestion [99,100], manure alone [101] and co-digestion of manure with energy crops [102]. Some are location-specific such as LCA of biogas in Europe [103] and co-digestion of pig slurry and energy crops in Italy [102] and a few are based on applications such as electricity [104]. A detailed summary of different LCA studies based on diverse geographic locations with multiple feedstock types and multiple products is shown in Table 1.11-1.13.

Table 1.11 Summary of 13 different LCA articles on AD (emphasize GHG emissions).

Functional Unit (FU) [Citation]		100 kWh of CHP electricity [102]	One metric ton of influent processed [105]	7,153 dry metric tons (t) of DM & 2,382 dry tons of FW per year [106]	1 ton of OFMSW [107]	1 kWh of electricity produced [99]	1 ton of MSW [108]
System boundary		Cradle - to - Gate	Cradle - to - Grave	Cradle - to - Grave	Cradle - to - Grave	Cradle - to - Grave	Cradle - to - Grave
Carbon accounting		Considers biogenic carbon emissions	Do not include biogenic emissions, only fossil emissions	Accounted for biogenic carbon through stoichiometric equation for FW and dairy manure	Do not consider the biogenic combustion emissions from biogas	Not accounted for the biogenic emissions	Not specified any information on biogas CO ₂ emissions but considers biogas CH ₄ combustion emissions
	DM		X	X			
	Pig manure	X					

Feedstock	Others	Energy crops (EC)		Bakery process waste			
	FW		X	X		X	
	MSW				X		X
	Sewage sludge						
Biogas utilization	As fuel				X		X
	As electricity	X	X	X	X	X	
	As heat	X	X	X			
Impact categories		AP, EP, GWP, ODP, POFP, CED, ADP	GWP	GWP, WEP, AAP, SP	GWP	GWP	GWP, AAP, EP
		Sub systems: 1. biomass production 2. biomass transport and processing 3.	1. Conventional management of slurry and food waste,	Scenario 1: Co-digestion of DM & FW, Scenario 2: AD of DM	1. Using OFMSW for electricity generation	Case 1. Biogas plants are fed with EC Case 2. EC are replaced by	AD of MSW for vehicle fuel

Results	Cases studied	bioenergy plant operation 4. digestate management	2. AcoD of food waste and slurry	and FW to landfill.	(S.S, M.S and L.S AD) 2. Using OFMSW for fuel generation Ref: Conventional incineration of OFMSW	209 tons FW from malls. Case 3. EC are replaced by 6809 tons of FW from malls and the food industry.	
	best case	-	AcoD Case	AcoD Case	-	Case 3	-
	Key results	The total net emissions of the overall system found to be $-0.016 \text{ kg CO}_2\text{-eq} / 100 \text{ kWh-e}$. The combustion emissions from biogas power plants contribute major impact with respect to GWP	Conventional management emissions: $6348 \text{ tCO}_2\text{-eq} / \text{year}$ AcoD emissions: $1836 \text{ tCO}_2\text{-eq} / \text{year}$	Scenario 1 emissions: $1.6\text{E}4 \text{ t CO}_2\text{-eq}$, Scenario 2 emissions: $2.7\text{E}4 \text{ t CO}_2\text{-eq}$	The reference scenario gives about $130 \text{ kg CO}_2\text{-eq/FU}$ than the medium and large-scale scenarios and about $80 \text{ kg CO}_2\text{-eq/FU}$ more than the small-scale scenario.	Emissions in $\text{kg CO}_2\text{-eq/kWh-e}$ Case 1: 0.37 Case 2: 0.36 and Case3: 0.15	Total GHG emissions reported: $61 \text{ kg CO}_2/\text{t MSW}$, and $0.25 \text{ kg CH}_4/\text{t MSW}$

Table 1.12 Summary of 13 different LCA review articles on AD (continued-emphasize GHG emissions).

Functional Unit [Citation]		1 MJ of electricity (MJe) [109]	1t FW volatile solid (VS) [110]	1000 tons of FW and 4400 tons of SS [111]
System boundary		Cradle - to – Grave	Cradle - to – Grave	Cradle – to – grave
Carbon accounting		Biogas combustion emissions in CHP for electricity generation are included	Combustion emissions from biogas are included	Not specified
Feedstock	DM	X		
	Pig Manure			
	Others	Silage maize		
	FW		X	X
	MSW			
	Sewage sludge			X
Biogas utilization	As fuel			X
	As electricity	X	X	
	As heat	X	X	

Impact categories		GWP, PMF, ODP, AP, abiotic depletion, POCP, EP, Human toxicity and freshwater ecotoxicity	GWP, AP, EP, ODP, POF, CED, ADP, HT, PMF, IR, TA, FEP, MEP, TE, FE, ME, ALO, ULO, NLT, WDP, MDP, FDP	ADPE, ADPFF, AP, EP, FWETP, GWP, HT, MAETP, ODP, POC, TET
Results	Cases studied	(a) biogas from maize: open storage (I-A), closed storage (I-B), (b) biogas from manure: open storage (II-A), closed storage (II-B) and (c) biogas from co-digestion of maize and manure: open storage (III-A), closed storage (III-B).	Case-1: AD for FW and sludge, Case-2: AD of FW, Case-3: FW to landfill	Mono-AD; Co-AD-30% (less methane yield), Co-AD-10% (less methane yield), Co-AD-neutral% (less methane yield), Co-AD+10% (less methane yield)
	best case	Biomass produced from manure with closed storage (II-B) had the least CO ₂ eq emissions	Case-2: AD of FW	Favorable at high methane yield
		Emissions from pathways (in g CO ₂ /MJe): (a) biogas from maize: open storage (I-A) was 140, closed storage (I-B) was 90, (b) biogas from	Case-1: 213 kg CO ₂ eq/FU,	Results in kg CO ₂ eq./FU

	Key results	manure: open storage (II-A) was -160, closed storage (II-B) was -330 and (c) biogas from co-digestion of maize and manure: open storage (III-A) was 70, closed storage (III-B) was 10.	Case-2: 169 kg CO ₂ eq/FU, Case-3: 181 kg CO ₂ eq/FU.	Mono-AD-7.01E+04; Co-AD-30% (less methane yield)-1.12E+05, Co-AD-10% (less methane yield)-9.12E+04, Co-AD-neutral% (less methane yield)-8.40E+04, Co-AD+10% (less methane yield)-7.53E+04
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Table 1.13 Summary of 13 different LCA articles on AD (continued-emphasize GHG emissions).

Functional Unit [Citation]	Per km of transport [112]	1 MJ biogas [113]	10,000 tons of OFMSW [114]	1 MJ of electricity [115]
System boundary	Gate - to - Grave	Cradle - to – Grave	Gate - to – Grave	Cradle - to – Gate

Carbon accounting		1% biogenic methane leak from AD and 1.5% from upgrading to methane	Combustion of methane is excluded from the study but credits for biogenic methane are included	Considers biogas combustion emissions but do not specify any information about CO ₂ separated during upgrading process	Considers both biogenic and fossil emissions
Feedstock	DM	X	X	X	X
	Pig manure				
	Others		Press fluid, and EC		Wheat, and grass
	FW	X		X	
	MSW			X	
	Sewage sludge				
Biogas utilization	As fuel	X		X	
	As electricity		X	X	X
	As heat			X	X

Impact categories		GWP, ODP, POCP, AP, EP	FED, GWP, AP, EP	GWP, POCP, FED	GWP, AP, EP, POCP
Results	Cases studied	1. Upgraded biogas (biomethane) from FW. 2. Upgraded biogas (biomethane) from manure. 3. Natural gas. 4. Electrical vehicle (electricity from hydropower). 5. Electrical vehicle (electricity from coal) 6. Biodiesel (HVO) based on waste cooking oil. 7. Biodiesel (FAME), based on rapeseed oil. 8. Biodiesel (FAME) based on palm oil. 9. Diesel (fossil)	1. Conventional biogas plant (CBP). 2. CBP with biogas upgrading to biomethane and gas grid injection. 3. CBP with expanded biogas storage (CBP-BS) 4. CBP-BS with addition of press fluid from the IFBB technology (CBP-BS-IFBB) 5. Flexible biogas production configuration (FBPC) 6. FBPC with addition of press fluid from the IFBB technology (FBPC-IFBB)	Case 0: Organics are not separated from household waste, which is combusted at a heating plant to provide heating to the municipality. Case 1: Waste is transported to a CHP plant to provide heating and electricity to the community. Case 2,3,4: AD of source separated organic waste to produce biogas and then used a vehicle fuel. Last 3 cases differ in the location of the plant.	local scenario with data of the real situation at farm vs Substituted system (general scenario with average data at a higher (national) level of aggregation)
	Best case	The fuels with lowest CO ₂ -eq emissions are electricity from hydropower	Flexible biogas production configurations profit from reduced usable BS requirements	Case2>Case 3>Case1> Cas0> Case4	varies with respect to impact category

	Key results	GWP: 0.11 kg CO ₂ -equivalents/km from Electricity(hydropower), 0.28 kg CO ₂ -equivalents/km from biogas (Food Waste), 0.41 kg CO ₂ -equivalents/km from biogas(manure).	In contrast to an alternative supply of power generators with natural gas, biogas supplied on demand by adapted biogas plant configurations saves greenhouse gas emissions by 54–65 g CO ₂ -eq/MJ and primary energy by about 1.17 MJ/MJ.	Results in ton of t CO ₂ -eq: Case 0 - 12561, Case 1- 12167, Case 2- 11949, Case 3- 12124, Case 4- 12674.	Global warming potential per functional unit varies between 3.8 g and 12.5 g of CO ₂ equivalent in both the biogas scenarios.
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AP: Acidification potential, EP: Eutrophication potential, FED: Fossil energy demand ODP: Ozone depletion potential, POFP: Photochemical oxidation potential, CED: Cumulative energy demand, ADP: Abiotic depletion potential, AAP: Air acidification potential, SP: Smog potential, WEP: Water eutrophication potential, OFMSW: Organic fraction of municipal solid waste, POCP: photochemical oxidant formation potential, POF: Photochemical oxidant formation, HT: Human toxicity, PMF: Particulate matter formation, IR: Ionising radiation, TA: Terrestrial acidification, FEP: Freshwater eutrophication, MEP: Marine eutrophication, TE: Terrestrial ecotoxicity, FE: Freshwater eutrophication, ALO: Agricultural land occupation, ULO: Urban land occupation, NLT: Natural land transformation, WDP: water depletion, MDP: Metal depletion, FDP: Fossil depletion, ADPE: Abiotic depletion element, ADPFF: Abiotic depletion fossil fuel, FWETP: Freshwater aquatic ecotoxicity, MAETP: Marine aquatic ecotoxicity, POC: Photochemical ozone creation, TET: Terrestrial ecotoxicity, HVO: Hydrotreated vegetable oil, FAME: Fatty acid methyl esters, IFBB: Integrated generation of solid fuel and biogas from biomass.

The listed LCAs were conducted based on ISO 14040, and ISO 14044 standards and the AD feedstocks reported in the study. Feedstocks reported in the LCAs are categorized into the conventional substrates such as the organic fraction of MSW [107, 108, 114], animal manure [102, 105, 106, 109, 112-115], or food waste/ kitchen waste/ bakery waste [99, 105, 106, 110, 111, 112, 114] and the other feedstocks including sewage sludge, or energy crops [102, 109, 111, 115]. System boundaries include either cradle-to-grave or cradle-to-gate and analyses are reported over a wide range of impact categories. The functional units of these studies were mainly focused on feedstock or application of the biogas (as fuel, electricity and heat). The major outcomes from the studies include that co-digestion of food waste is environmentally advantageous compared to traditional waste management due to avoiding high impacts of methane emissions to the environment [105, 106, 111]. Energy from biogas plays a significant role in the environmental assessment; the higher the energy output the lesser the environmental impacts [111]. The following section summarizes the assumptions, limitations and key results of the LCAs in Table 1.11-1.13.

Lijo et al., 2014 [102] conducted an LCA of an operational biogas power plant in Italy co-digesting pig slurry and energy crops for electricity and heat generation. The functional unit (FU) used in this study was 100 kWh of CHP electricity. The system boundary for Lijo study did not include the pig slurry management. The avoided product perspective was used to account for digestate in the overall impacts of electricity by substituting the digestate for synthetic fertilizer. The total net emissions of the system were found to be $-0.016 \text{ kg CO}_2 / 100 \text{ kWh-e}$. The combustion emissions from biogas power plants contributed major impact with respect to GWP and the emissions might be significantly reduced by taking credit for the avoided manure management emissions.

Ebner et al., 2015 [105] investigated a comparative LCA of conventional management of food waste (FW) and dairy manure relative to the anaerobic co-digestion of manure and food waste to generate electricity. The functional unit (FU) used in this study was one metric ton of influent processed. The system expansion method was used to evaluate the emissions avoided by displacing inorganic fertilizers and grid electricity but did not completely look at avoiding different landfill scenarios in the conventional case and did not consider the biogenic emissions during the combustion of biogas. The key results from the Ebner study showed a 71% reduction in GHG emissions for AcoD compared to conventional.

Chen et al., 2015 [106] compared disposing bakery waste in uncovered landfill site and AD of manure system (base case) with AcoD of bakery waste and dairy manure to produce electricity, heat and agricultural products. The functional unit used in this study was 7,153 dry metric tons (t) of dairy manure (DM) & 2,382 dry tons of FW per year. This study did not consider allocation of co products, avoided emissions from synthetic fertilizer or electricity and biogenic emissions such as combustion of biogas. The key results from this study showed that AcoD had high potential for mitigation of GWP (around 67% reduction compared to base case) and landfill of bakery waste alone contributed only 20% of overall emissions in base case.

The Bolin et al. 2009 [107] LCA focused mainly on application of biogas as electricity and as vehicle fuel compared to base case incineration (combustion and plant operation) in Singapore. The functional unit used in this study was 1 ton of organic fraction of municipal solid waste (OFMSW). The base case scenario is compared to biogas (as a fuel and electricity and heat) scenario by adding makeup inorganic fertilizer and electricity from natural gas. The scenarios were based on biogas usage (electricity and heat or fuel), in the biogas as vehicle fuel, part of the produced biogas was upgraded to biomethane to replace biodiesel in vehicles, and remainder for electricity generation. The key results from Bolin's [107] study showed that production of biogas had 82.5% emission savings compared to conventional incineration and using biogas for vehicle fuel seemed to be more beneficial environmentally compared to electricity generation.

The Xu et al., 2015 [110] study looked at three different scenarios of treating FW; (1) the AD of FW and sewage sludge, (2) AD of FW, and (3) FW to landfill. Wastewater from AD was sent to sewage sludge plants in cases 1 and 2 the FW was landfilled (the emissions include electricity consumption and recovery, raw materials consumption, leachate treatment, and direct gas emissions). The functional unit used in this study was 1 ton of volatile solids (VS). Combustion emissions from biogas were included in the analysis. The study did not consider the avoided emissions from FW and electricity. The key results showed a significant difference in the environmental impacts. Case (3) had much lower GHG emissions with 169 kg CO₂ eq/FU (66% emissions from electricity used in AD plus 21% direct emissions) compared to the landfill case with 181 kg CO₂ eq/FU (CaO (41%) +transport (34%)).

LCA of upgraded biogas (biomethane) as a transportation fuel was conducted in the Lyng et al., 2019 [112] study. Vehicle traveled per km was used as a functional unit, and 9 different scenarios were evaluated (Upgraded biogas (biomethane) from food waste, upgraded biogas (biomethane) from AD of manure, natural gas, Electrical vehicle (electricity from hydropower), Electrical vehicle (electricity from coal), Biodiesel (HVO) based on waste cooking oil, Biodiesel (FAME), based on rapeseed oil, Biodiesel (FAME) based on palm oil, Diesel (fossil)). 4 different life cycle stages were considered, including 1) Production of the fuel, (2) distribution of the fuel, (3) production and maintenance of the vehicle, and (4) driving. Biogenic carbon emissions were not considered in the analysis and were assumed to make a negligible contribution in the assessment. The avoided emissions from short time manure storage are not included. The results from Lyng's [112] study showed that the biggest emissions are for Electricity from coal power (1.09 kg CO₂/FU), natural gas (0.84 kg CO₂/FU) and diesel from driving vehicles (0.92 kg CO₂/FU), whereas with renewables most of the emissions are from processing or production of biogas or hydroelectric power. Electricity from hydro power had the least emissions (0.11 kg CO₂/FU) and among food waste biogas and manure biogas production, FW biogas production had much lower emissions than manure (0.28 kg CO₂/FU).

LCAs of different biogas configurations were evaluated in the Hahn et al., 2015 [113] study. The functional unit used in that study was 1 MJ of biogas. The Hahn [113] study does not include biogenic CO₂ emissions but did account for biogenic methane credits.

The key savings are achieved from replacing natural gas and synthetic fertilizers and avoiding emissions from conventional manure management. The scenarios are listed in Table 1.11 and key results range from 54 and 66 g CO₂-eq MJ⁻¹.

The LCAs reviewed above showed diverse results mainly due to inconsistencies in applying methodology, variations in assumptions, and system boundaries used. Given the importance of GHG emissions for LCAs and how complex the AcoD bioenergy systems are, the use of food waste and manure for bioenergy touches on many other processes in the technosphere (landfill processes, conventional manure management, fertilizer production/use, conventional electricity production) with implications on GHG emissions. Therefore, these associated processes should be included in biogas / biomethane LCAs. Also, many of the studies in Table 1.11-1.13 report LCA results on an input basis (e.g. ton of FW and manure processed) rather than on output basis (output of electricity or biomethane, etc.). As a result of these methodology variations, it is very difficult to compare LCA results when the FU is so different and when the methods are so diverse as in the collection of literature. There is an urgent need to develop recommendations for standardization of LCAs for biogas / biomethane production so that equivalent comparisons between studies can be made.

1.9 Review of existing frameworks on sustainability assessment of bioenergy systems

There are several sustainability assessment frameworks of bioenergy systems, which have appeared in the literature recently (Table 1.14). Dunnet et al 2007 [116] developed a framework for optimization of biomass-to-heat production using mixed integer linear programming (MILP). This study factors in multiple parameters associated with design and operations (location, crop moisture content, transportation, ambient drying rates and seasonal demands etc.) for optimization of economic impact. However, this framework includes only a single economic objective function, and does not address or optimize any social or environmental impacts. Based on Dunnet's work, Zamboni et al 2009 [117] proposed a framework for optimization of corn-based bioethanol production. To some extent, Zamboni's study addressed some of the disadvantages in Dunnet's study by simultaneously optimizing both economic and environmental impact categories (but not societal impacts) using MILP. The indicators optimized in that study are GHG emissions and production cost.

Table 1.14 Bioenergy sustainability framework review.

Model Authors	LCA	Social	Policy	Economic	Infrastructure & Logistics
Dunnet et al. [116]				X	X

Zamboni et al. [117]	X			X	X
Mansoornejad et al. [118]	X		X	X	X
You et al. [119]	X	X		X	X
Ozcan et al. [120]	X	X	X	X	X
Elia et al. [121]	X			X	X
Chen et al. [122]	X	X		X	
Jin et al. [123]	X*	X*	X*	X*	X*
Corsano et al. [124]	X		X	X	

* = Time-dependent model

Mansoornejad et al. 2010 [118] further expanded the modeling by adding the effect of policies in the supply chain for a forest-based biorefinery. Both environmental and economic impact categories were addressed, but the model did not address social impact categories or the uncertainties in the data layers and market conditions. The Corsano et al. 2011 [124] model is a mixed integer non-linear programming (MINLP) optimization framework that accounts for various process and design variations in a bioethanol plant and solves the problem using a single economic object function for an optimum solution. Elia et al. 2011 [121] focused on multi-objective MILP process designs on hybrid coal, biomass and natural gas to liquid fuels plants. That study integrated the LCA with techno-economics and optimized both environmental and economic impact categories but did not address any key issues in social sustainability. Recently, You et al. 2012 [119] proposed a multi-objective life cycle optimization framework for optimizing the cellulosic biofuel economic, environmental and resource sustainability criteria simultaneously with multiple constraints such as supply seasonality and geographical diversity, biomass degradation, feedstock density, diverse conversion pathways and byproducts, infrastructure compatibility, demand distribution, regional economy, and government incentives. That study used Aspen Plus simulation models for obtaining the inputs for the techno-economic analyses.

Ozcan et al. 2014 [120] modeled the multi-objective (social, economic and environmental) optimization framework of bioethanol production systems using a multi-objective mixed integer linear programming (MOMILP) framework. One objective function in this

framework was optimized while keeping the other objective functions as constraints, thereby decreasing the parameters range, and solved for the optimum design. There are different software tools to aid in the optimization of the social impact category for bioethanol systems. The Jobs and Economic Development Impact (JEDI) model developed by NREL and IMPLAN are input-output models, which can be used to calculate indicators such as: 1. Output (refers to economic activity or value of production) 2. Labor income and 3. Employment. The indicators such as total cost, CO₂ emissions, energy utilization, fossil resource usage, employment, and social acceptance are optimized in that study. Although not a bioenergy optimization, the Chen et al. 2004 [122] model combined process simulation with techno-economic analyses and life cycle assessments for multi-objective optimization using the analytic hierarchy process (AHP) for maleic anhydride (MA) production using a genetic algorithm-based MILP. In that approach, one single sustainability score was obtained by pairwise comparison of design alternatives. The MA process parameters such as reaction temperature and pressure, mass separating agent flow rate, etc. are varied within ranges to optimize the objective functions. Jin et al. 2016 [123] addressed all the three dimensions of sustainability (social, economic and environmental) using a systems dynamic integrated sustainability model. Indicators such as greenhouse gas emissions, biofuel price, and employment were estimated on a transient scale for corn-ethanol bioenergy production.

The objective of this literature review is to develop an understanding of prior conceptual modelling frameworks for systems analysis of bioenergy production. These frameworks combine LCA, TEA, social, process modelling and policy elements. Based on this review, I propose a conceptual modeling framework for systems analysis for sustainability for biopower production in Wisconsin for conversion of mixtures of food waste and dairy manure with anaerobic digestion.

1.10 Research objectives for this dissertation

According to the information presented above, this dissertation addresses the current gaps in knowledge on the circular economy and the AcoD of organic waste, in building life cycle assessment skills, and refining laboratory skills in biomass conversion through the following research objectives

Obj. 1: Review literature on sustainability of Bio-CH₄ production in the U.S. (Chapter 1)

Obj. 2: Understand and improve the life cycle assessment (LCA) skills (Chapter 2 and Chapter 3)

Obj. 3: Understand and improve enzymatic hydrolysis laboratory skills on biomass (Chapter 4)

Obj. 4: Systems analysis for sustainability of future Bio-CH₄ production in the U.S. (Chapter 5)

This dissertation is divided in four parts, Chapter 1 addresses objective 1 and Chapter 2 and 3 accomplishes objectives 2, Chapter 4 presents the progress on objectives 3, and, Chapter 5 presents the results of objectives 1, 2 and 4. Finally, Chapter 6 presents the conclusions and future work derived from the results of the performed research.

1.11 References

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2 Carbon footprint and energy analysis of Bio-CH₄ from a mixture of food waste and dairy manure in Denver, Colorado¹

Abstract

Anaerobic digestion (AD) is a possible alternative to landfilling of food waste and conventional manure management in order to reduce methane emissions. We use the method of life cycle assessment in this study, and key results show that the AD Bio-CH₄ pathway has 15.5% lower greenhouse gas (GHG) emissions compared to the prior practice of composting of food waste and manure in Denver, CO. GHG emissions for Bio-CH₄ production from AD conversion of food waste and manure with avoiding of food waste landfilling and conventional management of dairy manure emits -3.5 kg CO₂ equivalents / kg Bio-CH₄ assuming the electricity was generated using collected landfill gas. This emission intensity is favorably compared to that of fossil natural gas equal to 4.3 kg CO₂ equivalents / kg CH₄ equivalents. This method for carbon foot printing can be used to evaluate climate mitigation potential of other AD Bio-CH₄ projects.

2.1 Introduction

2.1.1 Food waste generation

The majority of municipal solid waste (MSW) is from the industrial, commercial and residential sectors, which together account for 254 million short tons per year according to recent statistics in the US [1]. Organic materials constitute the majority portion of MSW in which 27% is paper and paperboard with food waste and yard trimmings accounting for 28%. The remainder is made up of plastic > metal > rubber-leather-textiles > wood > glass. The generated MSW is managed by different methods out of which only 12% is processed through incineration and energy collection systems, 53% is disposed to landfills, and 35% goes to recycling and composting [2]. In the USA, out of all the generated MSW the second highest component is organic food waste with 14.6% of total waste. When disposed in a landfill, food waste releases the highest amount of methane emissions per dry weight of disposed materials. Furthermore, the wastage of food is about 30-40% of the food supply, equaling more than 20 pounds of food per person per month. With the conversions of dry solids in food waste to methane, 216 Mg of dry food waste generates 4700 dekatherms of Bio-CH₄ through anaerobic digestion (AD), which is equivalent to 105.19 Mg of fossil

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natural gas (by taking the lower heating value of 47.14 MJ/kg). According to 2013 EPA report the US generates 36 million wet tons / yr of food waste, which if entirely converted to Bio-CH₄ has a potential to replace .74% of US total natural gas usage of 548 million tons annually (see A.4 of Appendix A for calculations). In the US, 97% of the total food waste is buried in landfills where it causes odor as decomposes and produces methane [3].

2.1.2 Landfills and GHG emissions

Currently in the US, 44% of the landfills use gas collection systems plus flaring to reduce GHG emissions and there are about 850 such flaring landfills out of a total 1908 landfills [4]. The landfill methane outreach program (LMOP) currently tracks new landfill gas to energy projects in the US, which reports that there are 652 such landfills turning the methane into useful energy sources (electricity mostly). From 2014 statistics, total methane emissions from landfills in the US are 102.8 million metric tons CO₂ eq. [5]. Methane is more efficient in trapping infrared radiation than CO₂ by 25 times. Methane emissions are significant, account for 11% of overall GHG emissions (CO₂ eq.) in US, and in which landfills account for 20% and natural gas and petrol accounts for 33% of methane emissions [6]. From these statistics, landfilling of MSW represents one of the highest methane emission sources.

2.1.3 Manure generation and management

According to the EPA 2012 report, 20% of the world's non-CO₂ GHG emissions are created from animal agriculture, and in the US, agriculture GHG emissions account for 9% of the total emissions, which is 618 million metric tons out of 6870 total million metric tons of CO₂ equivalents [6]. Animal agriculture emissions include mostly enteric fermentation, the respiration of cattle and other animals. Manure management has great environmental impact, as it accounts for 14% of the overall GHG emissions from the agriculture sector. From among the US overall manure management emissions, nearly 43% of CH₄ emissions are from dairy farms [7]. Key sources for manure production in the US are cattle, swine and poultry, among which the cattle produced 920 million wet tons of manure, poultry 80 million wet tons, which includes litter, and swine production accounts for 110 million wet tons of manure in the year 2007 [8]. By considering the percentages of nutrient concentrations from Combs et al. 1998, it is estimated to represent 7.44 million tons of N and 2.58 million tons of P from total manure (cattle, swine and poultry), assuming the moisture contents of cattle, swine, and poultry are 76, 80 and 40 respectively [9]. In comparison, US annual agricultural field application of commercial fertilizers in 2007 is about 13.1 million equivalent tons of N and 4.5 million equivalent tons of P. The most conventional manure management systems include: 1. Uncovered anaerobic lagoons, 2. Digesters (includes covered anaerobic lagoons), 3. Solid manure storage, 4. Dry Lots (includes feedlots), 5. Storage pits, 6. Liquid or Slurry systems, 7. Deep bedding systems (cattle and swine), 8. High-rise houses for poultry production without litter, 9. Poultry production with litter, 10. Aerobic treatment, and 11. Manure composting [10]. From the Intergovernmental Panel on Climate Change [11] manure methane emission factors are

from 0.02 (most of the poultry breeds), to 1 (beef cattle) and 53 (dairy cows) kilograms per head per year [12], US EPA estimates the total methane emissions of 2.478 million tons of CH₄/yr. from livestock [12].

2.1.4 Composting for management of food waste

According to US 2014 statistics, there were 347 composting facilities accepting food waste from 36 states in the US, with 87 accepting mixed organics (leaves, vegetable scraps, tea bags etc.). Composting consumes more energy than land filling, but significant energy savings in composting are due to the compost replacement of chemical fertilizer in agriculture [13]. Compost, when applied to the field, has benefits such as reducing water runoff, soil erosion, and enhancing the metabolism of microorganisms, which improves the soil fertility. On the other side, it also has a negative impact on the environment such as CH₄ and CO₂ emissions from compost piles and uses fossil fuel for transportation and in the composting equipment. Out of 254 million tons of MSW in 2013, only 3% of the 37 million tons of food waste is diverted from landfills to composting and it is reported that the composting methane emissions in the US are 3.3 million tons of CO₂ equivalents [5].

Both landfilling and composting of food waste has a high potential for uncontrolled methane emissions, so there is a necessity for reliable alternatives for the management of food waste that is produced each year. Biological treatments are the alternate way for the reduction of solid waste residues by biological activity [14-17]. Anaerobic treatment of food waste and manure has the potential to reduce methane emissions from both controlled and uncontrolled sources, as our study shows.

2.1.5 LCA Literature review

LCA studies have found AD to be more advantageous (i.e. it has less environmental impacts) than other organic waste disposal methods, such as incineration and landfilling. Most of the prior LCA work reported lower greenhouse gas emissions for Bio-CH₄ as a transportation fuel from different- substrates such as energy crops and food waste compared with the fossil methane [18-20]. Morero et al. conducted an LCA on optimization of AD process to see the effect of adsorption and desorption in the process [21]. Owen et al. performed an LCA on the emissions from manure management processes and their studies highlighted the areas to concentrate on to mitigate the GHG emissions [7]. ROU conducted an LCA of a windrow composting system in Australia including compost use and post application impacts [22]. Only a few LCA studies have analyzed transient landfill emission scenarios, and results show that the gas collection systems with flaring had higher emissions when compared with a landfill gas-to-energy scenario [23]. A prior life cycle carbon footprint found that emissions were much lower for windrow composting, high solids anaerobic digestion, or for co-digestion of the organic fraction of MSW with either industrial wastes or sewage sludge compared with the baseline process of composting of the food waste while landfilling of the remaining organic fraction [24] (with electricity generation of captured landfill gas). However, to date as far as we know no

studies have analyzed the entire consequential life cycle assessment of Bio-CH₄ produced from AD of mixtures of food waste and dairy manure.

2.1.6 Research Objectives

The main research objective of this work is to model the cradle-to-grave environmental impacts (greenhouse gas emissions and fossil energy demand) of the anaerobic digestion of food waste mixed with dairy manure at a specific location near Denver, CO. The prior practice at this location was composting of the food waste and manure, and this prior case is modeled as a comparison. Additional analyses include a more general case of diverting food waste from landfills and animal manure from conventional manure management processes to produce Bio-CH₄ in AD facilities. Our study also investigates avoiding different landfilling scenarios (uncontrolled, gas collection and flaring and gas collection and electricity generation operating at steady state). Finally, in an effort add more realism to the LCA modeling an investigation of the transient response of avoided landfill emissions was conducted.

2.2 Materials and Methods

2.2.1 Goal and Scope

The goal of this study is to make a consequential comparative life cycle analysis in two separate cases. Case 1 analyzes the use of food waste from Denver, CO restaurants and dairy manure in the vicinity of LaSalle, CO for compost production, which was the prior use of these waste materials, versus a new Bio-CH₄ production system. Case 2 is a more general case for the prior use of food waste and dairy manure that assumes food waste was landfilled with (Scenario-1) uncontrolled emissions from the landfill, (Scenario-2) a gas collection system with flaring of the collected landfill gases, and (Scenario-3) which represents landfilling of the food waste with a gas collection system and electricity generation. In all scenarios, conventional manure management is included as part of the avoided pathways. The impact category of primary interest is greenhouse gas emissions; however, fossil energy consumption is also evaluated. Scenario analyzes are modified to include transient landfill emissions that are avoided when food waste is instead used for Bio-CH₄ production.

2.2.2 Functional Unit

The basis for the analyses reported here in both cases is the processing of both the food waste and dairy manure for one day of operation of the Heartland AD facility near LaSalle, CO. This basis translated to 216 Mg (dry) of food waste (refer Table A-41 in Appendix A for moisture content) and 62 Mg (dry) dairy manure (refer Table A-41 in Appendix A for moisture content) converted in the AD process. The functional units we have chosen are mainly used in the analyses as a reference to compare the LCA results to the different alternatives. In Case 1 the functional unit is on the basis of 1 day of operation of the

Heartland AD Bio-CH₄ facility to compare to the business-as-usual (BAU) composting of these wastes, and Case 2 is on the basis of 1 kg of Bio-CH₄ produced and used in place of BAU landfilling. The Bio-gas composition was assumed to be 65% CH₄, 29% CO₂ and 6% H₂O on volume basis [25] (refer to Table A-3 in Appendix A for calculation on mass basis). All the calculations are based on the total feedstock input of 278 Mg (dry basis) / day which results in an output Bio-CH₄ of 99.15 Mg, which constitutes 35.66% of initial feedstock (food waste + manure).

2.2.3 System boundary

In Case 1, the framework for the analysis is designed to model the change to the environment when the pathways in the BAU composting system are changed to the Bio-CH₄ system. Both systems must provide the same societal benefit for production of compost, nutrients for agriculture, and energy from methane (or fossil natural gas). The system boundary for Case 1 BAU composting system is shown in Figure 2.1 and includes different pathways that are operating in the prior use of the food waste and manure. Pathway 1 is composting of food waste and manure. The composting process accounts for the emissions from transportation of feedstock (food waste, manure and wood chips), windrow process emissions (including decomposition), and compost land application emissions. The emissions from the composting process are calculated from prior studies [21,26,27] and are presented in A.1 of Appendix A. Pathway 2 includes manufacturing and use of synthetic fertilizers that will be replaced by nutrients in digestate that is produced in the AD system. This accounts for the emissions from manufacturing, transportation to fields and field application (calculation for synthetic fertilizer emissions from cradle-to-grave are considered from US average fertilizer mix attested to in A.1 of Appendix A). Pathway 3 in the BAU case is the fossil natural gas that is replaced by the Bio-CH₄ produced in the AD system, and therefore fossil natural gas is modeled. Accounted for were all the emissions from cradle-to-grave of fossil natural gas (extraction, process, transport, and combustion).

Figure 2-1 System boundaries for the case 1 Business-as-Usual (BAU) system

The Case 1 Bio-CH₄ system shown in Figure 2.2 also includes multiple pathways and processes. The first is AD of food waste and manure including the whole lifecycle of the AD Bio-CH₄ pathway starting from the transportation of food waste and manure until the end use of Bio-CH₄ product, byproduct compost and digestate (input data provided by Ag Energy). Secondly, compost pathway produces more compost from food waste than the AD Bio-CH₄ pathway, therefore, to provide the same societal benefit, the remaining compost is made up by equivalent amounts of peat imported from Canada. The peat pathway considers all emissions from cradle-to-grave. The data regarding the infrastructure for storage of food waste and manure, for biogas production and purification are not included in the study because their impacts are assumed negligible for facilities that last decades when compared to the material and energy inputs to the processes during the life of the AD facility.

Figure 2-2 System boundaries for the case 1 Bio-CH₄ system

In Case 2, a modeling approach equivalent to that in Case 1 has been taken. However, LCA results can be obtained by taking the difference between two systems (BAU landfill system and Bio-CH₄ system) and combining into a single Bio-CH₄ system by considering the credit for emissions from avoided BAU landfill systems. This approach is a consequential LCA because, in addition to modeling the direct AD Bio-CH₄ pathway, avoided emissions are also modeled for all co-products that displace others in the market as well as avoided pathways in the BAU of landfilling and manure management. Three scenario analyses are studied in case 2 illustrated in Figures 2.3 & 2.4. The system boundary for case 2, scenario-1 (Bio-CH₄ system with avoiding uncontrolled landfilling) has multiple pathways in its life cycle: 1. AD Bio-CH₄ pathway, 2. avoiding uncontrolled landfilling, 3. avoiding manure management, 4. avoiding synthetic fertilizers and 5. avoiding peat production and use. Avoided uncontrolled landfill pathway includes the emissions from the transportation of food waste from Denver to the landfill and emissions during the landfill process (see Tables A-53, A-56 – A-58 in A.3 of Appendix A for details). Bio-CH₄ system uses manure for production of Bio-CH₄, so an emissions credit is taken assuming an equal amount of manure is managed by anaerobic lagoons. The emissions from manure management are calculated from Silver et al 2015 [7]. The compost produced in the AD Bio-CH₄ pathway is assumed to be met by an equivalent amount of Canadian peat in the BAU system so the emissions from the peat pathway are considered as credit to the Bio-CH₄ system. Digestate produced in the Bio-CH₄ system is assumed to displace the manufacture and application of synthetic fertilizers, so the emissions from synthetic fertilizers are accounted for as a credit to the Bio-CH₄ system and the emission factors for fertilizer land application as well as compost land application are taken from EPA's Waste Reduction Model (WARM) [28].

Figure 2-3 System boundaries for the case 2 Bio-CH₄ scenario avoided BAU with different landfill systems

Figure 2-4 Case 2 Bio-CH₄ avoided BAU with different landfill scenarios pathways

Case 2, Scenario-2 Bio-CH₄ system with avoided landfill gas collection and flaring includes multiple pathways, which are the same as Scenario 1 except for the avoided pathway of landfilling with gas collection system and flaring (see Tables A-54, A-56 – A-58 in A.3 of Appendix A for details). Case 2, scenario-3 Bio-CH₄ system with avoided landfill gas collection and electricity generation also includes multiple pathways like

scenario-2, except the avoided landfill electricity is made up by the electricity generated with natural gas (see Tables A-55, A-56 – A-58 in A.3 of Appendix A for details).

2.2.4 Allocation

Case 1 is a consequential system, and therefore no allocation is needed. For Case 2, allocation is avoided by expanding the system boundary to include environmental savings from displacing production of materials in the market by co-products from Bio-CH₄ production (fertilizers and peat) and by avoiding the food waste landfilling and manure anaerobic lagoon storage for the waste management. Peat is selected as an alternative for compost in the Bio-CH₄ life cycle in both cases. Both compost and peat have different characteristics (Compost consists of humic carbon and peat does not) but can be compared on a 1:1 volume basis [26]. AD digestate fertilizers replace synthetic fertilizers in the analysis.

2.2.5 Inventory Analysis

All the inputs to the different pathways in Cases 1 and 2 are listed in Tables 2.1-2.11 below (the reader is referred to A.3 of Appendix A for more information about specific eco-profiles used). Different eco-profiles are used to calculate the impacts of each process input in the pathways (refer A.1 in Appendix A). Emissions in CO₂ equivalents for peat manufacturing, packaging, transport and market for both scenarios are from a Canadian peatmoss study [29] listed in Table 2.12.

Table 2.1 Inputs to AD Bio-CH₄ pathway (basis of 1 day): case 1 and case 2.

AD pathway (Bio-CH ₄)	Process		Amount	Unit
	1.Manure transportation from local farm to facility (refer table A-41, A-42 of Appendix A for the moisture content)	Inbound trip	4.69x10 ³	t*km
		Return trip	3.75 x10 ³	t*km
	2.Food waste transportation from Denver to facility (refer table A-41, A-42 of Appendix A for the moisture content)	Inbound trip	5.76 x10 ⁴	t*km
		Return trip	4.61 x10 ⁴	t*km
	3.AD process	Electricity	132	MWh
		Natural gas	337878. 4	MJ
	4. Bio-CH ₄ Combustion emissions (Bio-CH ₄ combustion)		99151.2	kg CH ₄ combust ed
	5. CO ₂ Fugitive emissions from AD (CO ₂ emissions from AD)		121956	kg CO ₂ emitted

	(refer table A-2 of Appendix A for the eco-profile used for the calculation includes the composition of Biogas)			
	6. Transportation of compost from AD to Denver market	Inbound trip	9.71 x10 ³	t*km
		Return trip	7.77 x10 ³	t*km
	7. AD digestate N field application (Liquid digestate N ₂ O emissions on field application)		2.34x10 ³	kg of N
	8. AD compost field application (CO ₂ emissions from AD compost soil application)		1.22 x10 ⁵	kg

Table 2.2 Inputs to compost pathway (basis of 1 day): case 1 BAU.

Compost pathway (BAU)	Process		Amount	Unit
	1.Manure transportation from local farms to compost facility (refer table A-50 of Appendix A for the moisture content)	Inbound trip	4.66 x10 ³	t*km
		Return trip	3.73 x10 ³	t*km
	2.Wood pallets transportation from nearby (refer table A-50 of Appendix A for the moisture content)	Inbound trip	221.3	t*km
		Return trip	177	t*km
	3.Food waste transportation from Denver to compost (refer table A-50 of Appendix A for the moisture content)	Inbound trip	8.11 x10 ⁴	t*km
		Return trip	6.49 x10 ⁴	t*km
	4.Diesel used in tractor for composting	Tractor	4.92 x10 ³	Kg
		Turner	16.8	kg
		Grinder	594	kg
	5.Composting decomposition emissions (CO ₂) (Composting Decomposition Emissions (CO ₂))		322.94	tons dry compost

	6.Composting decomposition emissions (CH ₄ &N ₂ O) (Composting Decomposition Emissions (CH ₄ and N ₂ O))		1.18 x10 ³	tons (wet) compost
	7.Compost land application (at 50% moisture) (CO ₂ Emissions from Compost Land Application)		395.3	tons wet compost
	8. Compost (wet) transportation from compost facility to Denver market	Inbound trip	44550.31	t*km
		Return trip	35640.24	t*km

Table 2.3 Inputs to natural gas pathway: case 1 BAU.

Natural gas pathway (BAU)	Process	Amount	Unit
	1.Emissions from natural gas transport, extraction processing, distribution and usage	3.97 x10 ⁶	MJ of heat

Table 2.4 Inputs to synthetic fertilizer pathway: case 1 BAU.

Synthetic fertilizer pathway (BAU)	Process		Amount	Unit
	1.Emissions from synthetic fertilizers manufacturing process and market	Nitrogen	2.34x10 ³	kg
		Phosphate	0.75x10 ³	kg
		Potassium	2.91x10 ³	kg
	2. Synthetic fertilizer transport from Denver market to farm Inbound trip Return trip		44.9	t*km
			35.9	t*km
	3. Fertilizer N field application (Emissions of N ₂ O from synthetic N fertilizer applied to Field)		2.34x10 ³	kg of N

Table 2.5 Inputs to peat pathway: case 1 Bio-CH₄.

Peat pathway (Bio-CH ₄)	Process		Amount	Unit
	1. Emissions from peat moss manufacturing, transport and use (Peat moss Manufacturing, Transport and Use (CO ₂ Emissions))		546	m ³ make up peat
	2. Transportation of Peat moss from Canada (Saskatchewan) to Denver	Inbound trip	1.42 x10 ⁵	t*km
		Return trip	1.14 x10 ⁵	t*km

Table 2.6 Inputs to avoided landfill without gas collection pathway: case 2 scenario-1.

Avoided landfill pathway uncontrolled emissions	Process		Amount	Unit
	1. Transportation of food waste from Denver to landfill	Inbound trip	8.42 x10 ³	t*km
		Return trip	6.74 x10 ³	t*km
	2. Emissions from landfill without gas collection CH ₄ and CO ₂ (Steady state) Uncontrolled		216.6	tons (dry) food waste input to landfill

Table 2.7 Inputs to avoided landfill with gas collection and flaring: case 2 scenario-2.

Avoided landfill pathway with gas collection and flaring	Process		Amount	Unit
	1. Transportation of food waste from Denver to landfill	Inbound trip	8.42 x10 ³	t*km
		Return trip	6.74 x10 ³	t*km
	2. Emissions from landfill with gas collection and flare CH ₄ and CO ₂ (Steady state) (Landfill Emissions GCS steady state)		216.6	tons (dry) food waste input to landfill

Table 2.8 Inputs to avoided landfill with gas collection & electricity pathway: case 2 scenario-3.

Avoided landfill pathway with gas collection and electricity generation	Process		Amount	Unit
	1.Transportation of food waste from Denver to landfill	Inbound trip	8.42 x10 ³	t*km
		Return trip	6.74 x10 ³	t*km
	2. Emissions from LFGE (landfill with gas collection and electricity generation) CH ₄ and CO ₂ (steady state)		216.6	tons (dry) food waste input to landfill
	3. Electricity generation from Natural gas		287	MWh

Table 2.9 Inputs to avoided synthetic fertilizer pathway: case 2.

Avoided Synthetic fertilizer pathway	Process		Amount	Unit
	1.Emissions from synthetic fertilizers manufacturing process and market	Nitrogen	2.34x10 ³	kg
		Phosphate	0.75x10 ³	kg
		Potassium	2.91x10 ³	kg
	2. Transportation of synthetic fertilizers from LaSalle market to fields	Onward trip	44.9	t*km
		Return trip	35.9	t*km
	3. Fertilizer N field application (Emissions of N ₂ O from synthetic N fertilizer applied to Field)		2.34x10 ³	kg of N

Table 2.10 Inputs to avoided peat moss pathway: case 2.

Avoided peat pathway	Process	Amount	Unit
	1.Emissions from peat moss manufacturing, transport and use (Solid digestate compost from	245	m ³

	AD) (Peat moss Manufacturing, Transport and Use (CO ₂ Emissions))			
	2. Transportation of Peat moss from Canada (Saskatchewan) to Denver	Inbound trip	6.4 x10 ⁴	t*km
		Return trip	5.12 x10 ⁴	t*km

Table 2.11 Inputs to avoided manure pathway: case 2.

Avoided manure pathway	Process	Amount	Unit
	1. Anaerobic lagoon emissions	40.49	tons (dry basis)
	2. Slurry storage tanks	6.23	tons (dry basis)
	3. Solid manure piles	15.58	tons (dry basis)

Table 2.12 GHG emissions for peat manufacturing, packaging transport and use.

Category	Unit	Harvest	Packaging	Transport	Soil application	In situ decomposition	Total
GHG Emissions	Kg CO ₂ equivalent	4.03	2.53	15.63	183	60.79	269.7

2.2.6 Impact Assessment

The main impacts analyzed in this study are: 1) global warming and 2) fossil energy use. Energy use impacts are quantified using the Cumulative Energy Demand method in SimaPro version 8.0.3.14, which accounts for all the process energy conversion efficiencies and other energy uses from cradle-to-grave. The global warming impacts are calculated by the IPCC 2013 GWP 100, a method in SimaPro with global warming potentials (GWP) of CO₂: 1, N₂O: 265, CH₄, fossil: 28 and CH₄, biogenic: 25.25. GWP values for all other greenhouse gases included in the developed inventory, such as refrigerants and some solvents, are also included in this method.

2.3 Results and discussion

2.3.1 Case 1 BAU composting versus Bio-CH₄

The GHG emissions from Case 1 are shown in Tables 2.13 and 2.14. The BAU composting system has total net emissions of 9.7×10^5 kg CO₂ eq. /day for 216 tons/day of dry food waste feedstock and 62 tons/day dry dairy manure. Main emission sources include, in decreasing order, composting process emissions, natural gas production and emissions, and field emissions for compost application. The Bio-CH₄ system emissions shown in Table 2.14 total 8.2×10^5 kg CO₂ eq./day for the same input rate of dry food waste and dairy manure and is mainly caused by Bio-CH₄ combustion, AD process-CO₂ separation, and peat manufacture-use. From this work, the Bio-CH₄ system exhibits 15.5% lower emissions than the BAU composting system.

Table 2.13 Case 1: Business as usual composting system (basis of 1 day).

Process	kg CO ₂ eq.	% Contribution
Composting Pathway		
1. Feedstock transport	29,592.63	3.06
2. Composting process equipment fuel use	20,796.49	2.14
3. Decomposition of feedstock in composting process	367,988.1	37.92
4. Transportation from compost facility to market	15,313.93	1.58
5. Land application of compost	173,939.4	17.93
Fossil Natural Gas Pathway		
6. Natural gas production and combustion	317,870.7	32.76
Synthetic Fertilizer Pathway		
7. Synthetic fertilizer production and market	18,904.28	1.95
8. Synthetic fertilizer transport from market to farm	13.92	0.0014
9. Synthetic N fertilizer soil application	25,786.51	2.66
Total	970,206	100

Table 2.14 Case 1: Bio-CH₄ system (basis of 1 day).

Process	kg CO ₂ eq.	% Contribution
AD Bio-CH₄ Pathway		
1. Manure transportation from dairy farm to AD	1,453.99	0.17

2. Food waste transport from Denver to AD facility	17,856.1	2.17
3. Anaerobic digestion Process	134,499.6	16.39
4. CO ₂ separation from AD biogas and venting	121,956	14.86
5. Biogas CH ₄ combustion	272,665.8	33.23
6. AD digestate soil application	25,786.5	3.14
7. AD compost transport to Denver	3,010.29	0.36
8. AD compost applied to land	53,824.3	6.56
Peat Pathway		
9. Peat manufacturing, transport, use	145,217.1	17.69
10. Peat transport from Saskatchewan to Denver	44,278.6	5.39
Total	820,548.3	100

For fossil energy use in case 1, the Bio-CH₄ system is calculated based on the input energy supply by electricity and natural gas for the AD process, transportation, peat process, and output energy production from Bio-CH₄ system with the help of SimaPro Cumulative Energy Demand method. Fossil energy use for Bio-CH₄ system is calculated to be 2.93×10^6 MJ/day, where as in the BAU composting system energy use was calculated to be 6.3×10^6 MJ/day, which includes the energy usage for process operations in natural gas, composting, and fertilizer pathways. When comparing the Bio-CH₄ system with the BAU composting system, the Bio-CH₄ system has 53.4% savings as shown in the Figure 2.5.

Figure 2-5 Fossil energy demand for BAU composting system and Bio-CH₄ system in units of MJ/day

2.3.2 Case 2 Scenario steady state analyses

The GHG emissions from individual pathways in scenario-1, scenario-2 and scenario-3 are shown in Figure 2.6. All emission calculations for CO₂ and CH₄ emissions in the three scenarios are reported in A.2 of Appendix A. In the steady-state scenario-1, the Bio-CH₄ system with the avoided BAU uncontrolled landfill system has $-17.76 \text{ kg CO}_2 \text{ eq. / kg of Bio-CH}_4$. Scenario-2 with avoided BAU landfill with gas collection system and flaring has $-5.49 \text{ kg CO}_2 \text{ eq. / kg of Bio-CH}_4$ production. Scenario-3 with avoided BAU landfill with gas collection and electricity generation has $-3.51 \text{ kg CO}_2 \text{ eq. / kg of Bio-CH}_4$ production. The main advantage of the AD process for production of Bio-CH₄ is the avoiding of landfill and manure management emissions because the savings are much greater than the emissions from the AD Bio-CH₄ pathway. Emissions from the AD Bio-CH₄ pathway are $6.1 \text{ kg CO}_2 \text{ eq. / kg Bio-CH}_4$, without considering the substantial avoided emissions, and by its own is higher than fossil natural gas ($4.3 \text{ kg CO}_2 \text{ eq. / kg Bio-CH}_4 \text{ eq. of fossil natural gas}$). In all scenarios, savings of emissions are greatest for the avoided landfill pathway, followed by avoided manure management, then peat production, and finally avoided synthetic fertilizers.

Figure 2-6 Case 2, Bio-CH₄ emissions avoiding different BAU steady-state landfill scenarios.

2.3.3 Case 2 transient analysis

When food waste is deposited in a landfill, emissions of CH₄ and CO₂ are not generated to full potential immediately, but instead the landfill AD processes require several decades to complete the biomass decomposition. In order to introduce a more accurate avoided landfill emissions calculation, a transient model for CH₄ and CO₂ generation and emissions from landfills was derived in A.2 of Appendix A for both uncontrolled landfills and for landfills with gas collection and flaring systems. The equation representing the avoided landfill emission rate for both CH₄ and CO₂, respectively, are

$$= M/2(1 - e^{-kt}) * 16/12$$

$$= M/2(1 - e^{-kt}) * 44/12$$

where M is the annual rate of food waste landfilled (metric tons carbon/yr.), which in our calculations is the same as the annual food waste C input rate to the AD Bio-CH₄ facility, k is a first order reaction rate constant for decomposition of food waste and production of Bio-CH₄ and CO₂ by the AD process (0.12 yr⁻¹), and t is time in years [27]. These avoided landfill emissions increase exponentially until steady-state is achieved after approximately 50 years (see A.2 of Appendix A for derivations).

Case 2 transient results are modeled for three scenarios. In Scenario-1, the Bio-CH₄ system avoids the BAU landfill assuming uncontrolled emissions. In scenario-2, the Bio-CH₄ system substitutes for a BAU landfill emissions with gas collection system and flaring. In

scenario-3, the Bio-CH₄ system substitutes for a BAU landfill emissions with gas collection and electricity generation. Figure 2.7 shows transient emissions from scenario-1, 2 and 3 over a 50-year time frame based on one kg of generated Bio-CH₄. The Bio-CH₄ emissions in scenario-1 drop sharply over the 50-year simulation. From our simulation, emissions from Bio-CH₄ are always lower than fossil natural gas over the entire simulation period from years 1 – 50 (except for scenario-1 at 1 year). The Bio-CH₄ system for scenario-1 has a savings of -17.76 kg eq. CO₂ emissions for a kg of Bio-CH₄ by the end of the 50-yr cycle.

Figure 2-7 Case 2, Bio-CH₄ emissions avoiding the BAU landfilling a) uncontrolled Scenario-1, b) gas collection system (GCS) & flaring scenario-2, and c) landfill gas collection with electricity generation (LFGE) scenario-3.

In scenario-2 most of the methane emitted in the uncontrolled landfill scenario is captured (assumption of 75% collection efficiency and is flared) using a gas collection system and flared as CO₂ thereby avoiding the emission of high GWP CH₄. The simulated results of the transient scenario-2 are shown in the Figure 2.7. In scenario-2, GHG emissions of AD Bio-CH₄ pathway are always lower than fossil natural gas over the entire 50-year modeling time. After 50 years avoiding the emissions from BAU with landfill gas collection and flaring system, the Bio-CH₄ emits -5.49 kg CO₂ eq./kg Bio-CH₄, thus reducing global warming effect with each unit of production of Bio-CH₄. These favorable emissions are compared to that of fossil natural gas, 4.3 kg CO₂ eq. / 1.06 kg fossil natural gas, which contains mostly fossil methane, where the factor of 1.06 is the ratio of LHV of BioCH₄ (50 MJ/kg) to fossil natural gas (47.14 MJ/kg). This comparison shows the significant benefit of the AD Bio-CH₄ pathway with respect to fossil natural gas. Scenario-3 is also shown in Figure 2.7 and has an overall savings of -3.51 kg CO₂ eq. /kg Bio-CH₄ by the end of 50 years.

2.3.4 Fossil Energy Consumption for Case 2

The steady-state fossil energy consumption for the Bio-CH₄ system when avoiding the BAU landfill, either uncontrolled or gas collection and flaring, is calculated as 1.69×10^6 MJ/99.15 tons of Bio-CH₄, or 17.06 MJ/kg Bio-CH₄. By comparison, fossil natural gas uses 59.0 MJ fossil energy /1.06 kg fossil natural gas. Fossil energy demand for the Bio-CH₄ system scenario-3 is calculated as 49.26 MJ/kg Bio-CH₄. Bio-CH₄ fossil energy consumption is 71.1 % lower than fossil natural gas in scenario-1 and scenario-2 and is 16.5 % lower in scenario-3. Figure 2.8 shows the contributions by different processes in the AD Bio-CH₄ toward the cumulative fossil energy consumption. The AD process is the largest contributor to fossil energy demand among all of the pathway stages in scenario-1 and scenario-2. The makeup of avoided landfill electricity generation using natural gas is the largest contributor to fossil energy demand in scenario-3.

Figure 2-8 Fossil energy demand for case 2, scenario-1, scenario-2, and scenario-3.

By summarizing the discussed GHG emission results from our study, we show that AD of food waste and dairy manure in scenarios that avoid landfilling provides the best reductions in GHG emissions compared to composting of the wastes. A similar conclusion was made from the study by Yoshida et al. on AD of food waste and organics in MSW [24], which also showed the best GHG emission savings for avoided landfilling rather than composting.

2.3.5 Broader impacts of AD in the US

If implemented on a national scale in the US, a savings of 0.74% of the present annual natural gas energy demand can be realized from production of Bio-CH₄ through AD of all food waste and a significant fraction of total dairy manure. Our results show that per kg of Bio-CH₄ produced from food waste and dairy manure, net emissions after avoiding landfilling with gas collection and flaring and avoiding conventional dairy manure management saves 5.49 kg CO₂ eq. emissions, the uncontrolled landfilling scenario saves

17.76 kg CO₂ eq., and the gas collection and electricity generation landfilling scenario saves 3.51 kg CO₂ eq. These savings do not factor in the additional emissions savings when fossil natural gas is displaced, so net savings will be larger still. From data on landfilling there are 850 landfills with flaring and gas collection, 400 uncontrolled landfills, and 658 landfills with gas collection and electricity generation, which if avoided in the future through AD of food waste would provide a weighted average savings of 7.37 kg eq. CO₂ emissions per kg of Bio-CH₄ produced from food waste and manure blend.

Based on the ratios provided by AgEnergy, 19 million short tons of manure from dairy production in the US alone can provide sufficient blending for the total 36 million tons of food waste that is landfilled. By diverting the food waste and manure to anaerobic digestion, approximately 0.41% of overall GHG emissions of the approximately seven billion tons CO₂ eq. can be saved in the US annually using approximately 100 Heartland-scale AD facilities. It is important to point out other sustainability benefits of Bio-CH₄ production from food waste and dairy manure beyond conservation of fossil energy and reductions in GHG emission. These potential benefits include the recycling of mineral nutrients from food waste and manure to agricultural fields and associated reduction of environmental impacts of in synthetic fertilizer production and conserving natural resources. Although water is consumed in the AD process, digestate water is delivered to surrounding agricultural fields to offset some irrigation water usage. Large-scale deployment of AD of food waste / manure mixtures in the US would stimulate economic growth and create many engineering, facility operator, and spinoff jobs. More comprehensive sustainability analyses should be conducted to better understand the full set of potential benefits and costs (loss of jobs in landfilling and natural gas industries, possible odor issues) from large-scale production of Bio-CH₄ in the US.

2.4 Summary and Conclusions

To date no studies have analyzed the entire consequential life cycle assessment of Bio-CH₄ produced from AD of mixtures of food waste and dairy manure. Therefore, this paper presents a life cycle assessment methodology-based analysis to investigate GHG emissions of Bio-CH₄ production from food waste and dairy manure. This study showed that the Bio-CH₄ system emits lower greenhouse gases and requires less net fossil energy during its whole lifecycle when compared to an equivalent amount of fossil natural gas. It also has lower emissions than other treatment processes in the US for these solid wastes, because the GHG emissions savings from avoiding the conventional management of manure and landfilling of food waste have a significant benefit on the overall GHG reduction potential of Bio-CH₄.

2.5 Acknowledgements

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3 Life cycle assessment of oilseed crops produced in rotation with dryland cereals in the inland Pacific Northwest²

Abstract

Purpose Oilseed crops are expected to become an important feedstock for production of renewable jet fuel. The objective of this study is to determine the life cycle energy and greenhouse gas (GHG) emissions of several 2- and 3-year crop rotations with cereals and oilseeds in a low precipitation environment of the inland Pacific Northwest. The purpose is to ascertain whether cropping intensification could improve energy efficiency and reduce GHG emissions.

Methods A life cycle assessment (LCA) was carried out to evaluate the fossil energy and carbon footprint of nine cropping systems characterized by different inputs applied to spring carinata [*Brassica carinata* (A.) Braun] and winter canola (*B. napus* L.) in rotation with wheat (*Triticum aestivum* L.) and other cereal crops. Grain yield and field activity data from cropping systems were acquired from a field experiment over a 5-year period. Gas emissions were measured weekly over 2 years using static chamber methodology and laboratory gas chromatography. Inputs for the LCA regarding fertilizers, machinery fuel use, and pesticides were from the field trials and literature for fuel use.

Results and discussion Emission results of winter wheat (WW) rotations are between 300 and 400 g CO₂ eq. kg⁻¹ WW, in the range for US average WW cropping emissions (i.e., 300–600 g CO₂ eq. kg⁻¹ WW). Reduced tillage fallow (RTF)-Winter oilseed (WO)-RTF-WW and summer fallow (SF)-WW rotation were the most promising, from a trade-off of GHG emissions versus total crop sales over 6 years per hectare with low emissions and high sales. The best oilseed result was 660 g CO₂ eq. kg⁻¹ for canola following RTF. Highest yields were observed when cereal or oilseed crops were planted following RTF. Efficiency in terms of Energy Return on Energy Investment was 3.85 for winter oilseed yields 1338.9 kg ha⁻¹ and 1.6 for spring oilseed yields 552.2 kg ha⁻¹.

Conclusions Compared to SF-WW, bioenergy oilseed cultivation may increase CO₂ equivalent emissions in 3-year cereal-based rotations due to increased inputs with inclusion of fallow-substitution cultivation. Fossil energy inputs required to produce oilseed crops were smaller than the total energy in final seed and thus oilseeds have the potential to reduce reliance on fossil fuels. Improving energy efficiency and encouraging adoption by

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growers will depend on ability to enhance agronomic performance with higher yielding, drought and cold tolerant oilseed varieties.

3.1 Introduction

The US aviation industry has expressed a strong interest in the development of a “drop-in” renewable jet fuel to supplement its fuel needs and reduce the industry’s carbon footprint [1]. Oil from industrial oilseed crops like carinata [*Brassica carinata* (A.) Braun] and rapeseed (*B. napus* L.) requires readily available oil and fat refining processes to be converted to renewable jet fuel. Several airlines have concluded long-term offtake agreements with biofuel suppliers of certified renewable jet fuel made from fats recovered from waste and vegetable oil, but deployment is currently limited to selected routes from certain airports. Wider deployment of renewable jet fuel is expected to occur with ongoing technology efficiency improvements and agricultural feedstock requirements will increase in proportion with this trend. Currently, many economic, societal, and environmental factors are challenging a stronger reliance upon agricultural feedstocks including competition with food, logistical costs, crop yields, land availability, and weather.

The inland Pacific Northwest (PNW) is a major agricultural region that offers great potential for increasing oilseed feedstocks. However, 70% (1.8 million ha) of total cropland in this region is dominated by low annual precipitation (< 350 mm). Wheat yields are water limited and excessive cropping depletes the soil profile of stored water. The 2-year summer fallow-winter wheat (SF-WW) cropping system is widely used to conserve soil water over the fallow period and has offered more yield stability and less economic risk compared to annual cropping [2]. Summer fallow is a practice in which fields are tilled but not planted and is used in semiarid regions to conserve soil water for the following year’s crop. Unfortunately, SF also leaves the soil susceptible to wind erosion and contributes to reduced air quality [3]. Wind erosion can be reduced by increasing cropping intensity and thus reducing SF acreage. A 3-year rotation of summer fallow-winter wheat-spring barley (SFWW-SB) was as profitable as SF-WW provided wheat followed fallow to maximize the yield of higher valued wheat and drought tolerant barley was utilized [4]. Reduced tillage fallow (RTF), consisting of a single undercutting operation with low disturbance V-blade sweeps, leaves most of crop residues on the soil surface that also help reduce wind erosion [5] and minimizes water loss by breaking soil water capillarity.

Cropping intensification may provide potential gains in soil conservation and air quality [4], and greater equity between food and biofuel production [6]. Specifically, planting oilseeds in rotation with WW to reduce SF may be a way to decrease competition for land between bioenergy crops and food crops but oilseeds must contend with hot, dry summers in the inland PNW. New carinata varieties for biofuel production are being developed that have increased vigor, drought and heat tolerance, and disease resistance [7]. Recently, the biotechnology company Agrisoma (Saskatoon, SK, Canada) released the first commercial carinata varieties for drier areas of Saskatchewan and Alberta. In southeastern Saskatchewan, this industrial crop achieved a 20% increase in yield and seed oil content over common unimproved varieties [8].

While bioenergy has become a national priority in the USA, there is growing concern of potential environmental problems associated with using agricultural land to produce energy crops. Life cycle assessment (LCA) is a critical, emerging scientific method of accounting for energy consumption and environmental impacts, and identifying areas of improvement in environmental and economic performance [9,10]. Life cycle assessments have evaluated biomass to energy conversion of various bioenergy cropping systems [11,12] but few have addressed energy and environmental performance of bioenergy cropping systems in semiarid environments of the western US.

Smith et al. (2007) [13] investigated the LCA energy balances of biodiesel production from canola in western Canada. Three broad areas of energy inputs included crop production, oil extraction, and transesterification of the vegetable oil into biodiesel. Total energy expenditure per unit of seed yield was 24% less for no-tillage than conventional tillage because less fuel energy was used for fuel and machinery manufacture. Overall, on-farm, nitrogen (N) fertilizer requirements for canola production accounted for up to 50% of the energy inputs per hectare. Energy output in biodiesel was 2.1 to 2.4 times greater than the energy input needed to produce and process the feed oil.

Gasol et al. (2007) [14] evaluated the energy balance and environmental impacts of production and distribution of carinata as a source of lignocellulosic biofuel in Mediterranean areas of southern Europe where this oilseed has shown adaptation and productivity. The utilization of carinata was based on harvesting the plant in its entirety including the aboveground biomass and seeds. The LCA determined environmental impact in several impact categories including global warming potential, ozone layer depletion, acidification, and eutrophication. The greatest energy consumption was associated with use of diesel for transportation and fertilizer for crop production. Net greenhouse gas (GHG) emissions were 12.7 g CO₂ equivalents MJ⁻¹ of crude biomass energy produced.

Shonnard et al. (2010) [15] assessed renewable jet fuel and diesel from camelina (*Camelina sativa* L. Crantz) grown in Montana, including rail transport of extracted oil to Washington for upgrading and use. The cultivation of camelina was based on rotation with WW and using measured nutrient inputs from a set of field trials in Montana over several years. Life cycle emissions for renewable diesel were reported to be 18.0 g CO₂ equivalents MJ⁻¹ fuel for camelina representing a savings of 80% relative to petroleum diesel. Similarly, Dangol et al. (2015) [16] found that camelina biodiesel production reduced CO₂ equivalent emissions by 69% with production of camelina in 3- and 4-year wheat-based rotations under 300–360 mm of annual precipitation in the inland PNW. Zaher et al. (2013) [17] used computer simulation to investigate emissions from winter wheat-based cropping systems in eastern Washington and found that on-farm N₂O contributed up to 40 and 70% of total CO₂ equivalent emissions under low and middle to high rainfall scenarios. Production of fertilizers contributed 13% of total emissions whereas fuel consumption varied across sites due to differences in machinery use with different topography, tillage, soils, and number of fallow years.

Information is lacking on the energy output and carbon (C) credits resulting from conversion of SF-WW to more intensive crop rotations in the dryland region of eastern Oregon and eastern Washington. The objectives of this study were to (1) estimate the life cycle energy and GHG emissions of several 2- and 3-year crop rotations with cereals and oilseeds in a low precipitation environment of the inland PNW, and (2) ascertain whether cropping intensification can improve energy efficiency and reduce GHG emissions from multiple agricultural operations. These results will be compared with the conventional SF-WW system.

3.2 Methods

3.2.1 LCA goal and scope

The goal of this LCA is to compute the cumulative energy demand (predominantly fossil) and C footprint among different cropping systems from multi-year field trials near Echo, Oregon, U.S (45° 43.3' N Lat., 119° 2.9' W Lon.). The LCA scope is a cradle-to-gate assessment where the gate is the roadside of the farmer's field. Net energy analysis is performed to calculate the input-energy required to produce the output-energy contained in the oilseeds. Average seed yields (kg ha^{-1}) were used to determine the output energy present in the oilseeds using lower heating value (LHV), while the direct and indirect input energy were determined from the field activity data such as diesel fuel for machinery use, fertilizers, pesticides, and other materials used. The GHG emissions are calculated based on emissions from (a) diesel combustion at each stage of crop production, as well as production and delivery of seed, fertilizers, and pesticides (b) direct field emission measurements of greenhouse gases (CO_2 , N_2O , and CH_4), and (c) cultivation and crop production activities involving use of fertilizers and herbicides. Details on direct field measurements are described below in "3.2.9 Measurement of Soil Gas Emissions".

3.2.2 LCA system boundaries

The system boundary for wheat, oilseed, and other crops includes seeding, cultivation, machinery operation (harvester, sprayer, and tractor), application of fertilizers and herbicides, and ends at the field edge (Fig. 3.1). Emission sources associated with each activity are represented by arrows. The primary differences between the three pathways are the activities associated with crop production, e.g., machinery used, fertilizer applied, herbicides and pesticides, etc. The transportation, manufacturing, and maintenance of machinery are not accounted for in this analysis because their impacts are negligible compared to fuel consumption during machinery operation [18]

Figure 3-1 Cradle-to-gate lifecycle system boundary for cereal and oilseed crops

3.2.3 Functional unit and crop rotations

There are a wide range of agricultural systems and each has multiple functionalities (food, feed, fiber, fuel, etc.), which makes the functional unit difficult to define. Hayer et al. (2010) [19] proposed three different functional units for agricultural production systems: (1) land management (ha of land), (2) production (kilograms of grain), and (3) economics (value of crops produced). Among these three options, we believe that kilogram of grain is the most appropriate and is consistent with our study's goal of understanding effects of incorporating energy cropping into rotation with food crops, and having a main focus on crop yields (kg ha⁻¹ year⁻¹).

The experiment consisted of nine crop rotations that included winter wheat (WW), winter oilseed (WO), winter triticale (WT), spring barley (SB), spring oilseed (SO), spring wheat (SW), and spring triticale (ST). Fallow was the first phase of each rotation as needed to build soil profile moisture for the crop in the second phase. Crops were grown in a fixed order year after year and included two 2-year rotations as WW and either SF or RTF, and six 3-year rotations as either a winter cereal crop followed by SO, or WO followed by a spring cereal (see Table 3.1 for specific rotations and abbreviations). A 4-year rotation of RTF-WW-RTF-WO was also included but was broken into two 2-year rotations as RTF-WW and RTF-WO. The net GHG emissions are also reported on per hectare basis over 6 years.

Table 3.1 Nine crop rotations used in the cropping systems study, Echo, OR

Crop rotation	Crop rotation abbreviation
Summer fallow-winter wheat	SF-WW
Reduced tillage fallow-winter wheat	RTF-WW

Reduced tillage fallow-winter wheat-spring barley	RTF-WW-SB
Reduced tillage fallow-winter wheat-spring oilseed	RTF-WW-SO
Reduced tillage fallow-winter oilseed-spring wheat	RTF-WO-SW
Reduced tillage fallow-spring oilseed-spring wheat	RTF-SO-SW
Reduced tillage fallow-winter oilseed-spring triticale	RTF-WO-ST
Reduced tillage fallow-winter triticale-spring oilseed	RTF-WT-SO
Reduced tillage fallow-winter wheat-reduced tillage fallow-winter oilseed	RTF-WW-RTF-WO

3.2.4 Allocation

The input data for each crop grown in rotation is allocated totally to that crop. For example, if wheat is grown in year 1 of a rotation, then the inputs for year 1 are all for wheat. This method is applied for all rotations in this study. The only time when allocation is an issue is when there is reduced tillage fallow (RTF) in the 3-year-two crop rotations. In this case, the RTF inputs are shared between the two crops and the allocation of RTF inputs are based on both mass yields of the two crops and market values. Total yields (kg ha⁻¹) from individual crops are considered for allocating the emissions based on mass whereas market price of crop is also considered for the allocation by market value. Prices for wheat were the average of elevator quotes at Lewiston, ID; Walla Walla, WA; and Umatilla, OR published online for 5 Oct. 2017. For barley, they were the average of elevator quotes at Lewiston and Wilbur, WA and for triticale the average at Wilbur. Prices for oilseed were the average of elevator quotes at Lewiston, Walla Walla, and Pomeroy, WA. Prices ranged from \$0.18 to \$0.20 kg⁻¹ for soft white winter wheat, \$0.26 to \$0.27 kg⁻¹ for hard red spring wheat, \$0.12 to \$0.15 kg⁻¹ for feed barley, \$0.11 kg⁻¹ for triticale, and \$0.37 to \$0.42 kg⁻¹ for canola. Complete calculations of allocation factors using the prices and yields of each crop rotation for both mass and market value can be found in section B.1.1 of Tables B-4 of the Electronic Supplementary Material.

3.2.5 LCA inputs

The primary datasets contain the field activities on the basis of crop production area for all 2- and 3-year rotations. Machinery use in agriculture is a key energy consuming activity in crop production and the field inputs for fuel consumption include multiple powered equipment with varied implements. The equipment used in this study include: (1) Sprayer—600-gal 70-ft 125–135 hp high clearance for pre-plant and post-harvest herbicide application; (2) Tractor—4-wheel drive (WD) 475 HP for seeding, rod weeding, tillage,

flail mowing and disking; (3) Bell 47 helicopter with Lycoming VO435 engine for aerial pesticide application; and (4) Combine harvester—350 HP for grain harvesting. In this region, a helicopter is used to apply chemicals when either the ground is too wet for wheeled machinery (early season) or the crop is tall and easily damaged by wheels (late season). Input inventory data were the weighted averages of 5 years of field data for spring crops and 4 years for winter crops (Tables 3.2-3.6) and spring crops averages were calculated by counting the total number of activities in 5 years for each rotation (both 2- and 3-year) and dividing by total number of data years. For example, the helicopter use in the field activities is limited and employed once in 5 years, so the input of the fuel consumption by helicopter activity is divided by 5 to account for the weighted average for 1 year. The equipment fuel consumption inputs for different field activities were calculated using the field rate, and the fuel usage factor from the equipment data website [20]. Depending on the density of the fuel used, the fuel rate was converted to units of kg ha⁻¹ (Tables 3.2 - 3.6). The inputs from the field for all the pesticides were measured on volume basis which is converted to mass basis using the bulk density values of each chemical obtained from each MSDS (material safety data sheet). Fertilizer and seed rates were measured in units of kg ha⁻¹. Detailed information on machinery, implements, fertilizers, seed rates and pesticides is provided in Tables B-8–B-17 of B.1.2 in Appendix B. These inputs were then divided by an average yield (kg ha⁻¹) to establish the inputs required per kg of crop (for average yields and standard deviations refer Table B-2 in B.1.1 of Appendix B). The details of field activities' input conversions are schematically represented and tabulated in Tables B-18–B-27 of B.1.3 in Appendix B.

Table 3.2 Annual inputs for two-year rotations includes both tillage and cropping; per ha.

	SF-WW	RTF-WW	RTF-WW	RTF-WO
Total Seed (kg)	128.49	128.49	128.49	6.10
Total unspecified pesticide (g)	1010.62	1247.80	1106.64	527.16
Glyphosate (g)	3243.31	6790.44	6791.09	5740.67
Total Diesel & Combustion ^a (kg)	50.17	37.14	37.14	34.42
Total Gasoline & Combustion ^b (kg)	0.72	0.89	0.86	0.30
Urea CO ₂ field emissions (kg)	44.49	44.49	44.49	44.49
Total N ₂ O field emissions (kg)	0.77	1.53	1.65	0.89
Total CH ₄ field emissions (kg)	-3.60	-3.11	-3.51	-3.19
Total Nitrogen fertilizer as N (kg)	61.88	61.88	61.88	61.58
Total Sodium Sulfate (kg)	58.40	58.40	58.40	58.40

Total Latex (g)	60.72	60.72	60.72	30.35
Total Ethoxylated alcohol (g)	366.35	549.53	549.51	424.25
Total Dichloropropene (g)	2800.47	3109.90	3109.90	2120.74
Total Dicamba (g)	-	-	101.33	-

a 3.24 kg CO₂ kg⁻¹ diesel combusted

b 2.85 kg CO₂ kg⁻¹ gasoline combusted

Table 3.3 Weighted average annual inputs for spring barley, spring triticale, winter triticale; per ha.

	RTF-WW-SB	RTF-WO-ST	RTF-WT-SO
Total Seed (kg)	122.30	112.67	124.47
Total unspecified pesticide (g)	935.14	935.14	898.40
Glyphosate (g)	2278.62	2278.62	1234.77
Total Diesel & Combustion (kg)	21.95	21.53	21.53
Total Gasoline & Combustion (kg)	0.42	0.42	0.42
Urea CO ₂ field emissions (kg)	44.49	44.49	44.49
Total N ₂ O field emissions (kg)	0.74	0.74	0.42
Total CH ₄ field emissions (kg)	-1.06	-1.06	-1.73
Total Nitrogen fertilizer as N (kg)	61.58	61.58	61.88
Total Sodium Sulfate (kg)	58.40	58.40	58.40
Total Latex (g)	30.35	30.35	30.35
Total Ethoxylated alcohol (g)	320.54	320.54	274.74
Total Dichloropropene (g)	1685.75	1685.75	1685.75

Table 3.4 Weighted average annual inputs for winter wheat and spring wheat crops; per ha.

	RTF-WW-SB	RTF-WW-SO	RTF-WO-SW	RTF-SO-SW
Total Seed (kg)	128.49	128.49	131.70	131.70
Total unspecified pesticide (g)	896.37	901.28	935.16	935.14
Glyphosate (g)	1234.77	1234.77	2278.62	2278.62
Total Diesel & Combustion (kg)	21.53	21.80	21.95	21.95
Total Gasoline & Combustion (kg)	0.42	0.42	0.42	0.42
Urea CO ₂ field emissions (kg)	44.49	44.49	44.49	44.49
Total N ₂ O field emissions (kg)	0.42	0.49	0.74	0.74
Total CH ₄ field emissions (kg)	-1.73	-1.68	-1.06	-1.06
Total Nitrogen fertilizer as N (kg)	61.88	61.88	61.58	61.58
Total Sodium Sulfate (kg)	58.40	58.40	58.40	58.40
Total Latex (g)	30.35	30.35	30.35	30.35
Total Ethoxylated alcohol (g)	274.74	274.74	320.54	320.54
Total Dichloropropene (g)	1685.78	1685.75	1685.75	1685.75

Table 3.5 Weighted average annual inputs for 3-year reduced tillage fallow; per ha.

	RTF- WW-SB	RTF- WW- SO	RTF- WO- SW	RTF- SO- SW	RTF- WO- ST	RTF - WT- SO
Total unspecified pesticide (g)	306.72	306.69	306.69	306.69	306.64	306.62
Glyphosate (g)	5556.35	5556.35	5556.35	7715.93	6482.40	5556.30
Total Diesel & Combustion (kg)	15.58	16.07	15.58	15.58	15.88	15.78
Total Gasoline & Combustion (kg)	0.42	0.42	0.42	0.42	0.42	0.42
Total N ₂ O field emissions (kg)	0.57	0.64	0.37	0.89	0.49	0.64
Total CH ₄ field emissions (kg)	-1.70	-1.51	-1.58	-1.26	-1.58	-1.51
Total Latex (g)	30.35	30.35	30.35	30.35	30.35	30.35
Total Ethoxylated alcohol (g)	274.74	274.74	274.74	274.74	274.74	274.74
Total Dichloropropene (g)	1424.10	1424.05	1424.10	1423.95	1424.10	1424.10

Table 3.6 Weighted average annual inputs for winter oilseed and spring oilseed crops; per ha.

	RTF- WW-SO	RTF- WO- SW	RTF- SO-SW	RTF-WO- ST	RTF- WT- SO
Total Seed (kg)	6.05	5.68	6.05	6.10	6.05
Total unspecified pesticide (g)	307.11	220.35	307.04	220.35	307.06

Glyphosate (g)	2309.04	803.33	2309.01	803.33	1713.93
Total Diesel & Combustion (kg)	21.80	20.94	21.80	21.11	21.80
Total Gasoline & Combustion (kg)	0.74	0.59	0.74	0.42	0.74
Urea CO ₂ field emissions (kg)	44.49	44.49	44.49	44.49	44.49
Total N ₂ O field emissions (kg)	0.79	0.49	0.49	0.67	1.16
Total CH ₄ field emissions (kg)	-1.33	-1.58	-1.31	-1.78	-1.19
Total Nitrogen fertilizer as N (kg)	61.58	61.58	61.58	61.58	61.58
Total Sodium Sulfate (kg)	58.40	58.40	58.40	58.40	58.40
Total Latex (g)	30.35	30.35	30.35	30.35	30.35
Total Ethoxylated alcohol (g)	241.09	149.48	241.09	149.48	241.09
Total Dichloropropene (g)	1685.78	1315.78	1685.75	1315.78	1685.75
Total Isopropyl amine (g)	298.49	-	298.49	-	298.49

3.2.6 Inventory analysis

The life cycle inventories for the inputs in Tables 3.2, 3.3, 3.4, 3.5 and 3.6 are obtained from both ecoinvent™ and US Life Cycle Inventory (LCI) databases in SimaPro (more information on ecoprofiles, which are cradle-to-gate inventories of emissions, other wastes, and primary materials consumed per amount (kg, kWh, etc.) of input used, in this study is found in Tables B-28– B-49 of B.2.1 in Appendix B). Ecoprofiles for pesticides not present in the data base are selected as “unspecified pesticides” in ecoinvent™. The combustion emission factors for diesel and aviation gasoline were calculated using environmental protection agency (EPA) emission factors [21] (3.24 kg CO₂ kg⁻¹ diesel combusted, and 2.85 kg CO₂ kg⁻¹ aviation gasoline combusted). Field emissions of urea CO₂ are estimated based on the stoichiometry of C in urea (0.733 kg CO₂ kg⁻¹ Urea). As there is no sodium

thiosulfate ecoprofile found in the database, inputs for S in sodium thiosulfate were converted to S in sodium sulfate using molecular weights. Ecoprofiles for N₂O and CH₄ emissions are created in SimaPro using direct field measurements (Detailed procedures for direct field emissions are in Tables B-50-B-78 of B.2.2 in Appendix B).

3.2.7 Impact assessment

The main impacts analyzed in this study are (1) climate change using global warming potentials and (2) cumulative fossil energy use. Energy use impacts are quantified using the Cumulative Energy Demand method in SimaPro v. 8.0.3.14, which accounts for all the process energy conversion efficiencies and other energy uses from cradle-to-gate. Global warming impacts are calculated by IPCC 2013 GWP 100- a method in SimaPro with global warming potentials (GWP) of CO₂: 1, N₂O: 265, CH₄, fossil: 28 and CH₄, biogenic: 25.25. Values of GWP for all other greenhouse gases are included in the developed inventory, such as refrigerants and some solvents.

3.2.8 Field experiment description and input data

This LCA is based on data from a cropping systems field experiment with cereals and oilseeds within a 6-ha field site at a private farm (45° 43.2' N, 119° 2.9' W) near Pendleton, OR. The research area is located on Ritzville silt loams (coarse-silty, mixed, super active, mesic Calcic Haploxerolls, 2–7% slopes) derived from loess. Ritzville soils are found throughout the region's low-precipitation farming areas. Mean annual precipitation at the site is 275 mm with about 70% occurring from November through March. Average annual air temperature is 13.1 °C. Previous cropping history was spring wheat in rotation with SF until 2010 when no-tillage was implemented. Starting in 2012, WW was grown. The experimental design was a randomized complete block with four replications. Individual plots were 3.66 m × 30.5 m. Except for RTF-WW-RTF-WO, each phase of each cropping sequence was present in each replication each year. Spring crops planted in 2013 followed WW allowing comparison of their yields from 2013 to 2017. Rotational phases of winter crops were established as early as 2014 and so their yields were provided from 2014 to 2017.

Rates for fertilizer N were based on an expected yield goal of 3360 kg ha⁻¹ for winter cereals and 2251 kg ha⁻¹ for spring cereals resulting in a requirement of around 120 kg N ha⁻¹ for each. Fertilizer N requirements for Brassica oilseeds are similar to those of cereals and thus were based on the same requirement. Residual soil NO₃-N + NH₄-N levels in fall 2013 revealed 125 kg N ha⁻¹ in the 0–60 cm depth and thus only a small response to added N was expected at the site. Liquid fertilizer was banded at planting about 3.75 cm below and to the side of each seed row. A solution of 79% urea-ammonium nitrate and 21% ammonium thiosulfate was applied at 166.5 L ha⁻¹ to give 56 kg N ha⁻¹ and 5.5 kg S ha⁻¹ to each planted plot each year.

Soft white winter wheat (cv. Bobtail or Jet) and winter triticale (cv. Trical 141) were planted in mid- to late-October at 133 kg seed ha⁻¹. Winter canola (cv. Amanda) was

planted during the same period at 6.7 kg ha⁻¹. Hard red SW (cv. Jefferson or Kelse), SB (cv. Champion or Lenetah), ST (cv. Forerunner), and SO (cv. ACC A110 or EM080814) were planted mid-March to early-April at rates of 138, 115, 112, and 6.7 kg ha⁻¹, respectively. Winter canola required replanting with spring canola (cv. InVigor L130) in early March of 2015 and 2016 due to winter kill. Planting was undertaken with a 3.05 m wide hoe-type drill (Seed Hawk, Inc., Langbank, SK, Canada) with 10 single side band knife openers for single pass seeding and fertilizing and 30 cm row spacing. Oilseeds were planted 1.25 cm below the soil surface and cereals at 2.5-cm depth.

The nine cropping systems differed in soil tillage and pest control methods. A tank-mixed application of formulated pyrasulfotole, bromoxynil, and mesosulfuron-methyl prior to canopy closure controlled broadleaf and grass weeds in all cereal plots. Summer fallowing consisted of disking in early May followed by cultivating and rod-weeding both in late May and mid-June for weed control each year. In reduced tillage plots, glyphosate was applied in mid-March and early May followed by tillage in July with wide V-blade sweeps that undercut the soil with minimum surface lifting. There are no chemical broadleaf weed control options for non-GMO carinata and canola, and thus the broad-spectrum herbicide glyphosate was applied 2 weeks before planting these crops in spring. In May, spring cereals received a mixture of bromoxynil and thifensulfuron-methyl to kill broadleaf weeds. Control of grassy weeds in carinata was done with quizalofop P-ethyl applied in May. An aerial application of lambda-cyhalothrin insecticide was made in early July to kill cabbage aphid (*Brevicoryne brassicae*) in oilseed plots. Postharvest weed management was done on crop stubble and fallow with paraquat to kill any weeds that might have escaped mechanical or chemical control during the growing season, which also served as a pre-planting treatment for the following year's winter crops. All plots were harvested with a self-propelled combine equipped with a 1.5-m header by cutting two 1.5 × 30.5 m lengths. Harvested and cleaned grain was oven dried to constant weight and weighed for determination of yield. All grain is presented as 100% dry matter weight. A yield value represented the average of the four replications across 5 years of the experiment. Seed oil concentration was determined on cleaned samples of canola and carinata (oven dried to constant weight) using a time domain, nuclear magnetic resonance spectrometer (SpinPulse CX-20, Cosa Xentaur, Yaphank, NY).

3.2.9 Measurement of soil gas emissions

Static chamber-based sampling methods were used to measure GHG emissions from soils in selected rotations. Using USDA-ARS GRACEnet protocol [22], surface soil N₂O, CO₂, and CH₄ fluxes were measured in the field from approximately 8:00 to 11:00 a.m. (local time) weekly or 24-h after precipitation events during growing season and monthly after crop harvest, depending on soil and environmental conditions, from 19 March 2015 to 30 September 2017, using a static chamber methodology [23]. Gas flux measurements were reduced after crop harvest because little emissions occur afterwards in the late summer or early fall due to reduced soil water content and temperature [24]. The chamber consisted of an aluminum anchor (10 cm × 43 cm × 76 cm) with a trough welded on top to hold water and a cover (Fig. 3.2), as a two-piece system. Total headspace volume of the chamber was

determined by adding the inside volumes of the anchor and the cover (39.68 ± 2.58 Liter, $n=48$). The anchor was inserted into the soil to a depth of ~ 9.5 cm by hand in each treatment. A carpenter's level was used at the top to level the anchor in the north-south and east-west directions. The cover (10-cm height) covered with mylar reflective material, with ports for ventilation and gas sampling port with stainless steel tubing, was placed at the top of anchor during sampling. The headspace volume in the anchor was determined by lining a plastic bag inside of each of the anchor and filling it with a known volume of water until the water was flushed out from the upper edge of the anchor. Anchors were installed in plots such that each covered three crop rows and inter-row of 30 cm after seeding. Anchors were placed in plots 24 h before first gas samples were taken to reduce effect of disturbance on the gas flux. Chambers were removed during tillage, planting, and fertilization operations and reinstalled near the initial location covering crop row and inter-row, with adjusted similar headspace volume as above. Gas samples were collected (~ 35 ml) through the sampling port using a 50-ml syringe at 0, 10, 20, and 30 min after the cover is placed on the anchors. After collection, the needle is flushed with some of the gas, and the remaining sample is injected into 12-mL evacuated Exetainer glass vials sealed with butyl rubber septa (Labco Ltd., High Wycombe, UK). Soil temperature and soil water content at the 0- to 10-cm depth for each sampling date were determined near the chamber at the time of gas sampling.

Concentrations of N_2O , CO_2 , and CH_4 inside the vials were determined with a fully automated gas chromatograph (Model 3800, Varian Co.) immediately or overnight upon return to the laboratory. The gas chromatograph was calibrated with a certified standard from Scott Specialty Gases (www.scottgas.com). Standards were run periodically throughout the sample run. Gas flux was calculated as changes in linear or curvilinear concentration gradient over time [23]. Total fluxes during the measurement period were calculated for each crop by linearly interpolating data points and integrating the underlying area [25]. The 2-year gas fluxes for each 2-year crop rotation were calculated by averaging total gas fluxes for the 2 years (2016 and 2017) and for each of the 3-year rotations were calculated from estimated fluxes in 2015 and averages of total gas fluxes for the 2 years (2016 and 2017).

Figure 3-2 Static gas chambers for the CO_2 , N_2O and CH_4 measurements

3.3 Results and discussion

In the 2014 crop year, grain production was severely affected by excessive dryness due to below average growing season (Sep.–Jul.) precipitation of 218 mm (79% of long-term). Crop productivity improved when precipitation returned to near normal in 2015 (273 mm, 99%) and 2016 (260 mm, 95%). Winter and spring crop yields improved further in 2017 due to above normal precipitation of 325 mm (118%). The LCA results presented below show intensity of GHG emissions and cumulative energy demand per kg of grain for food and energy cropping systems. These results are divided into three categories: (i) wheat, (ii) oilseed, and (iii) other crops. In Figs. 3.3, 3.4 and 3.5, the bar charts represent stacked columns with each column in the bar showing the respective input contributions to overall GHG emissions. Each bar contains a range bar, which looks at the variabilities in yield with respect to emissions intensity. The results show the direct field CH₄ and N₂O emissions, which includes a combination of overall atmospheric methane uptake (as credit) and N₂O emissions.

Figure 3-3 Greenhouse gas emissions of winter wheat (WW) and spring wheat (SW) in seven different crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms

Figure 3-4 Greenhouse gas emissions of spring oilseeds (SO) and winter oilseeds (WO) in different crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms

Figure 3-5 Greenhouse gas emissions of spring barley (SB), spring triticale (ST), and winter triticale (WT) in other crop rotations based on mass allocation; numbers enclosed in white boxes indicate the total GHG emissions in kilograms

3.3.1 Greenhouse gas emissions

Figure 3.3 shows GHG emission intensities of wheat from 2- and 3-year rotations in which RTF emissions are allocated based on mass (3-year rotations only). Among all rotations,

fertilizer is the largest contributor to GHG emissions due to its large input load and high carbon intensity of production. Next in importance are field CH₄ and N₂O emissions, then diesel fuel, herbicides/pesticides, seeds, urea CO₂ emissions, and aviation gasoline. The highest GHG emissions among all the wheat rotations is from SW in RTF-SO-SW with 1.05 kg CO₂ eq. kg⁻¹ grain due to low yield of spring wheat following SO. The lowest emissions are from WW in RTF-WW-SB with 0.30 kg CO₂ eq. kg⁻¹ grain due to its high yield. Comparing SF-WW and RTF-WW results, the effect of RTF compared to SF shows a slightly higher emission intensity. This is most likely due to higher residue cover and higher N₂O in the RTF treatments compared to SF. Decomposition of previous crop roots and residue due to higher soil water content in the RTF created anaerobic conditions near soil surface, which combined with elevated nitrate from residual nitrogen probably contributed to high N₂O emission [24]. This is a tradeoff between increased N₂O emission from the soils, and conserving soil water and protecting soil from erosion in this soil with low soil aggregate stability and poor soil structure. Both SF and RTF were sinks for CH₄ with CH₄ uptake results consistent with other dryland production systems [24, 26]. The effect of more intensive cropping of WW in the RTF-WW-SB or RTF-WW-SO rotations compared to RTF-WW shows slight benefits based on higher WW yields and lower GHG field emissions. Spring wheat in rotations RTF-WO-SW and RTF-SO-SW exhibited lower yields and higher GHG emissions compared to WW in RTF-WW-SB and RTF-WW-SO because SW was cultivated after the oilseed cropping year whereas WW was grown after RTF.

Though the amount of the fertilizer and yield for WW in the SF-WW and RTF-WW rotations is nearly the same (see Table B-2 of B.1.1 in Appendix B for yields and Tables B-8 and B-9 of B.2.2 in Appendix B for inputs), there is a noticeable difference in their emissions (0.34 vs. 0.39 kg CO₂ eq. kg⁻¹ WW). The main reason is due to the direct N₂O emissions from the soils under the RTF system. The RTF-WW cropping system has higher N₂O field emissions compared to disk tillage during SF, though diesel use is lower than SF-WW, and herbicide use higher. Winter wheat in RTF-WW-SB has lower GHG emissions compared to that in the RTF-WW-RTF-WO rotation and other 2-year rotations due to slightly higher yield of wheat as well as low measured field emissions (see Table B-2 in B.1.1 of Appendix B for the average yields of crops). The results of these WW rotations are within the range of 300–400 g CO₂ eq. kg⁻¹ grain, which are in good agreement with the literature for US average WW cropping emissions between 0.3–0.6 kg CO₂ eq. kg⁻¹ WW [27].

Figures 3.4 and 3.5 show the GHG emission intensities for the oilseed and other crops for RTF emissions allocated based on mass for the 3-year rotations. Fertilizers are the largest contributor to overall emissions in oilseed and other crops, the same as are in wheat. Relative importance of other cropping inputs is similar as in Fig. 3.3 for wheat, except impacts of seed are negligible for oilseed crops due to the small input rate. Among all oilseed rotations, WO in RTF-WO-RTF-WW and RTF-WO-SW have the least overall GHG emissions with 0.66 and 0.75 kg CO₂ eq. kg⁻¹ oilseed. Winter triticale in RTF-WT-SO stands out to be the lowest, and ST in RTF-WO-ST the highest GHG emissions out of

all the other crop rotations with emissions of 0.55 and 1.9 kg CO₂ eq. kg⁻¹ of grain. From Figs 3.3, 3.4, and 3.5, it can be concluded that the winter crops had significantly lower emissions than spring crops with fertilizer being the largest source of emissions. Rotations with WW had the least emissions and highest yields.

Oilseed emissions range from 823.4–975.1 kg CO₂ eq. ha⁻¹ by converting the Fig. 3.4 results (kg CO₂ eq. kg⁻¹ oilseed) using the yields (kg ha⁻¹) from Table B-2 of B.1.1 in Appendix B, which shows good agreement with the literature values between PNW oilseed emissions of 811.5 kg CO₂ eq. ha⁻¹ [16] and southern Europe B. carinata emissions of 1068 kg CO₂ eq. ha⁻¹ [14].

Emission intensity results using market value allocation (MVA) were similar to Figs 3.3, 3.4 and 3.5 except for the 3-year rotations. There was a little difference between market value allocation (MVA) and mass allocation (MA) for the 3-year rotations, due to allocation of only RTF inputs between the two crops and RTF inputs yield much lower GHG emissions than the actual crop inputs. Therefore, allocation method was unimportant in this study. The details of market value allocation results and graphs (Figs B-1, B-2 and B-3) can be found in B.3.1 of Appendix B. Among the wheat crops, the RTF-WW-SB rotation had lowest GHG emissions with 0.30 kg CO₂ eq. kg⁻¹ grain, whereas RTF-SO-SW was highest with 1.05 kg CO₂ eq. kg⁻¹ grain. For oilseeds, winter canola in RTF-WO-SW had the least emissions (0.77 kg CO₂ eq. kg⁻¹ grain) and spring oilseed in RTF-WT-SO had the highest emissions (1.90 kg CO₂ eq. kg⁻¹ grain). For other cereals, winter triticale in RTF-WT-SO had the lowest emissions with 0.51 kg CO₂ eq. kg⁻¹ grain and spring triticale in RTF-WO-ST had the highest emissions (1.79 kg CO₂ eq. kg⁻¹ grain).

3.3.2 Cumulative energy demand (CED)

Figures 3.6, 3.7 and 3.8 show the cumulative energy demand results of wheat, oilseed and other crops using both mass and market value allocation. Though not shown, fossil energy dominates the energy demand results. Embodied biomass energy is not included in these LCA results, a common practice in crop LCAs (e.g., crop eco-profiles in ecoinventTM), because we wanted to quantify the energy invested by pathway inputs. Winter wheat in RTF-WW-SB had the lowest energy consumption based on both MA and MVA whereas spring wheat in RTF-WO-SW had the highest (Fig. 3.6). Among all oilseed rotations, WO in RTF-WW-RTF-WO had the least energy demand and spring oilseed in RTF-WT-SO the highest (Fig. 3.7). For other crops, WT in RTF-WT-SO stood out as the lowest in energy demand and ST in RTF-WO-ST the highest (Fig. 3.8).

Figure 3-6 Cumulative energy demand for different wheat crop rotations (MA: mass allocation; MVA: market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ

Figure 3-7 Cumulative energy demand for different oilseed crop rotations (MA: mass allocation; MVA: market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ

Figure 3-8 Cumulative energy demand for other crop rotations (using both mass and market value allocation); numbers enclosed in white boxes indicate the total cumulative energy demand in MJ

The results of these WW rotations are within the range of 3.1–3.7 MJ kg⁻¹ grain, which are within the literature values for US average WW cropping of 3.1–4.9 MJ kg⁻¹ grain [28]. The cumulative energy demand for the production of oilseed ranges from 5894 to 15,113 MJ ha⁻¹ depending on the intensity of cropping system (these range of values obtained by multiplying the CED results with respective yields of cropping systems, refer to Table B-2 of B.1.1 for average yields (kg/ha) in Appendix B), which can be compared with the published studies reporting 7790 MJ ha⁻¹ [14] and 5677 MJ ha⁻¹ [16]. The variance in the range of values differs because of intensity of cropping and climatic conditions.

In this study, energy investment compared to energy return for oil in oilseed (Fig. 3.9) is calculated with the cumulative energy demand (CED) results (Fig. 3.7) by accounting for the oilseed meal produced when oil is extracted, without allowance for additional burdens from the extraction process. This allocation of CED burdens to the oil in oilseed was determined using an energy allocation approach (remainder goes to oilseed meal). An energy allocation factor (EAF) is determined by using the LHV of oil (37.5 MJ kg⁻¹ oil) and LHV of oilseed meal (18.2 MJ kg⁻¹ oilseed) and the average oil concentrations (36.3% oil for RTF-WO-RTF-WW rotation) in oilseed. The details of the calculations for the energy investment on energy return for oil are in Tables B-5, B-6 and B-7 of B.1.1 in Appendix B. Energy return on investment (inverse of the numbers in Fig. 3.9) is higher for

winter oilseed and spring oilseed (Fig. 3.9). For example, it is 3.85 for winter oilseed yields 1338.9 kg ha⁻¹ in RTF-WW-RTF-WO versus 1.6 for spring oilseed yields 552.2 kg ha⁻¹ in RTF-WT-SO. The reason can be traced to higher yields from a winter oilseed crop as a result of more plant available water following RTF.

Figure 3-9 Intensity of energy demand for different oilseed crop rotations; numbers enclosed in white boxes indicate the total value

3.3.3 Comparison of crop rotations

Greenhouse gas emission results from Figs. 3.3, 3.4, 3.5 and 3.6 were summed over 6 years, which is the shortest period of time common to all 2- and 3-year rotations, to compare all cropping rotations on an area basis (ha). For example, for SF-WW, 3 years of WW plus 3 years of SF are included, while similar summations are included for other cases, as appropriate. The exception is RTF-WW-RTF-WO in which there are two possibilities; (i) RTF-WW-RTF-WO is a combination of 33.3% WW, 16.6% WO and 50% RTF, and (ii) RTF-WO-RTF-WW with 33.3% WO, 16.6% WW and 50% RTF in this rotation. Emissions from the 3-year rotations are distributed equally with 33% each between the RTF and two crops. The emissions in tons of CO₂ eq. ha⁻¹ range from 2.95 to 4.01 metric tons CO₂ eq. ha⁻¹ (Fig. 3.10). Overall, the 3-year rotations exhibit higher emissions because one RTF year (low inputs) is replaced with one cropping year (high inputs) per 6-year period. The RTF-WW rotation shows high emissions because of the relatively high measured soil emissions compared to other plots.

Figure 3-10 Overall greenhouse gas emissions of all the rotations over 6 years in tons of CO₂ eq. ha⁻¹; numbers enclosed in white boxes indicate the total value of emissions

An additional analysis of these data yielded total value of crop sales per unit area over 6 years for each of the crop rotations. Sales value for 3-year rotations are lower compared with 2-year rotations even though in 3-year rotations four crops are produced in a 6-year period (Fig. 3.11). The main reason is due to the low total crop yields of the 3-year crop rotations over 6 years compared to that of the 2-year crop rotations. The high price (\$0.39 kg⁻¹) for oilseeds compared to soft white wheat (\$0.19 kg⁻¹) and hard red wheat (\$0.27 kg⁻¹) on average, (refer Table A-1 of B.1.1 in Appendix B for the detailed information on crop price) does not compete with the 2-year rotation due to low yields. The RTF-WW rotation has the highest sales value over 6 years among all the crop rotations with \$1758 ha⁻¹ and RTF-WT-SO rotation is least with \$827 ha⁻¹. The RTF-WW-RTF-WO rotation contains two possible alternatives, one with two WW crops and one oilseed crop, and a second with one WW and two oilseed crops. The alternative of integrating winter oilseed into WW cropping in a 4-year rotation shows approximately the same sales returns per unit area as the 2-year rotations with WW, and SF or RTF. None of the more intensive crop rotations (3-year rotations) containing one less fallow year per 6-year period yielded comparable sales results as the 2-year rotations, though it is recognized that error bars are quite large.

Figure 3-11 The total sales value of all the rotations over 6 years in dollars/hectare. Variability bars demonstrating the observed range in crop yields obtained from standard deviations of the means (n = 11–14 varies with rotation); numbers enclosed in white boxes

The SF-WW and RTF-WO-RTF-WW rotations exhibited higher sales value and lower GHG emissions compared to all others (Fig. 3.12). Each of the 3-year rotations showed higher GHG emissions compared to the 2-year rotations because of one more year of high inputs for cultivation in a 6-year period. In addition, these higher emissions did not translate into higher value of sales for any of the 3-year rotations in this study.

Figure 3-12 The total sales value against total emissions of nine dryland crop rotations over 6 years; entries enclosed in white boxes indicate the rotation name

3.4 Conclusions

This study investigated the integration of bioenergy oilseeds into food grain cropping under low precipitation, non-irrigated conditions in the inland PNW. Cradle-to-farm gate carbon footprint and cumulative energy consumption of intensified dryland cropping systems were determined on the basis of 1 kg of grain. Carbon dioxide equivalent emissions depended on crop yield. Highest yields and lowest emissions were observed when cereal or oilseed crops followed RTF. For all WW rotations, greenhouse gas (GHG) emissions for WW were in the lower range from literature for US average conditions, providing evidence for the validity of these field trials. From a trade-off plot of GHG emissions versus total sales over 6 years per hectare, the SF-WW and RTF-WO-RTF-WW rotations were shown to be the most promising with low emissions and high sales. This study also demonstrated that incorporating bioenergy oilseed into dryland wheat production systems can help provide feedstock for production of renewable jet fuel. Fossil energy invested for bioenergy return for oilseed oil production showed net positive returns of nearly a factor of 2–4 across all spring and winter varieties. Further improvements in agronomic performance and energy efficiency will come from higher yielding, drought and cold tolerant oilseed varieties, and increased use of renewables in sectors providing farm inputs (renewable energy, biochemical, bioplastics, etc.), and are needed if Brassica oilseed crops grown in low precipitation areas of the inland PNW are to effectively reduce reliance on fossil fuels.

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4 Synergistic Effects Between Hydrolysis Time and Microporous Structure in Poplar³

Abstract

Enzyme accessibility plays an important role in controlling the rate of conversion of cellulose to glucose in biomass. The goal of this study is to measure the cellulose accessibility due to the effect of dilute acid pretreatment (DAP) and enzymatic hydrolysis (EH) time of *Populus* biomass. NMR cryoporometry technique was applied to measure pore size distribution and pore volume over a wide range of pore sizes (range from 0 Å to 10,000 Å) for both pretreated and enzymatically hydrolyzed biomass substrates. The results showed a clear shift in the pore size ranges (from smaller to larger) as the DAP (acid concentration 0.5% wt. and temperature 160 °C) and EH time increases. In most cases, the pore volume increases with the time of treatment, which clearly suggests internal pore expansion. A linear correlation is observed between initial rate of enzymatic hydrolysis of pretreated poplar and absolute pore volume greater than the critical pore size (51 Å) and showing the effect of residual enzyme activity on surface of woodchips.

4.1 Introduction

Biofuels have received a great deal of attention because of their potential for reducing dependence on fossil fuels as well as lowering greenhouse gas emissions from vehicles. Among many other techniques, biochemical conversion of lignocellulosic plant biomass is considered a promising avenue for production of biofuels [1-3]. Plant biomass is the only currently available sustainable source of organic carbon for fuels and chemicals. In the United States, recent estimates have shown that up to 1.15 billion (B) dry metric tons of biomass could be available as feedstock at \$60/dry t annually by 2030 for biofuel and biochemical production [4]. Therefore, lignocellulosic biomass is believed to play a significant role in the future sustainable energy supply with the potential to supply 80 B gallons biofuel/yr assuming a yield of 70 gallons/dry t biomass. However, current biochemical conversion technologies for producing biofuels from biomass are still not ready for cost-effective commercial scale application. It is believed that one reason behind this is because of the great natural resistance of biomass to enzymatic attack, which is known as biomass recalcitrance [5-7].

Biochemical conversion of lignocellulosic biomass typically includes five steps: size-reduction, pretreatment, enzymatic hydrolysis, fermentation, and separation. Generally, some type of pretreatment is first applied to biomass to overcome the biomass recalcitrance

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by changing the biomass structure, which allows various enzymes to attack biomass carbon components (i.e., cellulose and hemicellulose) more efficiently [8-11]. During the enzyme hydrolysis process, hydrolytic glucanase enzymes convert solid, crystalline-structured cellulose into short soluble sugars by these three major activities: 1) endoglucanases randomly cut $\beta(1,4)$ glucosidic bonds of cellulose chains on solid substrate surface, 2) exoglucanases cut bonds only at the ends of cellulose chains on solid substrate surface, and 3) β -glucosidases hydrolyze only soluble oligomer sugars into glucose [12]. Typical endoglucanases and exoglucanases, such as *Trichoderma* species' EG1 (Ce17B), CBH1 (Ce17A) and CBH2 (Ce16B), contain two separate domains: one binding domain and another catalytic domain. These enzymes use the binding domain to adsorb onto long cellulose chains on solid substrate surface to form an enzyme-substrate complex, then use the catalytic domain to cut off the $\beta(1,4)$ glucosidic bonds of cellulose chains [5,13-15]. These enzymes have similar physical size about 5 nm in diameter [16,17]. As a result, these enzymes can not only access (i.e., adsorb and cut) the external surface area of the biomass particles, but also internal surface area (e.g., surface of cracks, channels and pores) in the interior of the biomass particles provided that these pores are larger than about 5 nm in dimension. In fact, in typical pretreated biomass substrate, the enzyme accessible surface area consists predominantly of such internal surface area [18,19]. Mechanical grinding (i.e., size reduction) helps increase mainly the external surface area, whereas the pretreatment changes the internal structure of the biomass by opening up cracks and pores within biomass particles, and effectively removing hemicellulose and redistributing lignin, resulting in increased internal surface area accessible to enzymes.

The performance of enzymatic hydrolysis of biomass is largely dependent on the characteristics of the substrate itself, namely, cellulose degree of polymerization, crystallinity, specific surface area (i.e., enzyme accessible surface area), and composition and distribution of biomass components [20,21]. Among them, the enzyme accessible surface area or porosity of biomass substrate is considered be a major substrate parameter that affects the hydrolysis rate and efficiency. Investigation of the changes in the characteristics of biomass porosity during both pretreatment and enzymatic hydrolysis processes could shed light on the molecular mechanism behind the hydrolysis and biomass recalcitrance and allow us to direct research toward more efficient and productive processes. On the other hand, such investigation could greatly help currently on-going computational modeling efforts which have now evolved to consider realistic morphology of the biomass substrate [22-26], as the information of pore size distribution of biomass substrate would be necessary for the construction of realistic substrate morphology and help improve the accuracy and predictive capability of the model. Meng and co-authors have studied the relationship of porosity and resulting enzyme accessible surface area with pretreatment conditions [27]. However, to our best knowledge, there have been only a few studies on examining the porosity changes for different degrees of enzymatic hydrolysis severity (time). Furthermore, as the enzymatic hydrolysis itself would change the porosity of the substrate, it would be interesting to examine the interactions between rate of enzyme hydrolysis and substrate porosity changes.

There is a wide range of techniques proposed in the literature to determine the pore size distribution and pore volume of biomass substrates, which includes N₂ adsorption, mercury intrusion porosimetry, Simons' stain, solute exclusion, protein adsorption, NMR cryoporometry and NMR relaxometry [28]. In the nitrogen adsorption method, the sample is dried and cooled to make the N₂ gas to pass through the pores and adsorb on the internal surfaces. Brunauer–Emmett–Teller (BET) model is used to correlate between the pressure and volume of gas adsorbed. This technique is very good in determining the surface area of substrate. However, drying of biomass substrates may disrupt the pore structure [29] compared to the natural state when moisture is present and causes overestimation of measurements of enzyme accessible pore volume due to small size of nitrogen compared to size of enzymes [30,31]. Mercury intrusion porosimetry is another technique that works on the same principle as N₂ adsorption and the Washburn equation is used to correlate the pore size based on pressure and volume of mercury adsorbed. This technique is not only used to determine pore size distribution but also specific surface area, and permeability. However, this technique also requires drying of biomass samples which disrupts the pores [29], mercury traps in smaller pores and crushing of pore walls due to high pressures makes the method not suitable to measure the actual inner volume of biomass pore [32].

Unlike the other techniques, solute exclusion can be performed on biomass samples in the wet state, and in this method the substrate is immersed in a known concentration of a solute that has been dissolved in water. The pores accessible to solute molecule will contribute to the change in solute concentration after adding the biomass substrate, and pores inaccessible to solute molecules (when larger molecular probes are used) will not contribute to such concentration change [33]. The final concentration of probe molecules determines the pore size and pore volume of substrate [34]. The pore size distribution and pore volumes are measured quantitatively in the wet state using solute exclusion with probe molecules of different size, but many studies reported that this method is not acceptable for pore size and pore volume measurements as there are challenges associated with pore shape and osmotic pressure [35]. The protein adsorption and Simon stain techniques work based on the principle of binding affinity of molecules and correlates to pore volume and pore size distribution using Langmuir adsorption equations. Simons' stains is a simple and quick technique used to measure the internal and external surface area of substrate, but the measurements can be qualitative and can be affected by shape of the pore [36]. The advantage of the protein adsorption method is that it can be perfectly applied to enzymatic hydrolysis because probing molecule and enzyme in the substrate have similar molecular size and binding module. However, non-cellulosic surfaces such as lignin are also included in the exposed surface area of probe [37].

There are many advantages of NMR cryoporometry, such as this technique can be applied on samples in wet state and the pore volumes are directly measured over a wide range of pore sizes unlike the other methods (solute exclusion and Simons' stain) that requires assumptions regarding the nature of adsorption (monolayer or multilayer adsorption) of the solute molecules. There are a small number of studies which use NMR cryoporometry to measure the pore size distribution and pore volume of biomass substrates [27] studied the cellulose accessibility of both untreated and pretreated (using dilute acid and steam

explosion) Populus substrates at different conditions of pretreatment using NMR cryoporometry over a pore size range of 1 to 10 nm. [38] looked at the effect of pyrolysis of different biochar samples over a temperature range of 250-550 °C. The Rawal et al. study investigated at much broader pore size range of 10-10000 Å compared to Meng's study. In response to the deficiencies mentioned regarding biomass substrate porosity and pore volume measurements (limited to DAP only, limited pore size range), this work employs NMR cryoporometry to measure the pore size distribution (range from sub 10 Å to 10,000 Å) of Populus samples for various enzymatic hydrolysis times after they are first acid pretreated, and the acid pretreatment time is changed to see the effects of initial substrate porosity on the subsequent enzyme hydrolysis behaviors. The overall pore volume and pore size distribution curves are investigated and compared. Then, the pore size distribution is grouped into several ranges (i.e., 0-10 Å, 10-100 Å, 100-1000 Å, 1000-10,000 Å) representing different groups of pore sizes relative to the actual physical size (about 5 nm=50 Å) of the hydrolytic enzymes that work on the solid substrate internal and external surfaces. The changes and trends are analyzed and compared. Our aim is to better understand how dilute acid and enzyme hydrolysis change microporous structure of biomass and also how substrate porous microstructure affects enzyme hydrolysis rates. Such knowledge could help improve hydrolysis inefficiency, overcome biomass recalcitrance, and improve modeling of enzyme hydrolysis of biomass.

4.2 Materials and methods

4.2.1 Dilute acid pretreatment

Hybrid poplar DN34 wood chips with a size less than 500-micron obtained from a University of Florida study [39] were used for this experiment. The DN34 strain of hybrid poplar is a genetic cross between *Populus deltoids* and *Populus nigra*. The biomass was debarked, flaked, dried to zero moisture, milled, sieved (+28–20 mesh) and stored in Ziploc™ bags at room temperature. The raw DN34 hybrid poplar composition was obtained from a previous study,[40] which provided a composition of 43.67 wt. % cellulose, 19.55 wt. % hemicellulose, 27.33 wt. % lignin and the rest inerts or extractives. The apparatus for pretreatment comprised of a rack of 12 tubular reactors made of stainless steel (SS) tubing and Swagelok fittings (6.75 mL volume, 3/8" outer diameter, 0.035" wall thickness), a silicon oil bath (Fisher Scientific Hi-Temp bath-Model 160A) containing Dow Corning 550 fluid.

Initially, bottom caps of the reactor tubes were tightened with a torque of 40 Newton meters using a wrench. All tightened reactors were placed in the rack facing the top open and bottom closed, then 1 mL of 0.5 wt. % dilute H₂SO₄ was added to each individual reactor tube. The pre-weighed 0.5 grams of dry poplar biomass was then introduced into each reactor tube with the help of a funnel and thin cue-tips. The mixture inside the reactor was stirred well for 5 minutes with the help of a narrow-pointed spatula and then 3.5 mL of diluted H₂SO₄ (0.5% wt.) was then added to the reactor resulting in 10 wt. % of solid in dilute acid. The reactor end caps were tightened with a torque of 40 Newton meters. All

tightened reactors were placed upside down in the rack for 5 minutes at room temperature, allowing the complete penetration of diluted H₂SO₄ through the poplar biomass, and this step was repeated for a subsequent 5-minute interval of time.

The oil bath temperature was initially set to 170 °C, and after reaching the set temperature, the 12 reactors were piled in a criss-cross pattern (3 tubes in each layer) in a metal basket. Then the basket containing 12 reactors was lowered into the silicon oil bath and the temperature inside the oil bath was maintained at 160 °C after the submersion. Note that an initial 5-minute heating up period was allowed so that the reactor contents would reach the target temperature of 160 °C, after which time the reaction period began. The reaction temperature and heating time for DAP were chosen based on a previous study by Morinelly et al.[41] Once the target reaction time was reached, three reactor tubes were taken from the oil bath with the help of metal tongs at each time point of 8, 13, 15, 21 and 40 min and placed in an ice bucket to terminate the reaction. These reaction times were chosen based on Morinelly's study to look over a desired range of pretreatment severities [41]. After cooling the reactors to room temperature (cooling time of 3-5 min), the top cap of each reactor was unscrewed using the wrench and the acid-biomass mixture from each reactor was transferred into a 50 mL glass beaker with the help of narrow pointed spatula and then neutralized using 30.7 µL 10 N NaOH to pH 5-6. From the liquid in the beaker, 2 mL was drawn using a 3 mL syringe (Monoject™) and the liquid was filtered through 0.2 µm nitrocellulose membrane filter (Millipore) into 2 mL HPLC vials. The wet biomass sample that remained in the beaker and reactor was washed and filtered with 100 mL deionized water (25 mL for 4 times) using 110 mm diameter Whatman filter paper and a vacuum pump. The wet biomass obtained after filtration was stored in Ziploc bags in the refrigerator (4 °C, moisture content approximately 70%). Liquid samples in vials were analyzed using high performance liquid chromatography (HPLC) for determining the concentration of sugars (glucose, xylose) and furfural. The triplicate samples at each time point were analyzed and the average of the three was used as final sugar or furfural concentration.

4.2.2 HPLC Analysis

Sugar standards and biomass samples were analyzed using an Agilent Series 1200 HPLC comprising of a Bio-Rad Aminex HPX-87P column with two deashing cartridges (BioRad-Catalog #1250139) to remove the interfering ions. Ultra-filtered water was used as eluant and the temperature of the column was maintained at 80 °C with a column pressure between 70-99 bar. Flow rate through the column was 0.6 mL/min and refractive-index detector (RID) temperature was set to 36 °C. The sugar concentrations of samples from acid pretreatment and enzyme hydrolysis were measured using a refractive index detector (RID) and furfural concentrations were determined with a diode-array detector (DAD). Both the detectors were calibrated using known sugar standards (xylose, glucose) and furfural at multiple concentrations (1, 2, 5, 10 g/L) in distilled water. [For calibrations, see C.1.2 of Appendix C]

4.2.3 Enzymatic Hydrolysis

The carbohydrate composition analysis was carried out on completely dried pretreated biomass samples (8, 13, 15, 21, 40 minutes DAP times) following the method from Kuchelmeister et al. [42](See section C.1.3 of SI for detailed description of composition analysis method) Enzymatic hydrolysis was conducted on all 5 pretreated biomass samples (8, 13, 15, 21, 40 minutes DAP time) that were never dried before. The main objective of the experiments was to produce additional monomer sugar (glucose) from the pretreated biomass samples and further open the biomass pore structure prior to NMR cryoporometry. The experiment employed a shaker table (Lab-line Instruments Inc., Model 3527), twelve 50 mL Erlenmeyer flasks, sodium citrate buffer (1 M, pH 4.9) to maintain neutral pH and antibiotics like tetracycline (Sigma-Aldrich) and cycloheximide (Sigma-Aldrich) to avoid microbial contamination. Two different enzymes were used in this experiment Accellerase 1500 (manufactured by DuPont) and Accellerase BG (DuPont).

The enzymatic hydrolysis experimental procedure was based on NREL's Laboratory Analytical Procedure (LAP) "Enzymatic Saccharification of Lignocellulosic Biomass" [43]. 0.5 grams of the wet pretreated poplar biomass was transferred into a 50 mL Erlenmeyer flask. Then 9.5 mL of distilled water was added to each flask using a 10 mL plastic pipette and 0.5 mL of sodium citrate buffer (1 M pH 4.5) was added to each flask. 40 μ L and 30 μ L of antibiotics tetracycline (10 mg/mL in 70% EtOH) and cycloheximide (10 mg/mL in dH₂O) were added to each flask, respectively. In order to determine the exact concentration of sugars in the solution, one control sample was prepared (in duplicate), which contained all the same compounds as the other biomass samples, except the biomass itself. The samples and controls were covered with parafilm and rubber stopper to avoid any leaks, then incubated for 1 hour at 50°C and at 140 rpm in the shaker table to equilibrate to the desired temperature. After 1 hour all the flasks were removed from the shaker table and enzymes were loaded into each flask including controls; Accellerase 1500 at 250 μ L per 1 gram of dry biomass (37.5 μ L for 0.15 gram of dry biomass in each flask) and Accellerase BG at 90 μ L per 1 gram of dry biomass (13.5 μ L for 0.15 gram of dry biomass). Each flask was placed back in the incubator after adding the enzymes. Flasks were removed after 0, 0.5, 1, 2, 4, and 24 hours of incubation (time 0 is 0 min after adding enzymes) and placed in ice to stop the reaction. 2 mL of liquid was drawn from each flask using a 3 mL syringe (Monoject™) and the liquid was filtered through 0.2 μ m nitrocellulose membrane filter (Millipore) into 2 mL HPLC vials. The wet biomass sample that remained in the flask was washed with 100 mL deionized water (25 mL for 4 times) using 110 mm diameter Whatman filter paper and with a vacuum pump to provide suction. The wet biomass obtained after filtration was stored in Ziploc bags in the refrigerator for testing the porosity using NMR cryoporometry. Liquid samples in vials were analyzed using HPLC for determining the concentration of sugars (glucose). All experiments were conducted in duplicate and the average of the two was used as final concentration.

4.2.4 NMR Cryoporometry Protocol

The protocol of an NMR Cryoporometry experiment involves absorbing a liquid into pores; freezing the liquid, and then warming the sample. For this work, 3 mm outside diameter standard NMR tubes were filled with biomass to a depth of 12 mm. Initially the water is simply added to the wet biomass samples using a pipette until there is clearly excess bulk water. This bulk water is then needed to obtain an accurate measurement of NMR total water signal corresponding to total water mass in the sample tube. This also ensures that the pores are fully filled. The drying process necessary to ascertain the dry sample mass was deferred to the end of the procedure to avoid the disruption of the pores. Weighings were performed so that the masses of all the dry solid and probe liquid (water) were known [See table C-1 of Appendix C for weight measurements of biomass samples]. Cryoporometry measurements could then be expressed in terms of volume of pore per mass of dry biomass. The weighed samples were inserted in the NMR probe and cooled down to nearly -80 °C. They were then warmed slowly, with an approximately inverse warming rate (it warms much more rapidly at say -20 °C than near 0 °C), which gives a uniform pore size resolution over the pore size range, until all the liquid was melted. To provide an example of the varying warming rate, at -10 °C, warming rate is 0.5 °C/min while at 0 °C, warming rate is 0.02 °C/min.

NMR spin-echo amplitudes were measured at a 2τ delay of 1 ms, as a robust way of determining the quantity of un-frozen water in the sample. This measurement time avoids signal both from the brittle ice in the pores ($T_2 \sim 10 \mu\text{s}$) and from a water component at pore surfaces ($T_2 \sim 150 \mu\text{s}$), sometimes described as bound water, but more correctly characterised as rotationally mobile ice [44,45]. The amount of liquid that has melted as a function of temperature gives a measure of the pore volume vs. melting temperature, and hence, via the Gibbs-Thomson equation, the pore size distribution.

4.2.5 Temperature control and Measurement

NMR Cryoporometry ideally needs very well controlled wide-range temperature ramps (typically from ~100 K to ~350 K). The temperature measurement needs to reflect as true a temperature measurement of the sample as possible, and this Mk2b apparatus is currently believed to give a precision better than 10 mK. [46] To achieve this level of accuracy, copper-constantan thermocouples supplied and calibrated by TC Direct were used, with as a 0 °C thermal reference an Omega Ltd. TRCIII Ice Point reference that keeps a pure sample of water partially frozen. The NMR Cryoporometric probe has cooling using a Peltier (thermoelectric) cooler unit, using a TTI QL564P computer-controlled power supply, adjusting the Peltier current directly from the main cryoporometry program [47]. A Haake F4 chiller unit set to +3 °C supplies cooling water to the heatsinks of the Peltier devices that cool the probe. (See C.1 of Appendix C for detailed description on cryoporometry materials and methods)

4.3 Results and discussion

4.3.1 Pretreatment

The results of dilute sulfuric acid pretreatment (DAP) of poplar with acid concentration (0.5% wt.) and temperature (160 °C) are shown in Figure 4.1 as a function of pretreatment time (min.). The percent yield of glucan relative to cellulose and xylan relative to hemicellulose are shown on the y-axis and pretreatment time on the x-axis. The error bars show the uncertainties in the measurements representing standard deviations of the triplicate experiments. The data show that xylan yield increases rapidly with pretreatment time early in the reaction period between 8 – 15 minutes, reaches a peak in yield at 21 minutes (82.4%) and decreases gradually until 40 min. due to dehydration of xylose to produce furfural. Glucan yield grows slowly over the time course of the reaction and is much lower than xylan. These results are in good agreement with the previous studies on the hardwoods such as Aspen using the same pretreatment conditions and similar experimental setup [41,48]. This suggests that with 21 min of dilute acid pretreatment the hemicellulose breaks down and thereby opening the micropores in the biomass for enzymes to interact with the substrate. However, with the 40 min acid pretreatment, this decreases the xylan yield (78.3%) due to the formation of more furfural from dehydration of xylose. [See C.1.4.1 of Appendix C for DAP % yield calculations]

Figure 4-1 Dilute acid pretreatment of poplar with acid concentration (0.5% wt.) and temperature (160 °C) as a function of pretreatment time. *Hemicellulose and cellulose content of raw dry poplar biomass (see paragraph 1 of materials and methods).

The results of the composition analysis for all the pretreated biomass samples is tabulated in Table 4.1. Glucan wt. composition increases from 58.5% for 8 min DAP sample to 69.5% for 40 min DAP sample, whereas xylan wt. composition drops from 13.5% for 8

min DAP sample to 5.1% for 40 min DAP sample. [See C.1.3.1 of Appendix C for cellulose composition calculations of pretreated samples]. Results for the enzymatic hydrolysis (EH) of dilute acid pretreated samples are shown in Figure 4.2. The enzymatic hydrolysis results are reported at different EH times (0, 0.5, 1, 2, 4 and 24 hr). The results show that the glucan percent yields relative to the cellulose in the pretreated biomass increases for all the pretreated samples with increased hydrolysis times, with the highest glucan yield occurring between 0-1 hr for all samples. The 8 min pretreated sample gives the least glucan yield (36.92% at 24 hr) compared to all other pretreated samples, presumably because of small pore sizes in 8 min pretreated sample that restrict enzymes from interacting with cellulose within micropores. The maximum glucan yield was obtained for the 40 min pretreated sample with 84.86% after 24-hr of hydrolysis. In general, higher pretreatment times allowed higher rates of production of glucose in the EH experiments. Error bars represent standard deviations from duplicate experiments [See C.1.4.2 of Appendix C for calculations on EH yields]. Meng et al. [49] investigated physical and chemical structural changes on switchgrass and poplar during both DAP and EH. The results show that after 24 hours of EH, glucose yield was approximately 43% and our glucan yields vary from 36.92% (8 min at 24 hr.) to 84.86% (40 min at 24 hr.). The differences in the results is mostly due to the differences in pretreatment conditions. The pretreatment conditions used in Meng's study, are 1% w/w H₂SO₄ (this study 0.5 wt. %) at 120 °C (this study at 160 °C) for 60 min (this study 8-40 min) much different from our study.

Table 4.1 Carbohydrate composition analysis of pretreated DN34 hybrid poplar samples.

DAP time	Xylan (wt. %)	Glucan (wt. %)
8 min DAP	13.5%	58.5%
13 min DAP	8.2%	62.3%
15 min DAP	7.4%	62.6%
21 min DAP	7.5%	67.1%
40 min DAP	5.1%	69.5%

Figure 4-2 The enzymatic hydrolysis of dilute acid pretreatment time samples as a function of hydrolysis time. Most error bars are within the size of the symbols.

*cellulose content of pretreated poplar biomass (see glucan in Table 1).

4.3.2 Cryoporometry

The micropore structure of biomass is comprised of both porosity (pore volume) and pore size distribution. The results in Figure 4.3. show the measured porosities (y-axis) in units of mL pore volume per g dry poplar biomass per Å pore size with respect to pore size (Å) (x-axis) as a function of pretreatment time (legend; increase in pretreatment time from 8 – 40 min.). The 8-minute sample shows a prominent peak in porosity beginning at 10 Å and extending up to approximately 40 Å with maximum peak height at 12.5 Å. As pretreatment time increases, the first prominent peak in porosity at the smaller pore sizes (10-30 Å) tend to shift their position to higher pore sizes (13 min, 24 Å; 15 min, 26.0 Å; 21 min, 26.7 Å; 40 min, 32 Å). The 8-minute sample shows a general decrease in porosity above 30 Å with increasing pore size, with a few small peaks in the highest pore size range between 1,000-10,000 Å. In contrast, at greater pretreatment times, a broad “plateau” in porosity appears between 50-1,000 Å, indicating creation of significant pore volumes at higher pore sizes with increase in time of pretreatment. At the highest pore sizes in the range of 1,000-10,000 Å, a few small peaks in porosity are found with the higher pretreatment time samples. These peaks are higher and shift further to the right (higher pore size) compared to the 8-minute sample.

To further detect the trends, the porosity (y) data as a function of pore size (x) in Figure 4.3 was integrated using MATLAB function ($z = \text{cumtrapz}(x, y)$), in order to obtain cumulative pore volume (z) as a function of pore size (x). Figure 4.4 shows the pore

volumes for different pore size ranges (0-10, 10-100, 100-1000, 1000-10,000 Å) for acid pretreated poplar over time (8, 13, 15, 21, 40 minutes). The C.2 in Appendix C explains how pore volumes were determined. The 100-1000 Å range showed a significant increase in the absolute pore volume from 0.1 mL/gram to above 2 mL/gram with increase in acid pretreatment time. A large increase in pore volume accessible to enzymes in the pore size range of 100-1000 Å in transitioning from 8 min DAP to 15 min DAP. Similarly, Figure 4.2, shows that the greatest increase in the hydrolyzability occurs in transitioning from 8 to 15 min of DAP throughout the EH times. Above 15 min DAP there is little increase observed in pore volume within the pore size range of 100-1000 Å and a similar small increase in hydrolyzability is observed in EH results in Figure 4.2. For the pore size ranges of 0-10 Å and 10,000-100,000 Å the absolute pore volumes were almost constant throughout the pretreatment time showing no significant influence of pretreatment. However, the pore size range 10-100 and 1000-10000 Å slightly increased in pore volume between pretreatment times of 8 – 15 min. But there is a slight decrease in the overall total pore volume from 21 min to 40 min. One reason may be the separation of fibers and cell wall disruption during the 40 min pretreatment. This could block the fiber cell lumen and pit in the cell wall, decreasing the corresponding total pore volume [50]. Overall, the absolute pore volume increases (0.5 mL/gram to 3 mL/gram) with an increase in the pretreatment time (8-min to 40-min).

Figure 4-3 Porosity distribution of dilute acid pretreatment over time (acid concentration (0.5% wt.) and temperature (160 °C)).

Figure 4-4 Absolute pore volume of acid pretreated poplar biomass over time.

Figure 4.5 presents the trends in the normalized pore volume fraction as a function of pore size ranges. [For detailed description of calculations, see C.2 of Appendix C] The normalized pore volume fractions were obtained by dividing the pore volume of individual pore sizes with the total pore volume. Figure 4.5 shows that pore volume fraction is negligible for the 0-10 Å pore size range, and for most samples, obtained at different pretreatment times, 10% of total normalized pore volume falls within the range of 10 to 100 Å. Most of the total pore volume fraction is distributed within the range of 100 to 1000 Å. Despite small peaks observed in Figure 4.3 at large pore size, there is still significant pore volume fractions (around 25%) present in the range of 1,000 to 10,000 Å for most samples. The 8-minute sample, however, shows just over half of pore volume fraction in the larger pore size range (1,000-10,000 Å). This trend was also observed in the raw biomass samples because these samples (8 min and raw biomass) are not much affected by pretreatment. However, with the increase in the pretreatment time, the effect of relative proportion of pore volume at the higher pore size decreases with growth in prominence of 100-1,000 Å there by creating more enzyme accessible pore volume fraction (around 70%) with increase in the pretreatment time. The biggest increase in total absolute pore volume occurs in the earlier pretreatment reaction time (8-15 min). This is expected based on the pretreatment trends shown in Figure 4.1, which show the largest increase in xylose concentration during these early times. The total absolute pore volume roughly remained constant on later pretreatment times (15, 21 and 40 min) approximately 3 mL/g and same trend is observed in Figure 4.2 in the sugar concentrations.

Figure 4-5 Normalized pore volume fraction of dilute acid pretreatment poplar biomass over time (acid concentration (0.5% wt.) and temperature (160 °C)).

Next, Figure 4.6 shows the effects of enzyme hydrolysis time on measured porosities (y-axis) in units of mL pore volume per g dry poplar biomass per Å pore size with respect to pore size (Å) (x-axis) for the 8 min dilute acid pretreatment samples. The 0-hour hydrolysis sample shows the prominent peak at 12.5 Å. At 4-hour hydrolysis prominent peak tend to shift to 20.47 Å and further 24 hours hydrolysis shifts to 21.61 Å. Because the enzymes (50 Å) are larger than these small pore sizes, the shift to larger size cannot be easily explained by enzyme action, and therefore these differences may be due to experimental variability. Similar to Figure 4.2, 0-hour sample shows a general decrease in porosity above 30 Å with increasing pore size, with a few small peaks in the highest pore size range between 1,000-10,000 Å. In contrast, at greater enzyme hydrolysis times, there appears a broad “plateau” in porosity between 30-1,000 Å, indicating creation of significant pore volumes at higher pore sizes. The “plateau” further shift (right) with increased hydrolysis time from 4-hours to 24-hours there by creating more pore volumes at larger pore sizes. [see C.3 of Appendix C for the porosity distribution of enzymatic hydrolyzed 13-, 15-, 21- and 40-min pretreated poplar biomass samples]

Figure 4-6 Porosity distribution of enzymatic hydrolyzed 8 min pretreated poplar biomass sample over time.

The absolute pore volume of all the enzymatic hydrolysis samples was calculated in the same way as described for the DAP samples in Figure 4.4, Figure 4.7, shows the effects of enzymatic hydrolysis as a function of DAP time (a) 8 min DAP, b) 15 min DAP, c) 21 min DAP, d) 40 min DAP) on the distribution of pore volume among different ranges of pore size.

The total absolute pore volume increases as the time of EH increases as shown in each chart a) to d). The absolute pore volume is negligible for the 0-10 Å pore size range and remained constant over the enzymatic hydrolysis time for all pretreated samples, which shows no effect of enzymes on 0-10 Å pore size range. Only about 10% of total pore volume falls within the range of 10 to 100 Å and mostly remained constant over the EH time. The biggest changes in pore volume for most samples is observed in the 100-1000 Å range, which is accessible to enzymes above 50 Å with the only exception in chart b), where the 1000-10000 range changes the most. Figure 4.7, charts a) and c) show similar behavior in that large increases in pore volume occur early in the reaction time (0-4 hr) in the range 100-1000 Å, while the larger changes occur between 4-24 hr in b). These observed increases in biomass pore volume are consistent with the sugar concentration measurements in Figure 4.2 where significant increases in concentration occur over 0-4 hr of EH, but also at later times from 4-24 hr. The change in pore volume over the 24 hrs of EH in each sample increase from less than 1 mL/g in the 8 min DAP biomass to over 2 mL/g for the 40 min DAP sample. It is worth mentioning that the total increase in pore volume over the DAP times of about 2.5 mL/g (Figure 4.4) is similar to the increase in pore volume for the 40 min DAP sample during EH of about 2 mL/g (Figure 4.7 d)). [see C.4 of Appendix C for the normalized pore volume graphs for 8-, 13-, 15-, 21- and 40-min pretreated poplar biomass samples with the time of EH]

Figure 4-7 Absolute pore volume of enzymatic hydrolysis poplar biomass over time a) 8 min of dilute acid pretreatment (DAP), b) 15 min DAP, c) 21 min DAP, d) 40 min DAP.

Figure 4.8 shows the relationship between initial rate of enzyme hydrolysis of pretreated poplar and absolute pore volume greater than 51 Å, which has been considered by others as a critical pore size for enzyme access to the interior of the biomass particle [16,17]. The initial rate of enzymatic hydrolysis was determined by fitting the data of concentration (y-axis) and time of hydrolysis (x-axis) to linear trend line with a zero intercept and finding the slope of the trend line using MS-Excel (For detailed plots and calculations see C.5 of Appendix C). It can be observed from Figure 4.8 that the initial rate of hydrolysis linearly increases with the pore volume of pretreated poplar >51 Å, with an intercept of 0.246, which specifies that, the effect of enzyme residual activity on surface of woodchips produces glucose at a rate of 0.246 g/L/hr.

Our NMR cryoporometry results for the dilute acid pretreatment (DAP) agree qualitatively with Meng et al. 2013 [27] in that pore size in poplar increases with longer pretreatment time. The quantitative results from Meng's study show that with the increase in DAP time from 10 min to 60 min the main peak shifts from 52 Å to 90 Å, starting at 15 Å for untreated poplar sample. Our results show that with an increase in pretreatment time from 8 min to 40 min, the first peak in the pore size distribution shifts from 12.5 Å to 32 Å, a relatively smaller shift. Meng's study did not report the pore volumes of pretreated sample and was limited to the smallest pore size range of 0-100 Å. However, there is a significant difference in the pretreatment conditions. Our pretreatments were carried with an acid concentration ~0.05 mol/L (0.5% wt.) at a temperature (160 °C), with 10% dry solids ratio, whereas in Meng's study, the pretreatments are performed at a concentration of ~0.15 mol/L sulfuric acid at 5% dry solids and at 150 °C. In another study, Ishizawa et al. 2007 [33] measured

pore size and pore volume using both solute exclusion and NMR thermoporometry (pore size range 20-200 Å). They reported that the pretreatment of corn stover samples created more accessible pore volume compared with untreated biomass when measured with solute exclusion and NMR thermoporometry, however little differences were observed in the pore volume between different pretreated samples using both methods. Furthermore, they could not detect shifts in pore size distribution with pretreatment compared to raw biomass using either method. The Ishizawa study used different pretreatment conditions, including 25 and 35% w/w solid loading with 0.03-0.06 w/w of acid/gram of dry biomass at 180 to 200 °C temp with constant residence time of 1 min. Apparently the pretreatment conditions are not different enough in the Ishizawa et al. study, especially at very short residence time, to observe significant changes. Overall, these studies mentioned above show that differences in the porosity results are observable due to the variations in the pretreatment conditions, and it can be observed that residence time in pretreatment plays a crucial role in changes of internal particle pore volume.

Furthermore, our enzyme hydrolysis results show more pore volume in the intermediate pore size range (100 Å -1000 Å) than in other studies. For example, Grethelein et al. 1985 [16] used the solute exclusion method assuming multi-layer adsorption resulting in pure phase solute in pores and looked at a pore size range of 0-110 Å, which showed that poplar with 0.41 w/w% acid pretreatment at 200 °C for 6 sec had an accessible pore volume of 0.7 mL/g above a nominal pore diameter of 51 Å. Also, the Grethelein et al. study showed a linear correlation with the initial rate of EH and pore volume associated with pore size greater than 51 Å with a zero intercept (no EH activity when pore volume is zero for pores > 51 Å). In contrast, Ishizawa et al. 2007 [33] reported no confirmed correlation between the rate of EH and accessible pore volume above a nominal pore diameter of 51 Å for dilute acid pretreated corn stover, which was measured using both solute exclusion and NMR thermoporometry (pore size range 20-200 Å) with a pore volume of up to 1 mL/g. They cite other reasons besides accessible pore volume that may control digestibility by enzymes such as cellulose crystallinity, cellulose-cellulose interaction and chemical composition. However, we note a large difference between our work and both Meng et al. and Ishizawa et al. studies, which do not account for the pore volumes over a wide pore size range as we do in our study. Kafle et al. [51] studied structural changes in Avicel, bleached softwood pulps (~80% cellulose and ~20% hemicellulose) and bacterial cellulose during EH. Interestingly, their results show no positive correlation between hydrolysis rate and structural or chemical changes in biomass, rather that surface contamination and adsorption onto a non-cellulosic species may affect digestibility by enzymes. However, Kafle's study [51] investigated the structural changes across many parameters including crystallinity, degree of polymerization, meso-scale packing of cellulose, while Ishizawa's and our study explored microporous structural changes.

Figure 4-8 Correlation of rate of hydrolysis with the absolute pore volume >51 Å in pore size.

In this study, NMR cryoporometry was applied to measure the pore size distribution and pore volumes of *Populus* biomass samples as a function of both DAP and EH time over wide pore size range (0-10000 Å). We show a positive correlation between both the macroscopic measurements of changes in sugar concentrations to the measured microscopic changes on porosity of the biomass samples. The results show that DAP expands pore volumes and increases the pore sizes, which allows enzymes to access more cellulosic substrates in enzyme hydrolysis. Furthermore, enzymatic hydrolysis creates more pore volume in intermediate pore sizes (100-1000 Å), which is greater than a size of an enzyme at the high end of this range. This study observes a strong linear correlation between the initial rate of enzyme hydrolysis of pretreated poplar and absolute pore volume greater than 51 Å and is in good agreement with the prior studies, except that we observed an effect of activity of enzymes when pore size is smaller than the critical size of 5 nm due to enzyme action on external particle surface. However, there is some variability in the normalized pore volume measurements (from 3-5 mL water / gram dry biomass) due to (presumably) some variability in moisture content of the biomass samples, in the accurate measure of biomass dry weight after cryoporometry, and small wood particles touching each other in the sample chamber, which may have small pockets of water, with then apparently very large pores, at the points of touching of particle to particle. In the future, using a single piece of wood chip should help remove the effect of signal from bulk water between the wood particles [45,52].

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4.5 References

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5 GIS-integrated optimization for locating food waste and manure anaerobic co-digestion facilities

Abstract

There is an increasing interest in continuous baseload low carbon renewable energy generation in the US. Several technologies have been developed to convert biomass into energy, and anaerobic digestion is one such technology to convert food waste and animal manure into power by biochemical conversion and combustion. Many studies have looked at the optimization of the biomass supply chains in combination with environmental impacts. However, there are very few studies in the literature on determining the optimum location of biopower plants fed by food waste and manure. This study evaluates the optimum locations, sizes, and the number of plants for biopower production in Wisconsin using both mixed-integer linear programming (MILP) and geographic information system (GIS) network analysis (ArcGIS V10). The main objective of the study is to maximize the profits for biopower facilities accounting for both the profits from the biopower supply chain and carbon credits. Furthermore, the model predicts the cost-effective supply chain networks between feedstock locations and biopower plants. From a predetermined set of 24 candidate locations, the model predicts facility capacities among a discrete set from 0.5 MW to 10 MW and matches sources of dairy manure and urban food waste to feed the facilities. Other decision variables include tipping fee for food waste, manure acquisition cost, and carbon credits of \$15/ton CO₂ savings, where greenhouse gas (GHG) savings for avoiding food landfilled and conventional manure management were taken from our prior study. The inclusion of a carbon credit increased the profitability of biopower production and predicted an increase in biopower production capacity from 15 to 76.8 MW in WI, representing 1% of its annual electricity consumption.

5.1 Introduction

Significant waste generation occurs in the overall value chain of food; from the production stage through consumption and end-of-life treatment. According to the Food and Agriculture Organization (FAO), about 33% of food production throughout the world is wasted annually [1]. Due to the increasing demand for food and natural resources by a growing population, a transition from linear to circular material flow for food is thought to be sustainable and useful. The linear material flow model is considered as “take-produce-consume-discard”, which is assumed to be unsustainable, as it extracts the resources for production and consumption but does not account for reuse of waste material or regeneration. Conversely, a circular economy provides a platform to circulate resources in a closed-loop system to prevent waste generation and promote reuse, recycle, refurbishing, and repurposing of products through different management methods [2]. In the linear material flow of food supply chain, food wasted in each stage starting from extraction, production, and consumption is ultimately landfilled thereby wasting a large amount of organic resources and generating pollution, such as GHG (methane) emissions.

The materials flows represented in Figure D-1 of Appendix D show the circularity of food and other organic waste using anaerobic digestion (AD) [3]. In a circular economy, food waste is seen as a resource and can be digested anaerobically to produce digestate (nutrients) and other useful products such as biomethane and compost [2]. Biomethane can be used as a low-carbon energy resource, while digestate and compost may be used to grow more crops for food production. The vegetable biomass from crops is reused to feed cattle in the farms to generate more manure and dairy products (such as cheese, milk etc.,). The products and byproducts from cattle manure managements can be reused as supplements for anaerobic digestion and for food production.

The US currently generates around 268 million U.S. short tons of municipal solid waste (MSW) per year, which mostly includes the waste from the industrial, commercial and residential sectors. The generated MSW is managed through different methods such as landfilling, composting, incineration and recycling. The make-up of MSW generated in the US (million U.S. short tons) before recycling, composting and landfilling is shown in Figure D-2 of Appendix D [4]. The second highest component of MSW is organic food waste, at 15% of MSW. On average 30%-40% of the food in the US is wasted every year in the overall food supply chain, which equals more than 20 pounds per person per month, amounting to 39 million tons (Figure D-2 of Appendix D). Of the food waste generation, about 5% is composted and 19% is combusted for energy recovery (presumably carried with combustibles in MSW like food packaging), leaving over 76% landfilled [4]. However, landfilling is environmentally harmful [5] since landfills account for 16.4% of US methane (CH_4) emissions and are the third largest contributor to methane emissions in the US inventory. The total methane emission from landfills in the US is 107.7 million metric tons (MMT) CO_2 eq. This accounts for 2.2% of overall US annual GHG emissions [6]. Methane emissions are more harmful than the emissions of carbon dioxide (CO_2) due to methane's global warming potential (GWP) that is 25 times more than carbon dioxide [7,8]. Another concerning issue is the GHG emissions created from animal wastes, which accounts for 10% of total methane emissions in the US [6]. Manure management in the US has a large environmental impact, as it accounts for 14% of overall GHG emissions from the agricultural sector [6]. Out of the US overall manure management emissions of 67.7 MMT CO_2 eq., nearly 52% of CH_4 emissions are only from dairy cattle ¹⁷⁶. Manure CH_4 emission factors are from a low of 0.02 (most of the poultry breeds) to 1 (beef cattle) and up to a high of 53 (dairy cows) kilograms per head per year [9]. Despite consuming more energy than landfilling, composting reduces direct GHG emissions and can save energy indirectly and may have other benefits when compost replaces some chemical fertilizer used in agriculture [10]. Composting results in other benefits, such as reduction in fertilizer runoff to receiving waters, reduced soil erosion, enhancing the metabolism of microorganisms, increase in soil carbon, and sustaining soil fertility [11]. In a nation-wide survey conducted in 2017, about 18.5% of industrial composting facilities accept food waste as part of their input, and 57% of facilities convert yard trimmings [12].

Both landfilling and composting of food waste have a high potential for uncontrolled methane emissions, so there is a necessity for reliable alternatives for the management of food waste that is produced each year. Biological treatments are the alternate way for the

reduction of solid waste residues [13-16]. AD of food waste and manure is one such method to reduce emissions and may have both economic and social benefits. Biogas from AD has multiple applications, including heating, power generation, biomethane injection into natural gas pipelines, and as a vehicle fuel. Currently 37 states in the U.S. set renewable energy targets to reach at least 20% of electricity needs using renewable energy sources [17].

Policies play an important role in promoting the biogas renewable energy implementation in the U.S. Federal policies supporting biogas production, including the Renewable Fuel Standard (RFS), the Farm Bill's Energy Title (IX), the AgSTAR program, and the EPA's Landfill Methane Outreach Program. The RFS program provides financial incentives for biogas-derived electricity used for transportation and approved biogas as an RFS qualifying feedstock in 2014. Some of the complementary state programs to the federal RFS include California's Low Carbon Fuel Standard (LCFS) and Oregon's Clean Fuels incentive programs [18]. The Farm Bill program provides grants and loan guarantees to agricultural producers and rural small businesses to produce renewable energy and improve energy efficiency. The AgSTAR program is jointly supported by EPA, DOE, and USDA to produce biogas at livestock operations as a means to reduce methane emissions.

The federal electricity Production Tax Credit (PTC) policy provides per kWh tax credits for qualified energy resources such as biogas. Currently, the PTC is valued at about 2.3 cents/kWh [18]. Under this policy a modification of a facility can also receive investment credits but should be an electricity generation facility. New market tax credits are another policy which allocates credits for the projects located in low-income regions. Apart from these policies and acts of legislation, numerous policies such as the National Gas Act, Clean Air Act, Clean Energy Standard, Carbon Pricing, and Renewable Portfolio Standards directly or indirectly aid the application of biogas at the national and state levels [19]. Renewable energy programs such as state-based Renewable Portfolio Standards (RPS) are already in effect on reducing the environmental impacts in the power generation sector in the US. Emissions from fossil power plants contribute around 31% to US total GHG emissions [20]. Carbon price and carbon trading are two major policy schemes that help to reduce emissions and achieve climate change goals in the US [20]. By setting a carbon tax of \$25 per ton CO₂ eq. and with an annual increase of 2%, the Congressional Budget Office (CBO) estimated that a total of \$1.1 trillion would be generated in 10 years in the US to expand renewable power production [21]. The major barriers limiting the development of biogas markets in the U.S. are low price of natural gas, high investment cost of plants, lack of support from federal agencies, and little knowledge on research and development in order to optimize the plants. So, there is a need for an integrated approach to overcome these barriers [22].

The objective of this study is to investigate both present and future outcomes regarding the policies and economic factors for improving biopower production in the US using a systems analysis approach. Due to uncertainties in climate change and market behavior, it is essential to consider the future challenges in modeling sustainable biogas supply chains [23]. Systems analysis combined with numerical optimization methods such as mixed-

integer linear programming (MILP) is used in this study to optimize bioenergy supply chains and address critical issues with transportation logistics, economics and environmental impacts. The proposed model in this study can be applied to any geographic location but is applied to the state of Wisconsin in the United States as a case study. Our study details the supply chain network for identifying the best sites for facility location, evaluates the future effect of policies, and provides information on environmental and economic impacts of biopower installations with different capacity levels at each potential location.

5.1.1 Review of biogas systems analysis

There have been a number of recent studies on the use of systems analysis for biogas production. A MILP optimization model was proposed by Yong Shin Park [23] to estimate the supply chain impacts of mono-digestion (animal manure-fed) biogas facilities in North Dakota with the inclusion of policies such as carbon credits. This model used GIS to identify the potential locations based on social, economic and environmental criteria. The results show that around 9-20 biogas power facilities can be installed with a varying cost of carbon credits from \$0 to \$100/ton of carbon price with an average AD size of 76,666 tons of manure input per year. Laasasenaho, et al. 2019 [24] studied the logistics optimization of bioenergy plants in Finland for both farm-scale and centralized systems using GIS and R programming. The feedstocks used were agricultural residues and woody biomass and the capacities were for a farm biogas plants (>100 kW) and centralized biogas plants (>300 kW) within 10 km radius of the selected region. The main objective was to minimize the transportation distances to feedstock location and candidate biogas facilities. The results showed that 13 farm-scale and 8 centralized biogas plants could be built with a possibility of 3 co-digestion facilities.

Bioteau, et al. 2012 [25] presented a GIS-based optimization model to locate potential sites for collective biogas plant (two or more farms owns a biogas facility) installations in 1000 km² wide area in France based on the energy potential and energy needs of the locality. Crop residues, pig slurry, food waste, sewage sludge and cattle manure were used as feedstocks under different geographic constraints to locate optimum sites but did not account for environmental or economic impacts in the analysis. Surprisingly, key outcomes showed the mapping of resource availability in the selected region but did not allow for decision making on future locations of the facilities since none of economic, environmental nor social impacts were considered. Balaman, et al. 2014 [26] presented a review of different optimization models on bioenergy systems and proposed a MILP based model to determine the locations, capacities of biogas plants and storages based on economic and geographic evaluation. Balaman's model can also predict both supply and product distribution networks and the waste biomass in the form of animal manure and energy crops was used as feedstock. Computational real-world data was used for a region in Turkey to validate the model. The proposed model was applied to all counties in Izmir and the economic results showed a mean payback period of 4.98 years and electricity sale, unused or unprocessed biomass (corn silage) had the biggest impact on the economics.

Despite the prior literature, there are few studies on the optimization of the biogas plant supply chain that simultaneously consider environmental, economic and policy impacts for co-digestion (AD of multiple feedstock) and none in North America. There are very few model-based approaches in the literature, where the inputs for the analysis are generated from data instead of models. A model-based approach is universally applicable and with a good model, we can optimize the conditions of the AD process. Most of the optimization models focus on many different feedstocks but there are very few studies focusing on co-digestion of AD with food waste and manure. This novel study develops the MILP framework-based model for optimization using GIS data for biogas plant supply chain considering geospatial datasets, bioenergy policies, life cycle environmental impacts and economic profit for anaerobic co-digestion of food waste and manure in Wisconsin. This study also shows the sensitivity of the optimization model to variations in key system inputs, such as manure acquisition cost, food waste tipping fee, and price of carbon.

5.2 Methods

5.2.1 Proposed systems analysis framework

This section describes the derivation of the proposed systems analysis framework and MILP model for biogas supply chain optimization with and without carbon credits. The purpose of this study is to develop a model capable of answering a number of questions, such as: i. Where are the optimum biogas power facility locations within Wisconsin? ii. What are their scales of biopower production? iii. How far or close are AD feedstocks to the facilities? iv. What effects do feedstock costs, tipping fees and scales of biopower production have on system profits in Wisconsin? v. What are GHG savings for maximum biogas power production in Wisconsin?

A systems analysis framework shown in the Figure 5.1 is employed for solving the optimization problem to address these questions. The framework contains 3 domains: database, simulation tools and impact categories. The database domain contains multiple data layers, and the simulation domain is the heart of the framework which uses multiple software tools to process the data, and these software tools communicate between each other. The last domain is impact categories in which, the outputs from multiple simulations are converted into impacts. This framework normalizes social, environmental and economic impacts based on a simple objective function based on costs and credits [27]. For each location, new data layers are processed through simulation software to obtain the new results addressing research questions. This problem is iteratively solved until the objective function is satisfied. In general, this model can be applied to any location with multi-product and multi biomass feedstocks. Both food waste and dairy manure feedstock are chosen for this study. They are transported from dairy farms and urban centers, respectively, to co-digestion facilities where waste biomass is converted to biopower. Multiple social factors are considered as constraints in this framework: avoiding disturbance to natural environment such as locating outside the high and medium developed regions, 200 meters away from road network, 200 meters away from surface

water, etc. These social factors are considered to identify the candidate locations for biogas power facilities in Wisconsin. A detailed analysis can be found in the following section.

Figure 5-1 Framework for the sustainability of AD co-digestion from food waste and manure mixture.

5.2.2 Identification of potential biogas plant locations in Wisconsin

This study uses GIS analysis (Arc GIS v.10) to identify potential locations for biogas power plant installations in Wisconsin. This analysis was focused on the state of Wisconsin, which has 72 counties, with a population of 5,822,434 [28]. In this analysis, each county population was multiplied by food waste per capita [29] to calculate total food waste in each county using a tool in ArcGIS. The county courthouse was selected to be the food waste collection point [shown in Figure D-3 of Appendix D]. According to 2012 concentrated animal feeding operations (CAFO) data, there are 240 dairy farms in Wisconsin, and the total count of dairy cattle obtained for each farm was multiplied by average manure per cow to obtain total manure available in each farm [shown in Figure D-4 of Appendix D] [30].

Table 5.1 Criteria for identifying suitable areas for AD in Wisconsin.

Electrical grid	Within 2 km of 200 V capacity grids
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Land cover	On land cover designated as barren, shrub, scrub, grassland, or pasture
Surface water	Outside a 200-meter buffer zone of all surface water
Public lands	Outside a 1 km buffer zone of all public lands
Developed lands	Outside a 250-meter buffer zone of medium and high use developed areas
Roads	Away from 200-meter buffer zone of road network

Table 5.1 shows different sustainability criteria (social, political, and geographic) for selecting candidate locations for the biogas power plants. These criteria can be changed to incorporate any future modification in the region. Suitable biogas power plant locations were evaluated by constraining the proximities to developed areas, road networks and public lands [31].

The 2016 National Land Cover Dataset (NLCD) for Wisconsin [32] was used to select the land areas. The areas with barren, shrub, scrub, hay or pastureland, and grasslands were selected, and all the other lands such as forest etc., were excluded to locate the suitable sites to build AD plants. The NLCD data was used to represent single-family houses, apartment complexes, rowhouses, and commercial or industrial regions while a buffer was applied to exclude high and medium level developed regions. It is also important to locate the plant in proximity to transmission lines to minimize the electricity distribution losses and costs. The electricity grid buffer was selected to include the area within 200-m distance from electric transmission lines. The transmission lines were chosen in such a way that they can withstand a minimum of 200V. The transmission lines below 200 V capacity and away from 200-m were excluded. An intersection of these buffers was used to create a data layer area, which satisfied the criteria to represent available areas for locating potential AD's.

The potential locations of biogas power plants were determined using primary energy input to output (PEIO) ratio to make the return on energy to be a net positive. Transportation distance is one of the critical constraints to achieve the PEIO ratio. From Poschl, et al. 2010 [33], it was indicated that a net positive PEIO ratio requires the transportation distance from manure farms to plant locations not to exceed approximately 13 miles. Two hundred and forty dairy farms from CAFO geocoded data were created as a layer on the intersected region from the above section, and a final buffer was applied to filter the existing region to buffer within 13 miles from farms. A total of 24 potential sites were located from the feasible region of Wisconsin, as shown in Figure D-5 of Appendix D.

5.2.3 Process simulation using Aspen +

Part of the inputs for the optimization model was obtained from a novel 2-stage AD process simulation using ASPEN Plus software shown in Figure D-6 of Appendix D, which is incorporated using the model adopted from Rajendran, et al. 2014 [34]. The two-stage co-digestion allows favorable conditions for different types of bacteria (acidogenic and methanogenic) in each stage and further improves biogas yields. In addition to these two reactors, a hydrolysis reactor was included to convert carbohydrates, proteins, lipids into sugars, amino acids, and fatty acids, respectively. The AD reaction kinetics were modelled using a FORTRAN subroutine in ASPEN Plus. The process parameters such as pH and growth rates were adjusted in the FORTRAN code to validate the simulation results with industrial data (Heartland Biogas LLC.) [29]. Reactor temperature conditions were optimized for better yields (30°C in reactor 1 and 60°C in reactor 2) and 46 reactions were solved simultaneously in ASPEN Plus in each reactor. Process energy minimization was carried out using heat integration with the software, Super Target. Multiple hot and cold stream values were provided from the process simulations into Super Target and these streams were matched. The results from heat integration show that matching air intake before the combustion with the stack gas stream, and matching Liquid 1 stream and Condenser steam in the Rankine cycle should significantly reduce the energy needs. The input and output parameters shown in Table 5.2 such as fertilizer and electricity production with respect to plant input capacity were obtained from process simulations run at each capacity level, from 0.578 MW to 9.25 MW. Investment costs and operating costs were obtained from Balaman, et al. 2014 [26] and were adjusted based on the current market conversion from euros to dollars.

Table 5.2 Input parameters from simulation values at different capacity levels.

	Capacity1 (0.57 MW)	Capacity2 (1.15 MW)	Capacity3 (2.3 MW)	Capacity4 (4.6 MW)	Capacity5 (9.2 MW)
Investment cost(\$/MW)	2.743	2.526	2.491	2.489	2.401
Plant input capacity (dry tons/day)	9	18	36	72	142
Electricity production (MW)	0.578	1.156	2.313	4.625	9.250
OM costs (\$/MW)	0.137	0.126	0.124	0.124	0.120
Fertilizer production (wet tons/day)	68	136	272	545	1090

5.2.4 LCA methodology

The goal and scope of the LCA is to determine the environmental impacts of biopower production for specific locations in WI with varied capacities. The system boundary for the study includes cradle-to-gate and does not include grid distribution or transportation

emissions from distribution of co-products digestate and compost (liquid fertilizer). The functional unit for this study was per kWh of electricity produced and the system boundary for LCA is shown in Figure D-7 of Appendix D, which includes emission credits from avoided landfilling of food waste, avoided manure management emissions, emissions from feedstock and transportation, emissions from AD process and combustion. The anaerobic co-digestion (AcoD) of food waste and manure produces two products; electricity and liquid fertilizer. In order to find the environmental impacts allocated between electricity and liquid digestate, a market value allocation was used, and the allocation factors were pre-determined (0.83 for electricity from biogas; Table D-1 of Appendix D for the calculations). The inputs for the LCA (Table D-2 in Appendix D) were obtained from the process simulations (ASPEN +) and GIS network analysis. The steady-state emissions for the avoided landfilling of food waste includes both biogenic and fossil emissions and the emission factors were obtained from our previous study [29]. Avoided manure management is divided into 3 pathways: slurry, lagoon and solid piles and emission factors for each pathway were obtained from the literature [35]. The combustion emissions were calculated based on the process simulation from species composition of the combustion stream.

The environmental impact analyzed in this study was global warming. The global warming impacts were calculated using the IPCC 2013 GWP 100a, a method in SimaPro 9.0, with GWP of CO₂: 1, N₂O: 265, CH₄, fossil: 28, and CH₄, biogenic: 25.25. GWP values for all other GHG's included in the developed inventory, such as refrigerants and some solvents, are also included in this method.

All the feedstock transportation distances to biopower facility were estimated using a Google script (provided in D.5 of Appendix D). Table D-2 of Appendix D lists results of different emission factors for inputs to biopower system, where all the emissions factors represent a life cycle scope (upstream processes included) and were obtained from the ecoinvent database or the literature.

5.2.5 Optimization model and formulations

In the following description is the list of inputs, decision variables, and assumptions considered for the model. The inputs used in the optimization model include: The availability of manure at each farm i (the calculation is based on an average 25 kg/day of dry manure produced per dairy cow and the amount is in dry metric tons per day), denoted by $A1[i]$; The availability of food waste at each city center j (the calculation is based on ~55 kg of dry food waste generated per person in US annually, and the amount is in dry metric tons per day) [29], denoted by $A2[j]$; The distance (miles) between each farm i to each potential co-digestion facility k (See Table D-3 of Appendix D), denoted by $D1[i,k]$; The distance (miles) between each city center j to each potential co-digestion facility k (See Table D-4 of Appendix D), denoted by $D2[j,k]$; Acquiring cost for manure (\$/dry ton), denoted by mc^{aa} and transportation cost denoted by m_{trans} (\$/wet ton mile) of manure (m), Acquiring cost (\$/dry ton), denoted by fwc^{aa} and transportation cost fw_{trans} (\$/wet

ton mile) of food waste (fw); Carbon price is converted as price of CO₂ equivalence (\$/ton CO₂).

The decisions in the optimization model includes: Locations of biogas plants (k); Capacity levels of biogas plants, in this study 5 different capacities were chosen; Amount of manure to be transported from the farm i to the biogas plant k , $X1[i,k]$; Amount of food waste to be transported from the city center j to the biogas plant k , $X2[j,k]$; Electricity generation at each plant, $E[k]$.

The assumptions in the optimization model include: Life of a biogas plant is assumed to be 20 years; Land cost and upstream distribution costs are not included in this study; Road transportation is the only mode of transportation and a constant distance is assumed from landfill location to county courthouse (70 miles); It is allowed to build more than one biopower plant at a specific location

5.2.6 Economic optimization equations

All the economic components in the objective function are calculated on a monthly basis, which mainly includes two terms 1) total income and 2) total costs. The income function consists of multiple components, such as revenues from the sale of electricity and liquid digestate fertilizer, a tipping fee if any is collected for food waste, carbon credits from avoided emissions of food waste transport, avoided emissions of uncontrolled landfilling of food waste, and avoided emissions of manure management. Costs consist of transportation of food waste and manure, the acquisition cost of manure, plant costs such as investment costs, operating and maintenance costs, and carbon costs from plant and transportation emissions. The objective function is formulated to maximize the profit (revenues-costs) under defined constraints (a total of 8), discussed in D.2 of Appendix D and is solved with the AMPL software using CPLEX solver.

5.3 Results and discussion

The results from this study show optimal plant locations and scales of power production under two scenarios. The first is a present case scenario (Scenario 1) without any carbon credits, without any charge of a tipping fee and with a manure acquisition cost of \$40 per dry ton. A second scenario (Scenario 2) is a future case of \$15 carbon credit per ton of CO₂ equivalents, \$20 tipping fee per dry ton of food waste, and with a manure acquisition cost of \$40 per dry ton.

Figure 5-2 Capacities and locations of the optimal biopower plants in Wisconsin (left: scenario-1 and right: scenario-2)

Results from Scenario 1 show that a total of 15 potential plants can be installed at 8 separate locations with different capacity levels [4, 3, 2, 1, and 0 at capacity levels 1-5, respectively, see Table D-5] without the inclusion of carbon credits. The total capacity of plants totals to 15 MW (0.12 TWh/ year) which is 0.2% of the total annual electric power consumption in WI. [36], as shown in Figure 5.2. Table D-5 of Appendix D shows potential plant locations and the installed capacities, with Dane county and Wheaton county have the potential to install the biggest capacity plants each [~10 MW combined]. Of the 24 counties potential with power plant locations 16 do not have any plants located there in this scenario. The results from the optimization model show multiple plants installations in locations of Dane county due to the discrete plant capacity levels assumed in the model.

Table D-6 of Appendix D shows the income and costs of each component in the objective function for Scenario 1. The total monthly cost of all the installed plants is \$ 831,512. Investment costs and food waste transportation costs contribute the greatest with 62% and 17%, respectively. Similarly, the total income generated from installed capacity is \$ 465,385, most of which (83%) is generated from electricity sales. The total profit from potential plants with the total capacity of 15 MW is \$85,735 monthly.

Results from Scenario 2 shows that a total of 20 potential plants can be installed with different capacity levels [5, 4, 6, 2, and 5 at capacity levels 1-5, respectively, see table D-7]. The total capacity of plants totals to 76.8 MW (0.61 TWh/ year) as shown in Figure 5.3, which is 1% of the total electric power consumption in WI on an annual basis (68 TWh) [36]. For additional context, full scale implementation of AD biogas power in Wisconsin has the same scale of production as annual electricity from petroleum (<1%) [36]. Table D-7 of Appendix D shows the potential plant locations and the installed capacities. Dane County, Jefferson, Auburn, and Holland county have the potential to install the most significant capacity [~10 MW] each. On the other hand, no plants are constructed in Doyle, Emerald, El Paso, Charlestown counties, and Pleasant valley.

Table D-8 of Appendix D shows the individual income and costs of each component in the objective function in Scenario 2. The monthly total cost of all the installed plants in scenario 2 is \$ 5,630,498. Investment costs and food waste transportation costs contribute the greatest with 40.8% and 37.79%, respectively. The transportation network diagram and distances between farm and potential biogas plant, county courthouse and biogas potential plants is shown in Figure D-5 and Table D-3, D-4 of Appendix D. Similarly, the total monthly income generated from installed capacity is \$ 8,474,483 with most of the revenue generated from carbon credits and electricity sales with 44% and 42%, respectively. The avoided food waste and manure management emissions contribute significant profits in terms of carbon credits. The total profit from potential plants with the 76.8 MW is \$2,843,985 monthly. The net emission savings in Scenario 2, after accounting for the 1% replaced electricity emissions (assumed to be from coal power plants) are found to be 3,947 thousand tons of CO₂ per annum. These emission savings represent 7.71% of total annual emissions from electricity (41,779 thousand metric tons of CO₂) [37]. Calculations are shown in Table D-9 of Appendix D. The figure 5.2 shows that with increased revenues in the scenario 2 the capacity of facilities in many locations increases, but the capacities in certain locations disappears in the shift from scenario 1 to 2. The disappearance of the capacities is mainly due to the economies of scale, the supply (food waste and manure) from a specific location in scenario 1 is taken up by the other facility in nearby a location.

Figure 5-3(A) Sensitivity analysis for the coefficients of objective function (manure acquisition cost and foodwaste (FW) tipping fee) with capacity of biogas facilities at varying carbon credits a) \$0 carbon credits

Figure 5-3(B) Sensitivity analysis for the coefficients of objective function (manure acquisition cost and foodwaste (FW) tipping fee) with capacity of biogas facilities at varying carbon credits b) \$5 carbon credits

Figure 5-3(C) Sensitivity analysis for the coefficients of objective function (manure acquisition cost and foodwaste (FW) tipping fee) with capacity of biogas facilities at varying carbon credits c) \$10 carbon credits

Figure 5-3(D) Sensitivity analysis for the coefficients of objective function (manure acquisition cost and foodwaste (FW) tipping fee) with capacity of biogas facilities at varying carbon credits d) \$15 carbon credits

Figure 5.3(A-D) shows results from a sensitivity analysis showing effects of food waste tipping fee (FWTF) and manure acquisition cost (MAC) on biogas plant capacities in WI at four carbon credit levels. At \$0 carbon credit (CC) and \$0 tipping fee, as the manure acquisition cost increases from \$0 to \$60 the total capacity of the plants for profit maximization decreases strongly from 55.6 MW to 1 MW. Due to the upward sloping iso-lines on the figure, there appears to be a trade-off between food waste tipping fee and manure acquisition cost, so that the same capacity may be achieved using multiple combinations of fees and costs at \$0 CC. At higher CC values, greater biogas power production capacities are achievable, up to a maximum of 80.28 MW, with less and less sensitivity to food waste tipping fee and manure acquisition cost on capacity. Even though there is an abundance of dairy manure available, it is not possible to build more plant capacity, because total food waste utilized in WI, ~925 dry tons per day, is the limiting resource.

Figure 5-4 Sensitivity analysis for the coefficients of objective function with objective function value (profits). MAC is manure acquisition cost (\$/ton), CC is carbon credits (\$/ton CO₂)

*** CC- Carbon credits, MAC- Manure acquisition cost**

Figure 5.4 shows the results of the sensitivity analysis of different coefficients of objective function with objective function value (profits), showing that the profits decrease with an increase in manure acquisition cost from \$0 to \$40. The rate of decrease in the profits are less at the \$0 food waste tipping fee (FWTF), \$0 carbon credits compared with other cases (FWTF-\$20, CC-\$10 and FWTF-\$40, CC-\$15). It is also found that with increase in the carbon credits and FWTF there is a significant increase in the profits. On the other hand, the profits increase with an increase in FWTF from \$0 to \$40. Maximum profits were calculated with \$15 carbon credits, \$0 manure acquisition cost, and \$40 tipping fee is ~\$3.8MM per month. Similarly, the lowest profits were determined with \$0 carbon credits, \$40 manure acquisition cost, and \$0 tipping fee, with a value of ~\$0.08MM per month (Figure 5.4).

The table D-10 of appendix shows the location-specific cost and incomes on a monthly basis for scenario 1. The electricity sales dominate in each location for scenario 1, and the main cost parameters include investment and operation cost followed by food waste transportation as the amount of food waste is used in larger proportion than manure. But in some of the locations the food waste transportation costs are less than the manure

transportation. This is mainly due to lower transportation distances from plant to food waste collection point compared to distance from plant to farms.

The table D-11 of appendix shows the location-specific cost and incomes on a monthly basis for scenario 2. In scenario 2, the carbon credits are dominant primarily by avoiding food waste landfilling, secondarily avoiding manure management and thirdly avoiding transportation, which together account for a total of \$3.6 million. The sales from electricity and fertilizer are most important revenues in scenario 2 followed by revenue from carbon credits. Unlike scenario 1, the most dominant cost parameters are food waste transportation followed by investment and operation costs. Investment and operation costs are less than food waste costs mainly due to economies of scale, as the capacities increase the relative importance of the investment and operating costs decreases. Conversely, the food waste resources input increases, which in turn increases the food waste transport costs in proportion to the plant capacity.

In summary, a mixed-integer linear programming model was developed to evaluate the optimum siting of biogas power generation facilities in Wisconsin, considering social, environmental and economic indicators and constraints. The model accounts for resource availability, transportation logistics, cost of the resources, policies and the optimization model decide the scales of production based on these parameters at each candidate location. This model investigated the effects of carbon policies on the optimal biogas power locations and system power generation capacities. The model also incorporated information on supply chain factors, such as dairy manure and food waste supply locations and amounts available. Wisconsin state GIS data was used in the model, and four scenarios were evaluated in this study: a base case with no carbon credits accounted for and future case scenarios with different levels of carbon credits. The future case scenario at the higher carbon credit level showed a 80% increased capacity compared to the base case scenario (15 MW- 72.6 MW).

From a sensitivity analysis, total profits, the capacity of a biogas plant, and location were very responsive to different carbon costs, manure acquisition costs, and tipping fees. The Jefferson county location is found to be optimal for installing a high capacity (18MW) biogas plant in the future case scenario with maximum profits due to the availability of more resources such as food waste and manure. The key limitation for this optimization model is locating multiple capacity plants in a single location, due to discrete set of predetermined capacities, which can be avoided by iteratively identifying and solving for the ultimate capacities. Systems analysis models, such as the one described here, can help policymakers to understand how the complexities of supply chain networks can affect outcomes such as biogas base load power generation capacities, economic benefits, potential to displace conventional power generation, and system-wide emissions savings potential.

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5.5 References

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6 Summary, Conclusions and Recommendations for Future Work

This dissertation presented a new a multi-criteria sustainable assessment framework that includes three domains; i. resource availability and logistics, ii. process modeling, and iii. impact assessment with primary application to optimum location and installation of sustainable biogas / biomethane power plants in the US. A mixed-integer linear programming model was developed to evaluate the optimum siting of biogas power generation facilities in Wisconsin, considering social, environmental and economic indicators and constraints. This model investigated the effects of carbon policies on the optimal biogas power locations and system power generation capacities. The model also incorporated information on supply chain factors, such as dairy manure and food waste supply locations and amounts available. Wisconsin state GIS data was used in the model, and four scenarios were evaluated in this study: a base case with no carbon credits accounted for and future case scenarios with different levels of carbon credits. The future case scenario at the higher carbon credit level showed a 70% increase in biogas power generation capacity compared to the base case scenario (50 MW- 84.4 MW).

In Chapter 2, the resource assessment and carbon footprint analysis (CFA) of biomethane produced from food waste and manure showed that based on the ratios provided by AgEnergy, 19 million short tons of manure from dairy production in the US alone can provide sufficient blending for the total 36 million tons of food waste that is landfilled. By diverting the food waste and manure to AD biomethane production, 0.41% of overall GHG emissions of the approximately seven billion tons CO₂ eq. can be saved in the US annually using 100 Heartland-scale AD facilities. It is important to point out other sustainability benefits of BioCH₄ production from food waste and dairy manure beyond conservation of fossil energy and reductions in GHG emission. These potential benefits include the recycling of mineral nutrients from food waste and manure to agricultural fields and associated reduction of environmental impacts in synthetic fertilizer production and conserving natural resources. Although water is consumed in the AD process, digestate water is delivered to surrounding agricultural fields to offset some irrigation water usage. Large-scale deployment of AD of food waste/manure mixtures in the US would stimulate economic growth and create many engineering, facility operator, and spinoff jobs. More comprehensive sustainability analyses should be conducted to better understand the full set of potential benefits and costs (loss of jobs in landfilling and natural gas industries, possible odor issues) from largescale production of Bio-CH₄ in the US.

Chapter 3, LCA of intensified cropping results show that compared to summer fallow-winter wheat (SF-WW), bioenergy oilseed cultivation may increase CO₂ equivalent emissions in 3-year cereal-based rotations due to increased inputs with inclusion of fallow-substitution cultivation. Fossil energy inputs required to produce oilseed crops were smaller than the total energy in final seed and thus oilseeds have the potential to reduce reliance on fossil fuels. Improving energy efficiency and encouraging adoption by growers

will depend on ability to enhance agronomic performance with higher yielding, drought and cold tolerant oilseed varieties.

In Chapter 4, the method of NMR cryoporometry was applied to measure the pore size distribution and pore volumes of populus biomass samples as a function of both dilute-acid pretreatment (DAP) and enzymatic hydrolysis (EH) time over a wide pore size range (0–10 000 Å). This study showed a positive correlation between both the macroscopic measurements of changes in sugar concentrations to the measured microscopic changes on porosity of the biomass samples. The results show that DAP expands pore volumes and increases the pore sizes, which allows enzymes to access more cellulosic substrates in enzyme hydrolysis. Furthermore, enzymatic hydrolysis creates more pore volume in intermediate pore sizes (100–1000 Å), which is greater than a size of an enzyme at the high end of this range. This study observes a strong linear correlation between the initial rate of enzyme hydrolysis of pretreated poplar and absolute pore volume accessible through pores greater than 51 Å and is in good agreement with the prior studies, except that we observed an effect of activity of enzymes when the pore size is smaller than the critical size of 51 Å due to enzyme action on external particle surface. However, there is some variability in the normalized pore volume measurements (from 3 to 5 mL water/gram dry biomass) due to (presumably) some variability in moisture content of the biomass samples, in the accurate measure of biomass dry weight after cryoporometry, and small wood particles touching each other in the sample chamber. In the future, using a single piece of wood chip should help remove the effect of signal from bulk water between the wood particles

Finally, the key conclusions from Chapter 5 includes a sensitivity analysis of total profits, the capacity of a biogas power plant, and location were very responsive to different carbon costs, manure acquisition costs, and tipping fees. The Jefferson County location in Wisconsin is found to be optimal for installing a high capacity (23MW) biogas plant in the future case scenario with maximum profits due to the availability of more resources such as food waste and manure. One limitation for this optimization model is locating multiple capacity plants in a single location, due to discrete set of predetermined capacities in the model, which can be avoided by iteratively identifying and solving for the ultimate capacities. Systems analysis models, such as the one described here, can help policymakers to understand how the complexities of supply chain networks can affect outcomes such as biogas base load power generation capacities, economic benefits, potential to displace conventional power generation, and system-wide emissions savings potential. The other limitations include the location of food waste collection points assumed to be county courthouses which do you account for the logistics of food waste separation and collection within each county. The buffers to determine the potential locations (site suitability analysis) can be automated using Python script to modify the buffers to understand the effects.

The designs can also be adapted to different socioeconomic regions going from small developing communities to big complexes operating in urban areas, with a special focus on countries that have shown increasing rates of food waste into the landfills. For the environmental assessment, more impact categories like water consumption, fossil energy

consumption, human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, and other categories of impact can also be included. Also, social indicators can be included which can focus on the effects of the facilities on the surrounding communities like potential employment and population dynamics.

Finally, the current economic model does not include the effects of regional economics from the construction of the facilities so this could also be evaluated and included in the systems analysis in future work.

A Supporting Information for Chapter 2

Carbon footprint and energy analysis of Bio-CH₄ from a mixture of food waste and dairy manure in Denver, Colorado

A.1 AD Bio-CH₄ Pathway Calculations and Eco-profiles

This part of the section gives the information on the calculations for the AD Bio-CH₄ Pathway (cradle to grave). AD Bio-CH₄ Pathway has different process operations involved which includes:

1. Eco-profile used for transportation is ‘Transport, freight, lorry 16-32 metric ton, EURO4 | market for | Alloc Def, S’
2. Eco-profile used for natural gas use in the AD process is ‘Heat, natural gas, at boiler condensing modulating >100kW/US- US-EI U’

This eco-profile (Table A-1) was created in SimaPro to estimate the emissions from the combustion of Bio-CH₄. Stoichiometric emission factors for Bio-CH₄ are determined in Table A-3.

Table. A-1. Eco profile for CH₄ emissions Bio-CH₄ combustion (basis 1kg Bio-CH₄)

Processes	Amount	Unit	Basis
Carbon Dioxide	$44/16 = 2.75$	kg	Per 1 kg of Bio-CH ₄

This eco-profile (Table A-2) is created to estimate the CO₂ emissions from AD process.

Table. A-2. Eco profile CO₂ emissions from AD process (basis 1kg Bio-CH₄)

Processes	Amount	Unit	Basis
Carbon Dioxide	1.23	kg	Per 1 kg of Bio-CH ₄ (.522 CO ₂ kg per 0.425 kg of Bio-CH ₄)

The densities used in the above mentioned eco-profiles are calculated depending on the biogas composition (on volume basis) ²⁰¹

Table. A-3. Density calculations

Volume			MW		Mass of Component	MW*P*V/R*T	
Biogas	1	m ³			Normal Conditions	Units	
Methane	0.65	m ³	16	g/mol	P	1	Atm
Carbon Dioxide	0.29	m ³	44	g/mol	T	298.15	K
H ₂ O	0.06	m ³	18	g/mol	R	82.06	cm ³ *atm/K*Mol.
Mass of CH ₄					0.000425	g*m ³ /cm ³	
					0.425092	Kg	
Mass of CO ₂					0.000522	g*m ³ /cm ³	
					0.521555	Kg	
Mass of H ₂ O					4.41E-05	g*m ³ /cm ³	
					0.044144	Kg	
Total mass of biogas					0.990791	Kg	
Density of Biogas					0.990791	kg/m ³	

A Colorado electricity grid was created in SimaPro to estimate the emissions from the consumption of electricity at the AD facility for both internal processes and for distribution of liquid digestate to local agricultural fields through pipelines.

Table. A-4. Eco-profile for the AD (anaerobic digestion) process electricity use is taken from “Colorado grid” basis 1kWh energy. Renewable is assumed to be equal portion of hydro, biomass, wind, and solar.

Processes	Amount	Unit
Electricity, natural gas, at power plant/US	0.22	kWh
Electricity, bituminous coal, at power plant/US	0.6	kWh

Electricity from hydroelectric power plant, AC, production mix, at power plant, < 1kV RER S	.18/4	kWh
Electricity, biomass, at power plant/US	.18/4	kWh
Electricity from wind power, AC, production mix, at wind turbine, < 1kV RER S	.18/4	kWh
Electricity, low voltage {RoW} electricity production, photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated Alloc Def, S	.18/4	kWh

It is assumed that the compost produced from AD has a moisture content of 50% and 50% by dry weight elemental carbon. Only 48% of the carbon is active and emitted as CO₂ ¹⁵¹. An eco-profile was created in SimaPro to determine these emissions.

Table. A-5. Eco-profile for CO₂ emissions from AD compost soil application: basis 1kg wet compost.

Processes	Amount	Unit	Basis
Carbon Dioxide	$.48*.5*.5*44/12 = 0.44$	kg	1kg wet compost, 50% moisture, 50% elemental carbon, 48% active carbon ¹⁵¹

The emission factor for N₂O from the application of liquid AD digestate to agricultural fields near LaSalle, CO is taken from the IPCC and includes both direct and indirect emissions ¹⁵⁰.

Table. A-6. Liquid digestate N₂O emissions on field application: basis 1kg N in liquid digestate

Processes	Amount	Unit	Basis
Dinitrogen Monoxide	$0.01325*44/14 = 0.04164$	kg	IPCC factor for N ₂ O Emissions from Fertilizer land use. .01325 kg N in N ₂ O / N in digestate applied to soil. 44 is MW of N ₂ O, 14 is for N.

A.1.1 Landfill pathway eco-profiles

This part of the section gives list of all the calculations and eco-profiles for the emissions from landfill for both steady-state case and transient scenario with gas collection, without gas collection and gas collection with electricity generation are listed below. References to the calculations described in section-A.2.

Table. A-7. Landfill emissions without gas collection system (uncontrolled) steady state (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	79730.50024/365/216.6344397=1.01	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 79730.50024 tons for 1 year) (A+D in Table A-32)
Methane	23721.47/365/216.6344397=0.29	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 23721.47 tons for 1 year) (E in Table A-32)

Table. A-8. Landfill emissions Gas Collection System (GCS) steady state (basis: 1 kg of dry food waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	128112/365/216.63443=1.62	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 128112 tons for 1 year: (A+B+D in Table A-31)
Methane	6128/365/216.6344397=0.077	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 6128 tons for 1 year) (C+E in Table A-31)

Table. A-9. Landfill emissions Gas Collection System and Electricity generation (GCSE) steady state (basis: 1 kg of dry food waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	128112/365/216.6344=1.62	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 128112 tons for 1 year: (A+B+D in Table A-31)
Methane	6128/365/216.6344397=0.077	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 6128 tons for 1 year) (C+E in Table A-31)

Electricity generation from Natural gas	104025/365= 287	MWh	104025 Mwh electricity is generated/year from collected CH ₄ annually (see Table A-46 for calculations)
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Table. A-10. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled) year 1 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	9015.890148/36 5/216.6344397= 0.114	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 9015.890148 tons for 1 year) (A+D in Table A-32)
Methane	2682.413598/36 5/216.6344397= 0.034	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 2682.413598 tons for 1 year) (E in Table A-32)

Table. A-11. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled) year 5 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	35973.47396/3 65/216.634439 7=0.45	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 35973.47396 tons for 1 year) (A+D in Table A-32)
Methane	10702.85176/3 65/216.634439 7=0.13	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 10702.85176 tons for 1 year) (E in Table A-32)

Table. A-12. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled) year 10 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	55716.13506/36 5/216.6344397 =0.704	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 55716.13506 tons for 1 year) (A+D in Table A-32) (E in Table A-32)

Methane	16576.70134/365/216.6344397=0.21	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 16576.70134tons for 1 year)
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Table. A-13. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled) year 20 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	72497.51245/365/216.6344397=0.91	kg	Daily Basis 216 tons of dry waste CO ₂ (from section-A.2 calculations CO ₂ emissions are 72497.51245tons for 1 year) (A+D in Table A-32)
Methane	21569.50783/365/216.6344397=0.27	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 21569.50783tons for 1 year) (E in Table A-32)

Table. A-14. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled) year 30 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	77551.96618/365/216.6344397=0.98	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 77551.96618 tons for 1 year) (A+D in Table A-32)
Methane	23073.31225/365/216.6344397=0.29	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 23073.31225tons for 1 year) (E in Table A-32)

Table. A-15. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled)
year 40 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	79074.33839/ 365/216.6344 397=1.000035	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 79074.33839 tons for 1 year) (A+D in Table A-32)
Methane	23526.24944/ 365/216.6344 397=0.298	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 23526.24944 tons for 1 year) (E in Table A-32)

Table. A-16. CH₄ and CO₂ emissions from landfill without gas collection (uncontrolled)
year 50 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	79532.86809/36 5/216.6344397 =1.01	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 79532.86809 tons for 1 year) (A+D in Table A-32)
Methane	23662.6715/365 /216.6344397= 0.299	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 23662.6715 tons for 1 year) (E in Table A-32)

Table. A-17. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 1
(basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	14486.90/365/2 16.6344397= 0.1832	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 14486.90 tons for 1 year) (A+B+D in Table A-31)
Methane	692.96/365/216 .6344397=0.00 876	Kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 692.96 tons for 1 year) (C+E in Table A-31)

Table. A-18. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 5
(basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	57802.83/365/216.6344397=0.731	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 57802.83 tons for 1 year) (A+B+D in Table A-31)
Methane	2764.90/365/216.6344397=0.034967	Kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 2764.90 tons for 1 year) (C+E in Table A-31)

Table. A-19. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 10 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	89525.70/365/216.6344397=1.13221	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 89525.70 tons for 1 year) (A+B+D in Table A-31)
Methane	4282.31/365/216.6344397=0.054157	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 4282.31 tons for 1 year) (C+E in Table A-31)

Table. A-20. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 20 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	116490.32/365/216.6344397=1.473226	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 116490.32tons for 1 year) (A+B+D in Table A-31)
Methane	5572.12/365/216.6344397=0.0704693	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 5572.12 tons for 1 year) (C+E in Table A-31)

Table. A-21. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 30
(basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	124611.91/365/216.6344397 = 1.575938	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 124611.91 tons for 1 year) (A+B+D in Table A-31)
Methane	5960.61/365/216.6344397 = 0.075382	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 5960.61 tons for 1 year) (C+E in Table A-31)

Table. A-22. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 40 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	127058.08/365/216.6344397 = 1.606874	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CO ₂ emissions are 127058.08 tons for 1 year) (A+B+D in Table A-31)
Methane	6077.61/365/216.6344397 = 0.076862	kg	Daily Basis 216 tons of dry waste (from section-A.2 calculations CH ₄ emissions are 6077.61 tons for 1 year) (C+E in Table A-31)

Table. A-23. CH₄ and CO₂ emissions from landfill with gas collection and flaring year 50 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	127794.86/365/216.6344397 = 1.61619	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 127794.86 tons for 1 year) (A+B+D in Table 31)
Methane	6112.86/365/216.6344397 = 0.0773	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 6112.86 tons for 1 year) (C+E in Table 31)

Table. A-24. CH₄ and CO₂ emissions from landfill with gas collection and electricity generation year 1 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	$14486.90/365/216.6344397=0.1832$	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 14486.90 tons for 1 year) (A+B+D in Table 31)
Methane	$692.96/365/216.6344397=0.00876$	Kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 692.96 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	$104025/365=287$	MW h	11773.93 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-25. CH₄ and CO₂ emissions from landfill with gas collection and electricity year 5 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	$57802.83/365/216.6344397=0.731$	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 57802.83 tons for 1 year) (A+B+D in Table 31)
Methane	$2764.90/365/216.6344397=0.034967$	Kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 2764.90 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	$104025/365=287$	MW h	46978.08 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-26.CH₄ and CO₂ emissions from landfill with gas collection and electricity year 10 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	89525.70/365/ 216.6344397 = 1.13221	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 89525.70 tons for 1 year) (A+B+D in Table 31)
Methane	4282.31/365/2 16.6344397 = 0.054157	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 4282.31 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	104025/365=2 87	MW h	72760.19 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-27.CH₄ and CO₂ emissions from landfill with gas collection and electricity year 20 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	116490.32/36 5/216.634439 7 = 1.473226	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 116490.32tons for 1 year) (A+B+D in Table 31)
Methane	5572.12/365/2 16.6344397 = 0.0704693	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 5572.12 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	104025/365=2 87	MW h	94675.14 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-28. CH₄ and CO₂ emissions from landfill with gas collection and electricity year 30 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	124611.91/365/216.6344397 = 1.575938	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 124611.91 tons for 1 year) (A+B+D in Table 31)
Methane	5960.61/365/216.6344397 = 0.075382	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 5960.61 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	104025/365=287	MWh	101275.80 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-29. CH₄ and CO₂ emissions from landfill with gas collection and electricity year 40 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	127058.08/365/216.6344397 = 1.606874	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 127058.08 tons for 1 year) (A+B+D in Table 31)
Methane	6077.61/365/216.6344397 = 0.076862	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 6077.61 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	104025/365=287	MWh	103263.88 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

Table. A-30. CH₄ and CO₂ emissions from landfill with gas collection and electricity year 50 (basis: 1 kg of dry waste)

Processes	Amount	Unit	Comment
Carbon Dioxide	127794.86/365/216.6344397 = 1.61619	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CO ₂ emissions are 127794.86tons for 1 year) (A+B+D in Table 31)
Methane	6112.86/365/216.6344397 = 0.0773	kg	Daily Basis 216 tons of dry waste (from section-2 calculations CH ₄ emissions are 6112.86 tons for 1 year) (C+E in Table 31)
Electricity generation from Natural gas	104025/365=287	MWh	103862.68 Mwh electricity is generated/year from collected CH ₄ annually (see Table 46 for calculations)

A.1.2 Peat pathway

This part of the section gives the information on calculations of Peat pathway emissions included in SimaPro. The calculations for the peat pathway emissions are based on the results of a study ¹⁵² and are considered as an eco-profile of CO₂ equivalent factor in each stage of overall lifecycle.

Table. A-31. Emissions from peat moss manufacturing, transport and use (basis 1 m³ peat-moss)

Category	Unit	Harvest	Package	Transport	Soil application	In-situ decomposition
GHG Emissions	kg CO ₂ equivalent	4.03	2.53	15.63	183	60.79

A.1.3 Composting pathway

This section gives the information on calculations of composting pathway emissions included in SimaPro.

Table. A-32. Eco-profile for composting decomposition emissions (CH₄ & N₂O). These factors are taken from IPCC biogenic report 3

CH ₄ emission factor for composting	0.004	kg CH ₄ /kg waste wet basis (From IPCC)
N ₂ O emission factor for composting	0.0003	kg N ₂ O/kg waste wet basis (From IPCC)

Table. A-33. Eco-profile for composting decomposition emissions (CO₂). This factor is taken from IPCC biogenic report 3.

CO ₂ emission factor for composting	0.44	kg CO ₂ /kg dry solid waste (From IPCC)
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Table. A-34. Eco-profile for CO₂ emissions from compost land application

Processes	Amount	Unit	Basis
Carbon Dioxide	.48*.5*.5*44/12 =0.44	kg	1kg wet compost, 50% moisture, 50% elemental carbon, 48% active carbon ¹⁵¹

Table. A-35. Diesel used in tractor for heartland LCA composting (basis: 0.0435 kg diesel)

Processes	Amount	Unit	Comment
Diesel {Europe without Switzerland} market for Alloc Def, S	0.00740066809 700986	kg	From SimaPro Database
Diesel {RoW} market for Alloc Def, S	0.03619933190 29901	kg	From SimaPro Database

A.1.4 Synthetic fertilizer pathway

The eco-profile used for P fertilizer is Phosphate fertilizer, as P₂O₅ | market for | Alloc Def, S. The eco-profile used for K fertilizer is Potassium fertilizer, as K₂O | market for | Alloc Def, S.

Table. A-36. Eco-profile for US mix fertilizer is" US_Mix_ecoprofile" basis 1kg nitrogen fertilizers, as N US Mix (heartland project), S

Processes	Amount	Unit	Comment
Ammonia, liquid market for Alloc Def, S	$.308 \times 17/14 = 0.374$	kg	.308 from Adom supplementary; 17/14 converts to N basis
Ammonia, liquid market for Alloc Def, S	$.008 \times 17/14 = 0.0097$	kg	.308 from Adom Supplementary for ammonia aqua; 17/14 converts to N basis
Ammonium nitrate, as N market for Alloc Def, S	0.038	kg	
Ammonium sulfate, as N market for Alloc Def, S	0.025	kg	
Urea, as N market for Alloc Def, S	0.166	kg	Nitrogen Solution Component
Ammonium nitrate, as N market for Alloc Def, S	0.132	kg	Nitrogen Solution Component
Potassium nitrate market for Alloc Def, S	0.0003	kg	for Sodium nitrate
Urea, as N market for Alloc Def, S	0.237	kg	
Urea, as N market for Alloc Def, S	$0.086/3 = 0.0287$	kg	0.086 is other fertilizers from liquid ammonia, ammonium nitrate, and urea
Ammonium nitrate, as N market for Alloc Def, S	$0.086/3 = 0.0287$	kg	0.086 is other fertilizers from liquid ammonia, ammonium nitrate, and urea
Ammonia, liquid market for Alloc Def, S	$0.086/3 = 0.0287$	kg	0.086 is other fertilizers from liquid ammonia, ammonium nitrate, and urea

Table. A-37. Emissions of N₂O from synthetic N fertilizer applied to field: (basis: 1kg synthetic N fertilizer)

Processes	Amount	Unit	Basis
Dinitrogen oxide	$0.01325 \times 44 / 14 = 0.042$	kg	IPCC factor for N ₂ O Emissions from Fertilizer land use. .01325 kg N in N ₂ O / N in digestate applied to soil. 44 is MW of N ₂ O, 14 is for N.,

A.1.5 Manure pathway

Table. A-38. Manure lagoon emissions (N₂O, CH₄ and CO₂) (basis: 1kg dry manure)

Processes	Amount	Unit	Comment
Carbon Dioxide	$368 / 2284.73 = 0.161$	kg	368 kg CH ₄ /hd/year for 2284.73 kg manure/hd/year ¹³¹
Methane	$687 / 2284.732824 = 0.301$	kg	yearly 687 kg CH ₄ /hd for 2284.73 kg manure/hd/year ¹³¹
Dinitrogen mono oxide	$0.9 / 2284.732824 = 0.000394$	kg	0.9 kg N ₂ O/hd/year for 2284.73 kg manure/hd/year ¹³¹

Table. A-39. Manure slurry storage emissions (N₂O, CH₄ and CO₂) (basis: 1kg dry manure)

Processes	Amount	Unit	Comment
Methane	$101 / 2284.73 = 0.0442$	kg	yearly 101 kg CH ₄ /hd for 2284.73 kg manure/hd/year ¹³¹
Dinitrogen mono oxide	$0.3 / 2284.73 = 0.000131$	kg	0.3 kg N ₂ O/hd/year for 2284.73 kg manure/hd/year ¹³¹

Table. A-40. Manure lagoon emissions (N₂O, CH₄ and CO₂) (basis: 1kg dry manure)

Processes	Amount	Unit	Comment
Carbon Dioxide	$754 / 2284.73 = 0.161$	kg	754 kg CH ₄ /hd/year for 2284.73 kg manure/hd/year ¹³¹

Methane	$13/2284.732824=0.00569$	kg	yearly 13 kg CH ₄ /hd for 2284.73 kg manure/hd/year ¹³¹
Dinitrogen mono oxide	$1.1/2284.732824=0.000481$	kg	1.1 kg N ₂ O/hd/year for 2284.73 kg manure/hd/year ¹³¹

A.1.6 Natural gas pathway

1. Eco-profile used for natural gas extraction, process and distribution is ‘Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Alloc Def, S’

Table. A-41.Heartland phase 1B water balance in AD Bio-CH₄ pathway

Heartland Phase 1B Water Balance		
Digester Feed	Gallons per day	Total Solids
Total Manure	157,475	11.0%
Total Paunch	48,482	23.7%
Total FOG Substrate	98,953	27.9%
Total Non-FOG Substrate	67,992	30.3%
Total CWCWD Water	42,658	0.1%
Total Lagoon Water Recycle	61,000	1.5%
Total Centrate Recycle	44,000	2.1%
Total Condensate/Once-Thru Recycle	<u>12,960</u>	<u>0.1%</u>
	533,520	14.8%

Table. A-42. Wood composition (percentage)

Wx1	48482	gallons
density	8	lb/gallon
solid fraction	0.237	
	0.000453592	Mg/lb

Total Paunch	41.69502576	Mg (dry basis)
Wx2	98953	gallons
density	8	lb/gallon
solid fraction	0.279	
	0.000453592	Mg/lb
Total fog Substrate	100.1817334	Mg (dry basis)
Wx3	67992	
density	8	lb/gallon
solid fraction	0.303	
	0.000453592	Mg/lb
Total non-fog substrate	74.75768049	Mg (dry basis)
Total Wx	216.6344397	Mg (dry basis)

Table. A-43. Calculation for carbon, CH₄, CO₂ potential in landfill

MCF	1	Generally, 1 for managed landfills
DOC	0.5	We assume, on dry basis food waste is 50% C so DOC is 0.5.
DOCF	1	We assume all the Carbon in the food waste is metabolized in the landfill by bacteria so DOCF is 1.
F	0.5	Generally assumed to be 0.5
$M' = MCF * DOC * DOCF * F$	0.25	Mg C / Mg waste (dry basis)
$L' = M' * 16/12$	0.333333333	Mg CH ₄ / Mg waste (dry basis)
$K' = M' * 44/12$	0.916666667	Mg CO ₂ / Mg waste (dry basis)
$M = M' * \text{Total } W_x$	54.15860	Mg C / day (dry basis)
$L = L' * \text{Total } W_x$	72.2114799	Mg CH ₄ / day (dry basis)

$K=K' \cdot \text{Total } W_x$	198.5815697	Mg CO ₂ / day (dry basis)
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M = Rate of food waste C (carbon) input to Landfill (Mg C /Mg waste)

M' = C generation potential factor (Mg C/Mg waste)

L' = CH₄ generation potential factor (Mg CH₄/Mg waste)

K' =CO₂ generation potential factor (Mg CO₂/Mg waste)

MCF = CH₄ correction factor (fraction), typically 1 for managed landfills

DOC = degradable organic carbon [fraction (Mg C in waste/Mg waste)]

$DOCF$ = fraction of DOC decomposed (fraction),

F = fraction by volume of CH₄ in landfill gas

A.2

Gives information on calculation of landfill emissions in both steady state and time-dependent state of two scenarios with uncontrolled and gas collection and flaring landfill systems.

A.2.1 Model derivation for the transient calculations of landfill anaerobic digestion (AD) emissions

Carbon input rate to the landfill from food waste = a constant M [Metric tons carbon / Year] (refer table 42a) in an amount equal to the annual input of Denver food waste to the LaSalle AD facility.

Amount of carbon depending on time = $\frac{d\mu}{dt}$, where μ is the amount of food waste carbon in the landfill at any time.

Degradation rate for carbon in landfill follows first order kinetics = $k\mu$, where k is a first order degradation constant [yr⁻¹]. $k=0.12$ /yr. ³

Carbon Balance on food waste transient emissions from a landfill:

(Rate of accumulation of carbon in landfill) = (rate of carbon input) – (rate of degradation of carbon by AD)

$$\frac{d\mu}{dt} = M - k\mu \Rightarrow \frac{d\mu}{dt} + k\mu = M$$

Which is in the form of $\frac{dy}{dx} + p(x)y(x) = Q(x)$

The solution for $y(x)$ for such an equation is given by $y(x) = e^{-\int p dx} (\int e^{\int p dx} Q(x) dx + C)$

So, the solution for $\mu(t)$ is $\mu(t) = e^{-\int k dt} (\int e^{\int k dt} M dt + C)$

$$\mu(t) = e^{-kt} (\int e^{kt} M dt + C) \Rightarrow \mu(t) = e^{-kt} \left(\frac{e^{kt}}{k} M + C \right)$$

Then $\mu(t)$ can be modified as $\mu(t) = \frac{1}{k} M + C e^{-kt}$

When $t=0$, the amount of food waste carbon in the landfill is zero, $\mu(t) = 0$, then the expression becomes $0 = \frac{1}{k} M + C$

Which gives for the integration constant, $C = -\frac{1}{k} M$

Then the expression for $\mu(t) = \frac{1}{k} M - \frac{1}{k} M e^{-kt}$

$$\mu(t) = \frac{1}{k} M (1 - e^{-kt})$$

The avoided carbon emissions from time dependent landfill are $k\mu$

$$= M(1 - e^{-kt})$$

The avoided CH_4 emissions from time-dependent landfill if 50% of food waste carbon is converted through AD to CH_4 is given by

$$= M/2 (1 - e^{-kt}) * 16/12$$

The avoided CO_2 emissions from time-dependent landfill if 50% of food waste carbon is converted through AD to CO_2 is given by

$$= M/2 (1 - e^{-kt}) * 44/12$$

Steady-state emissions occur when time goes to infinity, in which case the term e^{-kt} becomes zero and therefore steady-state CH_4 emissions are $M/2 * 16/12$ and for CO_2 steady-state emissions are $M/2 * 44/12$. Figures 1 & 2 flow diagram shows the landfill CO_2 and CH_4 generation and emission scenarios for both uncontrolled and controlled landfill systems.

Figure. A-1 Flow diagram of landfill emissions with gas collection system and flaring

Table. A-44. Landfill emissions with gas collection system and flaring

Pathway (landfill gas collection and flaring)	A (Mg CO ₂ / year)	B (Mg CO ₂ / year)	C (Mg CH ₄ / year)	D (Mg CO ₂ / year)	E (Mg CH ₄ / year)
Year1	8196.2	6085.7	22.3	204.9	670.6
Year5	32703.1	24282.0	89.1	817.5	2675.7
Year10	50651	37608.3	138.1	1266.2	4144.1
Year20	65906.8	48935.8	179.7	1647.6	5392.3
Year30	70501.7	52347.5	192.2	1762.5	5768.3
Year40	71885.7	53375.1	196.0	1797.1	5881.5
Year50	72302.6	53684.6	197.1	1807.5	5915.6
Steady state	72482.2	53818	197.6	1812.0	5930.3

99% of the collected methane is used to produce the electricity so the collected methane is B1 in the Table A-45

Table. A-45. Landfill emissions with gas collection system and electricity generation

Pathway (landfill gas collection and flaring)	A (Mg CO₂/ year)	B1 (Mg CH₄/ year) for electricity	C (Mg CH₄/ year) Fugitive emissions	D (Mg CO₂/ year)	E (Mg CH₄/ year) oxidation emissions
Year1	8196.2	2212.99	22.3	204.9	670.6
Year5	32703.1	8829.85	89.1	817.5	2675.7
Year10	50651	13675.78	138.1	1266.2	4144.1
Year20	65906.8	17794.84	179.7	1647.6	5392.3
Year30	70501.7	19035.48	192.2	1762.5	5768.3
Year40	71885.7	19409.16	196.0	1797.1	5881.5
Year50	72302.6	19521.70	197.1	1807.5	5915.6
Steady state	72482.2	19767.89	197.6	1812.0	5930.3

Electricity generation is calculated based on the efficiency of IC engine, which is assumed 35% efficient and the heating value of methane is 37 MJ/m³ with density 0.656 kg/m³ and Calculation for the electricity generation with collected methane in landfill for case 2 scenario A.3:

Table. A-46. Calculation for electricity generation from a landfill with gas collection system and electricity generation

Heating Value of CH ₄	37	MJ/m ³
Density of CH ₄	0.656	kg/m ³
Efficiency of I.C engines	0.35	35% efficient in general
Joule	0.00027	wh
Electricity produced	0.00532	Mwh/kg CH ₄

Table. A-47. Year wise electricity generation from a landfill with gas collection system and electricity generation.

Pathway (landfill gas collection and electricity generation)	B1 (Mg CH₄/year) for electricity	Electricity produced in Mwh /year
Year1	2212.99	$2212.99 \times 0.00532 \times 1000$ =11773.93
Year5	8829.85	$8829.85 \times 0.00532 \times 1000$ =46978.08
Year10	13675.78	$13675.78 \times 0.00532 \times 1000$ =72760.19
Year20	17794.84	$17794.84 \times 0.0053 \times 1000$ =94675.14
Year30	19035.48	$19035.48 \times 0.00532 \times 1000$ =101275.80
Year40	19409.16	$19409.16 \times 0.00532 \times 1000$ =103263.88
Year50	19521.70	$19521.70 \times 0.00532 \times 1000$ =103862.68
Steady state	19767.89	$19767.89 \times 0.00532 \times 1000$ =104025

Figure. A-2 Flow diagram of landfill emissions without gas collection system

Table. A-48. Landfill emissions without gas collection system

Pathway (uncontrolled landfill system)	A (Mg CO ₂ / year)	D (Mg CO ₂ / year)	E (Mg CH ₄ / year)
Year1	8196.2	819.6	2682.4
Year5	32703.1	3270.3	10702.8
Year10	50651.0	5065.1	12174.9
Year20	65906.8	6590.6	21569.5
Year30	70501.7	7050.1	23073.3
Year40	71885.7	7188.5	23526.2
Year50	72302.6	7230.2	23662.6
Steady state	72482.2	7248.2	23721.4

A.3 Calculations of inputs into SimaPro

Gives more information on calculations of inputs to the analysis in SimaPro. The inputs for the AD Bio-CH₄ pathway shown in Table A-49 along with comments on the

assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Tables A-1 - A-6, A-41.

A.3.1 Case 1: AD Bio-CH₄ pathway

Table. A-49. All the input data for AD Bio-CH₄ pathway provided by Jim Potter, Ag energy LLC.

Pathway	Process	Amount	Unit	Comment
AD Bio-CH ₄ pathway	1.Manure transportation	$114000 \times 8 / 2.205 / 1000 \times 7 \times 1.62 = 4.69 \times 10^3$	t*km	7 miles distance from farm to facility (A total manure transported is 114,000 gallons/day, assumed 8lb/gallon as density of substrate)
		$114000 \times 8 / 2.205 / 1000 \times 7 \times 1.62 \times 0.8 = 3.75 \times 10^3$	t*km	Return trip is empty, the truck uses 80% of the fuel
	2.Food waste transportation	$200000 \times 8 / 2.205 / 1000 \times 49 \times 1.62 = 5.76 \times 10^4$	t*km	49 miles distance from Denver to AD facility (total food waste transported from Denver is 200,000 gallons, assumed 8lb/gallon as density of substrate)
		$200000 \times 8 / 2.205 / 1000 \times 49 \times 1.62 \times 0.8 = 4.61 \times 10^4$	t*km	Return trip is empty, the truck uses 80% of the fuel
	3.AD process; electricity and heating of inlet food waste and manure	$5.5 \times 24 = 132$	MWh	AD facility used 5.5 MW line; Colorado grid eco-profile used (provided in Table 4)
		$533520 \times 8 \times 1 \times (125 - 50) = 3.2 \times 10^8$	btu	Natural gas emissions: 533520 gallons/day in section 1 table 41. (Phase 1B Water balance), 8 lb. / gallons, 1 btu / (lb. F). 125 F for AD temp. 50 F for Colorado Average

	4. Bio-CH ₄ Combustion	$4700 \times 1054.8 / 50 = 99151.2$	kg	4700 dekatherms, 1054.8 MJ/d ekatherm, Lower heating value 50 MJ/kg (Biogas composition 65% CH ₄ , 29% CO ₂ , 6% H ₂ O by volume). Eco profile listed in Table 1 is used.
	5. CO ₂ Emissions from AD	$4700 \times 1054.8 / 50 = 99151.2$	kg	4700 dekatherms, 1054.8 MJ/d ekatherm, Lower heating value 50 MJ/kg (Biogas composition 65% CH ₄ , 29% CO ₂ , 6% H ₂ O by volume). Eco profile listed in Table 1 is used.
	6. Transportation of compost from AD to Denver	$244.66 \times 500 \times 49 \times 1.62 / 1000 = 9.71 \times 10^3$	t*km	320 cu.yd. of compost is transported from AD facility to Denver market. Density- 500 kg/m ³ . Denver city 49 miles away from AD facility.
		$.8 \times 244.66 \times 500 \times 49 \times 1.62 / 1000 = 7.77 \times 10^3$	t*km	From Facility to Denver 80% of the fuel consumed on offload truck
	7. Digestate land application of N	$217 \times 23.74 = 5.15 \times 10^3$	lb.	217000 gallons/day digestate 23.74 lb N content as N fertilizer/1000 gallons digestate, which emits as N ₂ O on land application (N ₂ O emission factor of 0.01325 is used) Eco profile listed in Table 6 is used ¹⁵⁰
	8. Compost field application	$320 \times 500 \times 0.76455 = 1.22 \times 10^5$	kg	320 cubic yards of solid compost, 500 kg/m ³ density, 0.76455 m ³ /cubic yard Eco profile listed in Table 5 is used.

The inputs for the BAU peat pathway shown in Table A-49 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A-1 in Table A-31.

Table. A-50 Case 1: peat pathway:

Pathway	Process	Amount	Unit	Comment
Peat pathway	1.Emissions from peat moss manufacturing, transport and use	790.63-244.66=546	m ³	320 cu. yd. of compost from AD, 790.63 cu. meter. of compost from composting process. Difference of 546 m ³ is replaced by Peat-Moss, conversion factor= 218/500 ¹⁵² . Eco profile listed in Table A-31 is used.
	2. Transportation of Peat-Moss from Canada to Denver	546*218*1200/1000=1.43 x 10 ⁵	t*km	1200 km from Saskatchewan to Denver city, Peat transported from Saskatchewan to Denver market. Density - 218 kg/m ³ ,
		.8*546*218*1200/1000=1.14 x 10 ⁵	t*km	Return trip is empty, the truck uses 80% of the fuel

The inputs for the BAU compost pathway shown in Table A-51 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section 1 in Tables A-32 - A-35.

Table. A-51. Case 1: BAU composting pathway

Pathway	Process	Amount	Unit	Comment
Composting pathway	1.Manure transportation	62/ (1-0.85) *7*1.62=4.6 x 10 ³	t*km	62Mg of dry manure transported from 7 miles (1.62 km/mile)) 85% moisture

		$.8*62/ (1-0.85) *7*1.62=3.73 \times 10^3$	t*km	On empty return trip, 80% of fuel is used.
	2.Wood pallets transportation	$44.26*5 = 221.3$	t*km	44.26 Mg of pallets transported from 5 km distance from composting facility
		$0.8*44.26*5 = 177$	t*km	On empty return trip 80% of fuel is used.
	3.Food waste transportation	$216/ (1-.7) *70*1.62 = 8.11 \times 10^4$	t*km	216 of food waste transported from 70 miles, 70% moisture content
		$0.8*216/ (1-.7) *70*1.62=6.49 \times 10^4$	t*km	On empty return trip 80% of fuel is used.
	4.Diesel used in tractor for composting	$5909.4*0.832 = 4.92 \times 10^3$	kg	5909.4 liters of diesel is used by process equipment and petroleum diesel has a density of 0.832 kg/liter ¹³¹ Eco profile listed in Table A-35 is used
		$20.2*0.832=16.8$	kg	Diesel used by turner ¹³¹ Eco profile listed in Table A-35 is used
		$713.8*0.832=594$	kg	Diesel used for grinding ¹³¹ Eco profile listed in Table A-35 is used
	5.Composting decomposition emissions (CO ₂)	322.94	ton	Decomposition emissions from feedstock 1. Food waste

				-216 Mg 2. pallets- 44.26 Mg 3.manure 62 on dry basis manure 413.675904 on wet basis (15% solids) Eco profile listed in Table A-33 is used ¹⁵⁰
	6.Composting decomposition emissions (CH ₄ &N ₂ O)	1180.05	ton	Decomposition emissions from feedstock 1.biowaste- 722.1103 Mg 2.pallets- 44.26 Mg (Supporting docs) 3.manure- 413.675904 on wet basis Eco profile listed in Table A-32 is used ¹⁵⁰
	7.Compost land application	1180*.335= 395.3	ton	33.5% of initial feedstock is converted to compost, a total of 1180 tons of feedstock ¹⁴⁹ Eco profile listed in Table A-34 is used.

The inputs for the BAU synthetic fertilizer pathway shown in Table A-52 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section 1 in Tables A-36, A-37.

Table. A-52. Case 1: BAU synthetic fertilizer pathway:

Pathway	Process	Amount	Unit	Comment
Synthetic fertilizer pathway	1.Emissions from synthetic fertilizers manufacturing process and market	217000/1000 * 23.74=5.15 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Ammonium-N (lb/1000/gal)

		217000/1000* 7.63=1.66 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Eco profile used: Phosphate fertiliser, as P ₂ O ₅ market for Alloc Def, S
		217000/1000* 29.55=6.41 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Eco profile used: Potassium fertiliser, as K ₂ O market for Alloc Def, S
	2. Transportation of synthetic fertilizers from LaSalle market to fields	13200*0.0004 53592*7.5=44 .9	t*km	7 miles from LaSalle market to farmlands, 217000/1000*29.55+217000/1000*7.63+217000/1000*23.74=13200 0.000453592 Metric tons/lb. 4.7 miles = 7.5 km
		.8*13200*0.000453592*7.5=35.9	t*km	Return trip is empty, the truck uses 80% of the fuel
	3. Synthetic fertilizers land application	217*23.74 = 5.15 x10 ³	lb.	217000 gallons/day digestate 23.74lb N content as N fertilizer/1000 gallons digestate, which emits as N ₂ O on land application (N ₂ O emission factor of 0.01325 is used) Eco profile listed in Table A-A-37 is used. ¹⁵⁰

The inputs for the BAU natural gas pathway shown in Table A-53 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1.

Table. A-53 Case 1: BAU natural gas pathway

Pathway	Process	Amount	Unit	Comment
Natural gas pathway	1.Emissions from natural gas extraction processing, distribution and usage	$4700 \times 1055.06 \times .8 = 3.97 \times 10^6$	kg	4700 dekatherms/ day 1055.06 MJ/Dekatherm. 0.8 is heat conversion efficiency.

The inputs for the avoided landfill without gas collection system (uncontrolled) pathway shown in Table A-54 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs are shown in Section A.1 in Tables A-7, A-10 - A-16.

A.3.2 Case 2: Avoided pathways to AD Bio-CH₄ pathway

Table. A-54. Avoided landfill pathway without gas collection system (uncontrolled)

Avoided	Process	Amount	Unit	Comment
Landfill pathway with gas collection and flaring	1.Transportation of food waste	$216.6 \times 2 \times 12 \times 1.62 = 8.42 \times 10^3$	t*k m	216.6 Mg dry basis, 2 is for 50% moisture, 12miles up, 1.62 km/mi
		$.8 \times 216.6 \times 2 \times 12 \times 1.62 = 6.74 \times 10^3$	t*k m	Return trip is empty, the truck uses 80% of the fuel
	2. CH ₄ and CO ₂ emissions from landfill without gas collection and flaring	216.6344	tons	Total Dry mass 216.63444 which accounts the emissions Eco profile listed in Table A-7, A-10 - A-16 is used

The inputs for the avoided landfill with gas collection and flaring pathway shown in Table A-54 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Tables A-8, A-17 - 23.

Table. A-55. Avoided landfill pathway with gas collection system and flaring

Avoided	Process	Amount	Unit	Comment
Landfill pathway with gas collection and flaring	1. Transportation of food waste	$216.6 \times 2 \times 12 \times 1.62 = 8.42 \times 10^3$	t*km	216.6 Mg dry basis, 2 is for 50% moisture, 12 miles up, 1.62 km/mile
		$.8 \times 216.6 \times 2 \times 12 \times 1.62 = 6.74 \times 10^3$	t*km	Return trip is empty, the truck uses 80% of the fuel
	2. CH ₄ and CO ₂ emissions from landfill with gas collection and flaring	216.6344	tons	Total Dry mass 216.63444 which accounts the emissions Eco profile listed in Tables A-8, A-17-23 is used

The inputs for the avoided landfill with gas collection and electricity generation pathway shown in Table A-56 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Tables A-9, A-24-30.

Table. A-56. Avoided landfill pathway with gas collection system and electricity generation

Avoided	Process	Amount	Unit	Comment
Landfill pathway with gas collection and electricity generation	1. Transportation of food waste	$216.6 \times 2 \times 12 \times 1.62 = 8.42 \times 10^3$	t*k m	216.6 Mg dry basis, 2 is for 50% moisture, 12 miles up, 1.62 km/mile
		$.8 \times 216.6 \times 2 \times 12 \times 1.62 = 6.74 \times 10^3$	t*k m	Return trip is empty, the truck uses 80% of the fuel
	2. CH ₄ and CO ₂ emissions from landfill with gas collection and electricity generation	216.6344	tons	Total Dry mass 216.63444 which accounts the emissions Eco profile listed in Tables A-9, A-24-30 is used

	3. Electricity generation from Natural gas	Varies over time	Mw h	Total electricity generated over 50 years starting from year 1 till the steady state is listed from Tables A-9, A-24-30
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The inputs for the avoided synthetic fertilizer pathway shown in Table A-55 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Tables A-36, 37.

Table. A-57. Avoided synthetic fertilizer pathway

Avoided	Process	Amount	Unit	Comment
Synthetic fertilizer pathway	1.Emissions from synthetic fertilizers manufacturing process and market	217000/1000* 23.74=5.15 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Eco profile used: Nitrogen Fertilizers, as N US Mix (Heartland Project), S in Table 36
		217000/1000* 7.63=1.66 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Eco profile used: Phosphate fertiliser, as P ₂ O ₅ market for Alloc Def, S
		217000/1000* 29.55=6.41 x10 ³	lb.	This N fertilizer is amount that would be displaced by digestate. Eco profile used: Potassium fertiliser, as K ₂ O market for Alloc Def, S
	2. Transportation of synthetic fertilizers	13200*0.0004 53592*7.5=44 .9	t*k m	4.7 miles from LaSalle market to farmlands, 217000/1000*29.55+217

	from LaSalle market to fields			000/1000*7.63+217000/1000*23.74=13200; 0.000453592 Metric tons/lb.;
		.8*13200*0.000453592*7.5=35.9	t*k m	4.7 miles = 7.5 km; Return trip is empty, the truck uses 80% of the fuel

The inputs for the avoided peat pathway shown in Table A-58 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Table A-31.

Table. A-58. Avoided peat pathway

Avoided	Process	Amount	Unit	Comment
Peat pathway	1.Emissions from peat moss manufacturing, transport and use	244.66	m ³	320 cu. yd. of compost from AD, Which displaces the equivalent peat production on volume basis of peat to compost assumed 1:1 ¹⁴⁹ Eco profile listed in Table 31 is used
	2. Transportation of Peat-Moss from Canada to Denver	244.66*218*1200/1000=6.4 x10 ⁴	t*k m	1200 km from Saskatchewan to Denver city, Peat transported from Saskatchewan to Denver market. 218 kg/m ³ ,
		.8*244.66*218*1200/1000=5.12 x10 ⁴	t*k m	Return trip is empty, the truck uses 80% of the fuel

The inputs for the avoided manure pathway shown in Table A-58 along with comments on the assumptions, conversion factors, and other values. Eco-profiles for each of these inputs shown in Section A.1 in Tables A-38-40.

Table. A-59. Avoided manure pathway

Avoided	Process	Amount	Unit	Comment
Manure pathway	1.Anaerobic lagoon storage emissions	$62.05 \times .65 = 40.3$	tons	62.05 metric tons of manure stored in lagoons daily if not transported to AD-65% of dry mass diverted to lagoon ⁵ . Eco profile listed in Table 38 is used
	2.Slurry storage emissions	$62.05 \times .1 = 6.21$	tons	62.05 tons of manure stored in slurries if not transported to AD facility 5-10 of dry mass % is sent to slurry tank Eco profile listed in Table 39 is used
	3.Solid pile emissions	$62.05 \times .25 = 15.5$	tons	62.05 tons of manure stored in slurries if not transported to AD facility 25% in Colorado the manure sent to solid pile ⁵ . Eco profile listed in Table 40 is used

A.4 Nationwide resource assessment

Table. A-60. Calculation of overall nationwide resource assessment on diversion of food waste and manure to Bio-CH₄ system.

99.15	tons Bio-CH ₄ /216 tons of dry food waste
From Jim Potter Heartland biogas data:	

4700	Dekatherms Bio-CH ₄ / 278 tons of dry food waste and manure	
1054.8	MJ/Dekatherm	
4957560	MJ Bio-CH ₄ /216 tons dry food waste and 62 tons of manure.	
Natural gas calculation:		
47.4	MJ/kg	Lower Heating Value
1000	kg/ton	
105.17	tons Natural gas eq./ 278 tons of dry food waste & manure	
4.03	Million metric tons of natural gas eq. / 8.28 million tons of dry food waste (36 million tons food waste /year in US 2015, 23% solids blended with 2.38 million tons of dry manure)	
Total Natural gas consumption	27,457,587	million cubic feet/year in US (2015 EPA)
0.044	lb/ft ³	
1,208,133.83	Million lb/year	
548.0	million metric tons/year	
0.0074	Ratio of eq. Natural gas produced through Bio-CH ₄ to US Natural Gas demand on equal energy basis	
0.74	% of total consumption displaced by food waste and manure through AD process.	

A.4.1 Calculation for estimating GHG emission savings nationwide in United States

On diversion of food waste from uncontrolled landfill saves 17.76 kg CO₂ eq./kg Bio-CH₄ and avoiding gas collection and flaring landfills saves 5.49 kg CO₂ eq./ kg Bio-CH₄

There are a total of 1908 landfills in the US under operation, out of which 400 are uncontrolled and 850 with gas collection and flaring, rest gas collection and electricity generation with a savings of 3.51 CO₂ eq. /kg Bio-CH₄

So overall savings are = $\frac{400*17.76+850*5.49+658*3.51}{400+850+658} = 7.37 \text{ kg CO}_2 \text{ eq. / kg of Bio-CH}_4$

8.28 million tons of dry food waste and 2.38 million tons of dry manure produces 3.8 million tons of Bio- CH₄. 3.8 million tons saves 7.37*3.8 million tons of CO₂=28.01 million tons of CO₂

There are about an overall 7 billion tons of CO₂ eq. in US and the savings from AD (Anaerobic digestion) on diverting the food waste and manure from landfills and manure piles would account for a savings of 0.41 % of overall GHG emissions.

A.5 References

- (1) Dennis Y. C. Leung & Jing Wang, An overview on biogas generation from anaerobic digestion of food waste. *International Journal of Green Energy*, 2016, 13:2, 119-131.
- (2) ICF International. *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)*: U.S. Environmental Protection Agency Office of Resource Conservation and Recovery; February 2016.
- (3) RTI International. *Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal Wastewater Treatment Ethanol fermentation*: U.S. Environmental Protection Agency; December 14, 2010.
- (4) Peat and peatland, Canadian environmental life cycle assessment, product fact sheet. 2016; <http://tourbehorticole.com/wp-content/uploads/2015/01/cycle.pdf>. Accessed 09/ 06, 2016.
- (3) Owen JJ, Silver WL. Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Global change biology*. 2015;21(2):550-565.
- (4) Saer A, Lansing S, Davitt NH, Graves RE. Life cycle assessment of a food waste composting system: environmental impact hotspots. *Journal of Cleaner Production*. 2013;52:234-244.

B Supporting Information for Chapter 3

Life cycle assessment of oilseed crops produced in rotation with dryland cereals in the inland Pacific Northwest 3

B.1 Yields and prices of spring and winter crops

B.1.1 Crop prices and allocation factors (economic and energy)

Section B.1.1 gives information on prices, yields and calculations of allocation factor (both mass and market value). Primary data received from USDA and Alberta Agriculture in Canada are typically in non-metric customary units (e.g., gallon, ounce, pound, bushel, acre, etc.).

Table. B-1. Crop prices of different cereal and oilseeds (spring and winter)

Crop	Price	Price per	Price per kg	Notes
Wheat (Soft White Winter)	\$5.40	Bushel	\$0.20	PNW Farmers, Lewiston, ID
Wheat (Soft White Winter)	\$5.40	Bushel	\$0.20	NW Grain, Walla Walla, WA
Wheat (Soft White Winter)	\$4.96	Bushel	\$0.18	United Grain (McNary)
Wheat (Hard Red Spring)	\$7.45	Bushel	\$0.27	PNW Farmers, Lewiston, ID
Wheat (Hard Red Spring)	\$7.02	Bushel	\$0.26	United Grain (McNary)
Wheat (Hard Red Spring)	\$7.46	Bushel	\$0.27	NW Grain, Walla Walla, WA
Barley (Spring, Feed)	\$3.20	Bushel	\$0.15	CHS Prime land, Lewiston, ID
Barley (Spring, Feed)	\$3.12	Bushel	\$0.15	PNW Farmers, Lewiston, ID
Barley (Spring, Feed)	\$3.00	Bushel	\$0.14	NW Grain, Walla Walla, WA

Barley (Spring, Feed)	\$2.45	Bushel	\$0.12	Central WA Grain, Wilbur, WA
Triticale (Winter)	\$2.58	Bushel	\$0.11	Central WA Grain, Wilbur, WA
Triticale (Spring)	\$2.58	Bushel	\$0.11	Central WA Grain, Wilbur, WA
Canola	\$0.17	lb.	\$0.37	NW Grain, Walla Walla, WA
Canola	\$0.19	lb.	\$0.42	Pomeroy Grain, Pomeroy, WA
Carinata (for rapeseed)	\$0.18	lb.	\$0.40	CHS Prime land, Lewiston, ID

Table. B-2. Average yields different rotation crops over 5 years including the standard deviation (SD) values

Crop(rotation)	Average yield per year (kg/ hectare)	+ve SD value	-ve SD value
WW(SF-WW)	2879.4	720.9	-720.9
WW(RTF -WW)	3036.4	527.7	-527.7
WW(RTF-WW-RTF-WO)	2995.3	170.3	-170.3
WO(RTF -WO-RTF -WW)	1338.9	374.7	-374.7
WW(RTF-WW-SB)	3242.3	533.2	-533.2
SB(RTF -WW-SB)	1182.2	471.5	-471.5
WW(RTF-WW-SO)	2918.5	453.9	-453.9
SO(RTF -WW-SO)	552.2	212.0	-212.0

WO(RTF -WO-SW)	1069.4	527.5	-527.5
SW(RTF -WO-SW)	1014.9	247.5	-247.5
SW(RTF -SO-SW)	1046.9	213.1	-213.1
SO(RTF -SO-SW)	920.5	456.5	-456.5
WO (RTF -WO-ST)	978.5	544.6	-544.6
ST(RTF -WO-ST)	500.9	186.2	-186.2
WT (RTF -WT-SO)	1756.8	487.5	-487.5
SO(RTF-WT-SO)	557.2	212.6	-212.6

Table. B-3. Total average sales values of individual rotation with SD and allocation factors based on price

Crop(rotation)	Average sales value (\$/ acre)	Average sales value with +ve SD (\$/ acre)	Average sales value with -ve SD (\$/ acre)	Market value allocation factor	Market value allocation factor with +ve SD	Market value allocation factor with -ve SD
WW(SF -WW)	224.93	281.25	168.61	N/A	N/A	N/A
WW(RTF -WW)	237.19	278.41	195.97	N/A	N/A	N/A
WW(RTF-WW-RTF-WO)	233.98	247.28	220.68	N/A	N/A	N/A
WO(RTF-WO-RTF-WW)	215.02	275.19	154.84	N/A	N/A	N/A

WW(RTF-WW-SB)	253.27	294.92	211.62	0.789	0.757	0.839
SB(RTF-WW-SB)	67.57	94.52	40.62	0.211	0.243	0.161
WW(RTF-WW-SO)	227.98	263.44	192.52	0.720	0.682	0.779
SO(RTF-WW-SO)	88.69	122.73	54.64	0.280	0.318	0.221
WO(RTF-WO-SW)	171.73	256.44	87.03	0.609	0.651	0.511
SW(RTF-WO-SW)	110.32	137.22	83.42	0.391	0.349	0.489
SW(RTF-SO-SW)	113.80	136.96	90.63	0.435	0.382	0.549
SO(RTF-SO-SW)	147.83	221.14	74.52	0.565	0.618	0.451
WO (RTF-WO-ST)	157.14	244.59	69.69	0.876	0.889	0.833
ST(RTF-WO-ST)	22.17	30.41	13.93	0.124	0.111	0.167
WT (RTF-WT-SO)	77.77	99.35	56.19	0.465	0.446	0.504
SO(RTF-WT-SO)	89.48	123.62	55.33	0.535	0.554	0.496

Table. B-4. Total average yield values of individual rotation with SD and allocation factors based on yield

Crop(rotation)	Average yield (kg/acre)	Average yield with +ve SD (kg/acre)	Average yield with -ve SD (kg/acre)	Mass allocation factor	Mass allocation factor with +ve SD	Mass allocation factor with -ve SD
WW(SF-WW)	1165.3	1457.0	873.5	N/A	N/A	N/A
WW(RTF-WW)	1228.8	1442.3	1015.2	N/A	N/A	N/A
WW(RTF-WW-RTF-WO)	1212.1	1281.1	1143.2	N/A	N/A	N/A
WO(RTF-WO-RTF-WW)	541.8	693.5	390.2	N/A	N/A	N/A
WW(RTF-WW-SB)	1312.1	1527.9	1096.3	0.733	0.695	0.792
SB(RTF-WW-SB)	478.4	669.2	287.6	0.267	0.305	0.208
WW(RTF-WW-SO)	1181.1	1364.8	997.4	0.841	0.815	0.879
SO(RTF-WW-SO)	223.5	309.3	137.7	0.159	0.185	0.121
WO(RTF-WO-SW)	432.8	646.2	219.3	0.513	0.558	0.414
SW(RTF-WO-SW)	410.7	510.9	310.6	0.487	0.442	0.586
SW(RTF-SO-SW)	423.7	509.9	337.4	0.532	0.478	0.642
SO(RTF-SO-SW)	372.5	557.3	187.8	0.468	0.522	0.358
WO (RTF-WO-ST)	396.0	616.4	175.6	0.661	0.689	0.580

ST(RTF-WO-ST)	202.7	278.1	127.3	0.339	0.311	0.420
WT (RTF-WT-SO)	711.0	908.2	513.7	0.759	0.745	0.786
SO(RTF-WT-SO)	225.5	311.5	139.4	0.241	0.255	0.214

Table. B-5. Lower heating values for oil and oilseed meal.

LHV oil	37.5	MJ energy/ kg oil	[4]
LHV oil meal	18.2	MJ energy/ kg oil meal	[5]

Table. B-6. Total average oil concentrations in oilseed of individual oilseed rotation and energy allocation factors based on LHV of oil and oil meal

Rotation	% oil in oilseed	Mass allocation MJ/ kg oilseed	Market value allocation MJ/ kg oilseed	EAF
RTF-WO - WW-RTF	36.3	6.67	-	0.54
RTF-WW-SO	34.5	14.1	14.7	0.52
RTF-WO-SW	39	7.64	7.87	0.57
RTF-SO-SW	34.075	9.31	9.58	0.52
RTF-WO-ST	38.925	8.88	9.5	0.57
RTF-WT-SO	35.075	14.2	15.5	0.53

Table. B-7. Intensity of energy demand (return on investment) for different oilseed crop rotations (using both mass and market value allocation)

Rotation	Mass allocation MJ energy consumed/ kg oil	MJ energy consumed / MJ energy in oil	Market value allocation MJ energy consumed/ kg oil	MJ energy consumed / MJ energy in oil
RTF-WO-RTF-WW	9.92	0.26	N/A	N/A
RTF-WW-SO	21.27	0.57	22.18	0.59
RTF-WO-SW	11.14	0.30	11.47	0.31
RTF-SO-SW	14.09	0.38	14.50	0.39
RTF-WO-ST	12.95	0.35	13.86	0.37
RTF-WT-SO	21.33	0.57	23.28	0.62

B.1.2 Input field activities

Section-B.1.2 provides the information on input field activities (averaged per year), and the conversion of the pesticides and fuel usage.

Tables B-8 - B-17 show the average input field activities per year for both 2-year and 3-year rotations on per acre basis. Data on fuel usage were derived using the Farm Machinery Cost Calculator available at

<https://www.agric.gov.ab.ca/app24/costcalculators/machinery/getmachimpls.jsp>.

Fuel usage is reported in liters per acre. Though Canada has converted to the metric system, non-metric units remain in use in the agricultural sector.

Table. B-8. Average input field activities for rotation SF-WW on the basis of per acre per year

SF Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Disked Summer Fallow	Tractor - 4WD 475 HP	Diesel	Disc - tandem HD 30-ft wing							71	12.78	5.555
Rod weeding/cultivating	Tractor - 4WD 475 HP	Diesel								71	18.67	6.084
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071

	ft 125-135 HP high clearance						Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70- ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Pre-plant herbicide application	Sprayer 600-gal 70- ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Cultivate (two passes)	Tractor - 4WD 475 HP	Diesel	44-ft Field cultivator							71	18.67	0.760
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143

WW Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-Harvest spray	Sprayer 600-gal 70-ft 125-135	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071

	HP high clearance											
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							AffinityBroad Spec	0.5	0.1			
							Osprey	4.75	0.95			
							Fitness	6	1.2			
							Liberate	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	32	6.4	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							Osprey	4.75	0.95			
							Liberate	6.4	1.28			
							Unfoamer	1.2	0.24			
							Solution 32	64	12.8			

Seeding winter wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	114.75	55	11				71	20	3.55
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			

Table. B-9. Average input field activities for rotation RTF-WW on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	44	8.8	18.2	50.9	0.071
							Rifle	12	2.4			
							Gunsmoke	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep							71	12.78	5.555
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071

Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquat e)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.1111
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	12.8	18.2	50.9	0.071
							Affinity BroadSpec	0.5	0.1			
							Liberate	6.4	1.28			

Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			

WW Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/a c	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			

							Unfoamer	1.5	0.3			
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding winter wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer	114.75	55	11				71	20	3.55
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	32	6.4	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							Osprey	4.75	0.95			
							Liberate	6.4	1.28			
							Unfoamer	1.2	0.24			
							Solution 32	64	12.8			
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							AffinityBro ad Spec	5	1			
							Osprey	4.75	0.95			

							Fitness	6	1.2			
							Liberate	3.2	0.64			
Spray for insects	Bell helicopter, Lycoming VO435 47	Avgas					Silencer	3.5	1.4			
							Tactic	1.6	0.64	75.7	352	0.107
Harvest	Combine 350 hp									56	10.67	5.248

Table. B-10. Average input field activities for rotation RTF-WO (RTF-WO-RTF-WW) on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep							71	12.78	5.555
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper									
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071

	HP high clearance											
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Cyclone (generic Paraquate)	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	44	8.8	18.2	50.9	0.071
							Rifle	12	2.4			
							Gunsmoke	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			
Spray for weeds	Sprayer 600-gal 70-ft 125-135	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			

	HP high clearance						Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-	Diesel					Roundup RT3	64	12.8	18.2	50.9	0.071

	ft 125-135 HP high clearance						Affinity BroadSpec	0.5	0.1			
							Liberate	6.4	1.28			
WO Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post- harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post- harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Cyclone (generic Paraquate)	64	12.8	18.2	50.9	0.071
Post- harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			

Seeding winter canola	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	5.464	55	11				71	20	3.55
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Lambda-CY	3.84	1.536	75.7	352	0.086
							Wetcat	5	2			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			

Table. B-11. Average input field activities for rotation RTF-WW (RTF-WW-RTF-WO) on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep							71	12.78	5.555

Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Post-harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for weeds	Sprayer 600- gal 70-ft 125-	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071

	135 HP high clearance											
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	12.8	18.2	50.9	0.071
							Affinity BroadSpec	0.5	0.1			
							Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			

							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	44	8.8	18.2	50.9	0.071
							Rifle	12	2.4			
							Gunsmoke	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			

WW Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	32	6.4	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp									56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071

	HP high clearance											
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding winter wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	114.75	55	11				71	20	3.550
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
		Diesel					Huskie	14	2.8	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance						AffinityBroad Spec	0.5	0.1			
							Osprey	4.75	0.95			
							Fitness	6	1.2			
							Liberate	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							Osprey	4.75	0.95			
							Liberate	6.4	1.28			
							Unfoamer	1.2	0.24			
							Solution 32	64	12.8			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			

Table. B-12. Average input field activities for rotation RTF-WW-SB on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep				71	12.78	5.555

Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper				71	12.78	1.111
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas		Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas		Silencer	3.5	1.4	75.7	352	0.086
				Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	32	6.4	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	48	9.6	18.2	50.9	0.071
				Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	12.8	18.2	50.9	0.071
				Affinity BroadSpec	0.5	0.1			
				Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	32	6.4	18.2	50.9	0.071
				Choice	6.4	1.28			
				Liberate	6.4	1.28			
				Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	44	8.8	18.2	50.9	0.071
				Rifle	12	2.4			
				Gunsmoke	6.4	1.28			
				Liberate	6.4	1.28			

				Unfoamer	1	0.2			
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WW Field Practices	Powered Equipment	Fuel	Implement	Seed rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticides	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
		Diesel					Gramoxone	64	12.8	18.2	50.9	0.071

Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance						Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding winter wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer	114.75	55	11				71	20	3.55
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	32	6.4	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							AffinityBroad Spec	0.5	0.1			
							Osprey	4.75	0.95			
							Fitness	6	1.2			
							Liberate	3.2	0.64			

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							Osprey	4.75	0.95			
							Liberate	6.4	1.28			
							Unfoamer	1.2	0.24			
							Solution 32	64	12.8			

SB Field Practices	Powered Equipment	Fuel	Implement	Seed rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071

Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel	N/a				Roundup Power Max	28	5.6	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding spring barley	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	109.2	55	11				71	20	3.55
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Brox-M	16	3.2	18.2	50.9	0.071
							Affinity Broadspec	0.6	0.12			
		Diesel					Vendetta	25	5	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance						Harmony Extra	0.5	0.1			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	15	3	18.2	50.9	0.071
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			

Table. B-13. Average input field activities for rotation RTF-WW-SO on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep				71	12.78	5.555
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper				71	12.78	1.111

Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas		Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas		Silencer	3.5	1.4	75.7	352	0.086
				Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	32	6.4	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Gly Star Plus	48	9.6	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	48	9.6	18.2	50.9	0.071
				Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	12.8	18.2	50.9	0.071
				Affinity BroadSpec	0.5	0.1			
				Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	32	6.4	18.2	50.9	0.071
				Choice	6.4	1.28			
				Liberate	6.4	1.28			
				Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	44	8.8	18.2	50.9	0.071
				Rifle	12	2.4			
				Gunsmoke	6.4	1.28			
				Liberate	6.4	1.28			
				Unfoamer	1	0.2			

Practice	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
WW Field Practices												
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp									56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
		Diesel					Gramoxone	64	12.8	18.2	50.9	0.071

Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance						Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding winter wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	114.75	55	11				71	20	3.550
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	32	6.4	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							AffinityBroad Spec	0.5	0.1			
							Osprey	4.75	0.95			
							Fitness	6	1.2			
							Liberate	3.2	0.64			

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	14	2.8	18.2	50.9	0.071
							Osprey	4.75	0.95			
							Liberate	6.4	1.28			
							Unfoamer	1.2	0.24			
							Solution 32	64	12.8			

SO, Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Harvest	Combine 350 hp									56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071

Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel	n/a				Roundup Power Max	28	5.6	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
							Landmaster	54	10.8			
Seeding B. carinata	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	5.406	55	11				71	20	3.550
Spray for aphids	Bell 47 helicopter, Lycoming VO435	Avgas					Warrior II	1.92	0.768	75.7	352	0.086
Spray for grassy weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Assure II	12	2.4	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for insects	Bell 47 helicopter,	Avgas					Lambda-CY	3.84	1.536	75.7	352	0.086

	Lycoming VO435						Wetcit	5	2			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Post- harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			

Table. B-14. Average input field activities for rotation RTF-WO-SW on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
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Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	48	9.6	18.2	50.9	0.071
				Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	12.8	18.2	50.9	0.071
				Affinity BroadSpec	0.5	0.1			
				Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	32	6.4	18.2	50.9	0.071
				Choice	6.4	1.28			
				Liberate	6.4	1.28			
				Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	44	8.8	18.2	50.9	0.071
				Rifle	12	2.4			
				Gunsmoke	6.4	1.28			
				Liberate	6.4	1.28			
				Unfoamer	1	0.2			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas		Silencer	3.5	1.4	75.7	352	0.086
				Tactic	1.6	0.64			
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep				71	12.78	5.556

Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas		Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup RT3	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper				71	12.78	1.111
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	32	6.4	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel		Roundup Power Max	64	12.8	18.2	50.9	0.071

WO Field Practices	Powered equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Lambda-CY	3.84	1.536	75.7	352	0.086
							Wetcit	5	2			
Harvest	Combine 350 hp	Diesel							0	56	10.67	5.248
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.072
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.072
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.072
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper						0	71	12.78	1.111
Seeding winter canola	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	5.083	55	11			0	71	20	3.550

233

SW Field Practice	Powered equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Seeding spring wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	117.6	55	11				71	20	3.550
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for insects	Bell 47 helicopter,	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			

	Lycoming VO435											
Harvest	Combine 350 hp	Diesel							0	56	10.67	5.248
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	25	5	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow		Diesel							0	71	12.78	1.111
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Brox-M	16	3.2	18.2	50.9	0.071
							Affinity Broadspec	0.6	0.12			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			

							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	15	3	18.2	50.9	0.071
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	28	5.6	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			

Table. B-15. Average input field activities for rotation RTF-SO-SW on the basis of per acre per year

RTF Field Practice	Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep							71	12.78	5.556
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-	Diesel					Gly Star Plus	48	9.6	18.2	50.9	0.071

	135 HP high clearance											
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	64	12.8	18.2	50.9	0.071
							Affinity BroadSpec	0.5	0.1			
							Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.072
							Choice	6.4	1.28			
							Liberate	6.4	1.28			

							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	12	2.4	18.2	50.9	0.071
							Rifle	12	2.4			
							Gunsmoke	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143

SO Field Practice	Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	28	5.6	18.2	50.9	0.071

Seeding B. carinata	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	5.406	55	11				71	20	3.550
Spray for aphids	Sprayer 600-gal 70-ft 125-135 HP high clearance	Avgas					Warrior II	1.92	0.768	75.7	352	0.086
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	32	6.4	18.2	50.9	0.071
							Landmaster	54	10.8			
Spray for grassy weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Assure II	12	2.4	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Glyster plus	48	9.6	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071

	135 HP high clearance											
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Spray for weeds	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600- gal 70-ft 125- 135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			
							Unfoamer	0.8	0.16			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Lambda- CY	3.84	1.536	75.7	352	0.086
							Wetcit	5	2			
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post-harvest spray	Sprayer 600- gal 70-ft 125-	Diesel					Gramoxone	64	12.8	18.2	50.9	0.072
							Gunsmoke	9.6	1.92			

	135 HP high clearance						Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143

SW Field Practice	Equipment	Fuel	Implement	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	28	5.6	18.2	50.9	0.071
Seeding spring wheat	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer	117.6	55	11				71	20	3.550
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup Power Max	64	12.8	18.2	50.9	0.071

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Brox-M	16	3.2	18.2	50.9	0.071
							Affinity Broadspec	0.6	0.12			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Vendetta	25	5	18.2	50.9	0.071
							Harmony Extra	0.5	0.1			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper							71	12.78	1.111
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	48	9.6	18.2	50.9	0.071
							Gunsmoke	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Roundup RT3	32	6.4	18.2	50.9	0.071
							Choice	6.4	1.28			
							Liberate	6.4	1.28			

							Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Huskie	15	3	18.2	50.9	0.071
							Liberate	6.4	1.28			
							Unfoamer	1	0.2			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas					Silencer	3.5	1.4	75.7	352	0.086
							Tactic	1.6	0.64			
Harvest	Combine 350 hp	Diesel								56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel					Gramoxone	64	12.8	18.2	50.9	0.071
							Gunsmoke	9.6	1.92			
							Liberate	9.6	1.92			
							Unfoamer	1.5	0.3			
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas					Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143

Table. B-16. Average input field activities for rotation RTF-WO-ST on the basis of per acre per year

RTF Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	Fertilizer	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liter)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
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											s/hour)		
Conservation tillage	Tractor - 4WD 475 HP	Diesel	30-ft wide blade sweep								71	12.78	5.556
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper								71	12.78	1.111
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Roundup Power Max	64	12.8	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Paraquat Concentrate	60	12	18.2	50.9	0.071
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avg as						Cyclone (generic Paraquat e)	64	25.6	18.2	50.9	0.143
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avg as						Silencer	3.5	1.4	75.7	352	0.086
								Tactic	1.6	0.64			

Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup Power Max	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup Power Max	32	12.8	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup RT3	64	25.6	18.2	50.9	0.143
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup RT3	48	9.6	18.2	50.9	0.071
								Gunsmok e	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup RT3	64	12.8	18.2	50.9	0.071
								Affinity BroadSp ec	0.5	0.1			
								Liberate	6.4	1.28			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup RT3	32	6.4	18.2	50.9	0.071
								Choice	6.4	1.28			

								Liberate	6.4	1.28			
								Unfoamer	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Roundup RT3	44	8.8	18.2	50.9	0.071
								Rifle	12	2.4			
								Gunsmoke	6.4	1.28			
								Liberate	6.4	1.28			
								Unfoamer	1	0.2			

WO Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/ac)	Fertilizer	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30-ft flail chopper								71	12.78	1.111
Harvest	Combine 350 hp	Diesel									56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135	Diesel						Paraquat Concentrate	60	12	18.2	50.9	0.071

	HP high clearance												
Post-harvest spray	Bell 47 helicopter, Lycoming VO435	Avgas						Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Gramoxone	64	12.8	18.2	50.9	0.071
								Gunsmoke	9.6	1.92			
								Liberate	9.6	1.92			
								Unfoamer	1.5	0.3			
Seeding winter canola	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	5.464	79% UAN - 21% ThioSul applied at 196 lb/ac	55	11				71	20	3.550
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas						Silencer	3.5	1.4	75.7	352	0.086
								Tactic	1.6	0.64			
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avgas						Lambda-CY	3.84	1.54	75.7	352	0.086
								Wetcit	5	2			
Spray for weeds	Sprayer 600-gal 70-	Diesel						Gly Star Plus	48	9.6	18.2	50.9	0.071

	ft 125-135 HP high clearance												
Spray for weeds	Sprayer 600-gal 70- ft 125-135 HP high clearance	Diesel						Roundup RT3	48	9.6	18.2	50.9	0.071
								Gunsmoke	3.2	0.64			

ST Field Practices	Powered Equipment	Fuel	Implement	Seed Rate (lb/acre)	Fertilizer	N (lb/ac)	S (lb/ac)	Pesticide	oz/acre	Avg oz/acre	Fuel Usage (liters/ hour)	Field Rate (acres/hour)	Avg. fuel use (liters/ acre)
Flail mow	Tractor - 4WD 475 HP	Diesel	Rears 30- ft flail chopper								71	12.78	1.111
Harvest	Combine 350 hp										56	10.67	5.248
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Roundup Power Max	64	12.8	18.2	50.9	0.072
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Paraquat Concentrate	51	10.2	18.2	50.9	0.072
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Paraquat Concentrate	60	12	18.2	50.9	0.072
Post-harvest spray	Bell 47 helicopter,	Avgas						Cyclone (generic)	64	25.6	18.2	50.9	0.143

	Lycoming VO435							Paraquate)					
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel	N/A					Roundup Power Max	28	5.6	18.2	50.9	0.071
Pre-plant herbicide application	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Roundup Power Max	64	12.8	18.2	50.9	0.071
Seeding spring triticale	Tractor - 4WD 475 HP	Diesel	55-ft air drill with packer wheels	100.6	79% UAN - 21% ThioSul applied at 196 lb/ac	55	11				71	20	3.550
Spray for insects	Bell 47 helicopter, Lycoming VO435	Avg as						Silencer	3.5	1.4	75.7	352	0.086
								Tactic	1.6	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Brox-M	16	3.2	18.2	50.9	0.071
								Affinity Broadspread	0.6	0.12			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Diesel						Vendetta	25	5	18.2	50.9	0.071
								Harmony Extra	0.5	0.1			
Spray for weeds		Diesel						Roundup RT3	48	9.6	18.2	50.9	0.071

	Sprayer 600-gal 70-ft 125-135 HP high clearance							Gunsmok e	3.2	0.64			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Roundup RT3	32	6.4	18.2	50.9	0.071
								Choice	6.4	1.28			
								Liberate	6.4	1.28			
								Unfoame r	0.8	0.16			
Spray for weeds	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Huskie	15	3	18.2	50.9	0.071
								Liberate	6.4	1.28			
								Unfoame r	1	0.2			
Post-harvest spray	Sprayer 600-gal 70-ft 125-135 HP high clearance	Dies el						Gramoxo ne	64	12.8	18.2	50.9	0.071
								Gunsmok e	9.6	1.92			
								Liberate	9.6	1.92			
								Unfoame r	1.5	0.3			

Table. B-17. Average input field activities for rotation RTF-SO-WT on the basis of per acre per year

Practice RTF	Fuel	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Spray for weeds	Diesel	Roundup Power Max	64	12.8	18.2	50.9	0.071
Conservation tillage	Diesel			0	71	12.78	5.556
Post-harvest spray	Diesel	Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Diesel	Roundup Power Max	64	12.8	18.2	50.9	0.071
Spray for weeds	Diesel	Roundup Power Max	32	6.4	18.2	50.9	0.071
Post-harvest spray	Diesel	Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Diesel	Gly Star Plus	48	9.6	18.2	50.9	0.071
Spray for weeds	Diesel	Roundup RT3	64	25.6	18.2	50.9	0.143
Post-harvest spray	Diesel	Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Diesel			0	71	12.78	1.111
	Diesel	Roundup RT3	48	9.6	18.2	50.9	0.071

Spray for weeds		Gunsmoke	3.2	0.64			
Spray for weeds	Diesel	Roundup RT3	64	12.8	18.2	50.9	0.071
		Affinity BroadSpec	0.5	0.1			
		Liberate	6.4	1.28			
Spray for insects	Avgas	Silencer	3.5	1.4	75.7	352	0.086
		Tactic	1.6	0.64			
Post-harvest spray	Avgas	Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Spray for weeds	Diesel	Roundup RT3	32	6.4	18.2	50.9	0.071
		Choice	6.4	1.28			
		Liberate	6.4	1.28			
		Unfoamer	0.8	0.16			
Spray for weeds	Diesel	Roundup RT3	44	8.8	18.2	50.9	0.071
		Rifle	12	2.4			
		Gunsmoke	6.4	1.28			
		Liberate	6.4	1.28			
		Unfoamer	1	0.2			

WT Field Practice	Fuel	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)	Pesticide	oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Post-harvest spray	Diesel				Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Diesel				Roundup Power Max	64	12.8	18.2	50.9	0.071
seeding winter triticale	Diesel	115.5	55	11				71	20	3.550
Post-harvest spray	Diesel				Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Diesel				Vendetta	32	6.4	18.2	50.9	0.071
					Harmony Extra	0.5	0.1			
Post-harvest spray	Diesel				Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Diesel							71	12.78	1.111
Spray for weeds	Diesel				Huskie	14	2.8	18.2	50.9	0.071
					AffinityBroad Spec	0.5	0.1			
					Osprey	4.75	0.95			
					Fitness	6	1.2			
					Liberate	3.2	0.64			

Spray for insects	Avgas				Silencer	3.5	1.4	75.7	352	0.086
					Tactic	1.6	0.64			
Harvest	Diesel							56	10.67	5.248
Post-harvest spray	Avgas				Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.072
Spray for weeds	Diesel				Huskie	14	2.8	18.2	50.9	0.072
					Liberate	6.4	1.28			
					Unfoamer	1.2	0.24			
					Solution 32	64	12.8			
Post-harvest spray	Diesel				Gramoxone	64	12.8	18.2	50.9	0.072
					Gunsmoke	9.6	1.92			
					Liberate	9.6	1.92			
					Unfoamer	1.5	0.3			

SO Field Practice	Fuel	Seed Rate (lb/ac)	N (lb/ac)	S (lb/ac)		oz/ac	Avg oz/ac	Fuel Usage (liters/hour)	Field Rate (acres/hour)	Avg. fuel use (liters/acre)
Pre-plant herbicide application	Diesel				Roundup Power Max	28	5.6	18.2	50.9	0.071

Seeding B. carinata	Diesel	5.406	55	11				71	20	3.550
Spray for aphids	Avgas				Warrior II	1.92	0.768	75.7	352	0.086
Post-harvest spray	Diesel				Roundup Power Max	64	12.8	18.2	50.9	0.071
Pre-plant herbicide application	Diesel				Roundup Power Max	32	6.4	18.2	50.9	0.071
					Landmaster	54	10.8			
Spray for grassy weeds	Diesel				Assure II	12	2.4	18.2	50.9	0.071
Post-harvest spray	Diesel				Paraquat Concentrate	51	10.2	18.2	50.9	0.071
Spray for weeds	Diesel				Gly Star Plus	48	9.6	18.2	50.9	0.071
Post-harvest spray	Diesel				Paraquat Concentrate	60	12	18.2	50.9	0.071
Flail mow	Diesel							71	12.78	1.111
Spray for weeds	Diesel				Roundup RT3	48	9.6	18.2	50.9	0.071
					Gunsmoke	3.2	0.64			
Spray for insects	Avgas				Silencer	3.5	1.4	75.7	352	0.086
					Tactic	1.6	0.64			
Harvest	Diesel							56	10.67	5.248

Post-harvest spray	Avgas				Cyclone (generic Paraquate)	64	25.6	18.2	50.9	0.143
Spray for weeds	Diesel				Roundup RT3	32	6.4	18.2	50.9	0.071
					Choice	6.4	1.28			
					Liberate	6.4	1.28			
					Unfoamer	0.8	0.16			
Spray for insects	Avgas				Lambda-CY	3.84	1.536	75.7	352	0.086
					Wetcit	5	2			
Post-harvest spray	Diesel				Gramoxone	64	12.8	18.2	50.9	0.071
					Gunsmoke	9.6	1.92			
					Liberate	9.6	1.92			
					Unfoamer	1.5	0.3			

B.1.3 Pesticides conversion

Section B.1.3 gives detailed information of conversions of pesticides from fluid ounces to grams (schematic diagrams presented below describe the calculation)

Table. B-18. SF-WW rotation conversions of pesticides from fluid ounce to grams

	Bulk Density from MSDS	Units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	Units	% Active gradient in Herbicide	Mass of active gradient	units
Round Up powemax	1.3565	g/ml	51.2	oz. (volume)/ac	29.57	ml/oz.	1513.98	ml/ac	2053.72	grams/ac	48.7	1000.161	gram s/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	gram s/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	gram s/ac
Vendetta	1.14	g/ml	6.4	oz. (volume)/ac	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.7427	gram s/ac
Osprey	0.92475	g/ml	1.9	oz. (volume)/ac	29.57	ml/oz.	56.18	ml/ac	51.96	grams/ac	4.5	2.337985	gram s/ac
Liberate	0.98	g/ml	5.12	oz. (volume)/ac	29.57	ml/oz.	151.40	ml/ac	148.37	grams/ac	100	148.3704	gram s/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	gram s/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	gram s/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/ac	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.60651	gram s/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/ac	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.07121	gram s/ac

Silencer	0.93	g/ml	2.8	oz. (volume)/ac	29.57	ml/oz.	82.80	ml/ac	77.00	grams/ac	11.4	8.778032	gram s/ac
Tactic	1.025	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	38.80	grams/ac	63.4	24.59656	gram s/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	gram s/ac
Unfoamer	1	g/ml	0.7	oz. (volume)/ac	29.57	ml/oz.	20.70	ml/ac	20.70	grams/ac	12.5	2.587375	gram s/ac
Paraquat dichloride	1.15	g/ml	44.4	oz. (volume)/ac	29.57	ml/oz.	1312.91	ml/ac	1509.84	grams/ac	43.2	652.2527	gram s/ac
Cyclone	1.1	g/ml	38.4	oz. (volume)/ac	29.57	ml/oz.	1135.49	ml/ac	1249.04	grams/ac	30.1	375.9601	gram s/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	gram s/ac

Table. B-19. RTF-WW rotation conversions of pesticides from fluid ounce to grams

	Bulk Density from MSDS	Units	Volume of herbicide applied	Units	Conversion Factor	units	Volume	units	Mass Herbicide applied	Units	% Active gradient in Herbicide	Mass of active gradient	Units
Round Up powemax	1.3565	g/ml	70.4	oz. (volume)/ac	29.57	ml/oz.	2081.73	ml/ac	2823.86	grams/ac	48.7	1375.222	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.839	grams/ac
Affinity Broadspec	1.21	g/ml	1.1	oz. (volume)/ac	29.57	ml/oz.	32.53	ml/ac	39.36	grams/ac	50	19.67884	grams/ac

Vendetta	1.14	g/ml	6.4	oz. (volume)/ac	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.7427	grams/ac
Osprey	0.92475	g/ml	1.9	oz. (volume)/ac	29.57	ml/oz.	56.18	ml/ac	51.96	grams/ac	4.5	2.337985	grams/ac
Liberate	0.98	g/ml	7.68	oz. (volume)/ac	29.57	ml/oz.	227.10	ml/ac	222.56	grams/ac	100	222.5556	grams/ac
Gunsmoke	1.195	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	135.69	grams/ac	80	108.5527	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/ac	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.60651	grams/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/ac	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.07121	grams/ac
Silencer	0.93	g/ml	2.8	oz. (volume)/ac	29.57	ml/oz.	82.80	ml/ac	77.00	grams/ac	11.4	8.778032	grams/ac
Tactic	1.025	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	38.80	grams/ac	63.4	24.59656	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.9	oz. (volume)/ac	29.57	ml/oz.	26.61	ml/ac	26.61	grams/ac	12.5	3.326625	grams/ac
Paraquat dichloride	1.15	g/ml	44.4	oz. (volume)/ac	29.57	ml/oz.	1312.91	ml/ac	1509.84	grams/ac	43.2	652.2527	grams/ac

Cyclone	1.1	g/ml	51.2	oz. (volume)/ac	29.57	ml/oz.	1513.98	ml/ac	1665.38	grams/ac	30.1	501.2801	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac

Table. B-20. RTF-WO (RTF-WO-RTF-WW) rotation conversions of pesticides from fluid ounce to grams

	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	units
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/ac	1797.00	grams/ac	48.7	875.1411	grams /ac
Round up RT3	1.3573	g/ml	60	oz. (volume)/ac	29.57	ml/oz.	1774.20	ml/ac	2408.12	grams/ac	48.8	1175.163	grams /ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams /ac
Liberate	0.98	g/ml	5.76	oz. (volume)/ac	29.57	ml/oz.	170.32	ml/ac	166.92	grams/ac	100	166.9167	grams /ac
Gunsmoke	1.195	g/ml	4.48	oz. (volume)/ac	29.57	ml/oz.	132.47	ml/ac	158.31	grams/ac	80	126.6448	grams /ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams /ac

Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz .	18.92	ml/ac	19.40	grams/ac	63.4	12.2982 8	grams /ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz .	37.85	ml/ac	42.77	grams/ac	50	21.3850 2	grams /ac
Unfoamer	1	g/ml	1.86	oz. (volume)/ac	29.57	ml/oz .	55.00	ml/ac	55.00	grams/ac	12.5	6.87502 5	grams /ac
Paraquat dichloride	1.15	g/ml	34.2	oz. (volume)/ac	29.57	ml/oz .	1011.29	ml/ac	1162.99	grams/ac	43.2	502.410 9	grams /ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz .	756.99	ml/ac	832.69	grams/ac	30.1	250.640 1	grams /ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz .	378.50	ml/ac	423.92	grams/ac	25	105.978 9	grams /ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz .	70.97	ml/ac	85.16	grams/ac	48.2	41.0478 9	grams /ac
Wetcit	1.02	g/ml	2	oz. (volume)/ac	29.57	ml/oz .	59.14	ml/ac	60.32	grams/ac	8.15	4.91630 8	grams /ac
Glystar plus	1.18	g/ml	19.2	oz. (volume)/ac	29.57	ml/oz .	567.74	ml/ac	669.94	grams/ac	41	274.674 5	grams /ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/ac	29.57	ml/oz .	45.42	ml/ac	49.96	grams/ac	22.8	11.3912 2	grams /ac

Table. B-21. RTF-WW (RTF-WW-RTF-WO) rotation conversions of pesticides from fluid ounce to grams

WW	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	units
Round Up powemax	1.3565	g/ml	70.4	oz. (volume)/ac	29.57	ml/oz.	2081.73	ml/ac	2823.86	grams/ac	48.7	1375.222	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.839	grams/ac
Affinity Broadspec	1.21	g/ml	0.2	oz. (volume)/ac	29.57	ml/oz.	5.91	ml/ac	7.16	grams/ac	50	3.57797	grams/ac
Vendetta	1.14	g/ml	6.4	oz. (volume)/ac	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.7427	grams/ac
Osprey	0.92475	g/ml	1.9	oz. (volume)/ac	29.57	ml/oz.	56.18	ml/ac	51.96	grams/ac	4.5	2.337985	grams/ac
Liberate	0.98	g/ml	7.68	oz. (volume)/ac	29.57	ml/oz.	227.10	ml/ac	222.56	grams/ac	100	222.5556	grams/ac
Gunsmoke	1.195	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	135.69	grams/ac	80	108.5527	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/ac	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.60651	grams/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/ac	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.07121	grams/ac

Silencer	0.93	g/ml	2.8	oz. (volume)/ac	29.57	ml/oz.	82.80	ml/ac	77.00	grams/ac	11.4	8.778032	grams/ac
Tactic	1.025	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	38.80	grams/ac	63.4	24.59656	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.9	oz. (volume)/ac	29.57	ml/oz.	26.61	ml/ac	26.61	grams/ac	12.5	3.326625	grams/ac
Paraquat dichloride	1.15	g/ml	44.4	oz. (volume)/ac	29.57	ml/oz.	1312.91	ml/ac	1509.84	grams/ac	43.2	652.2527	grams/ac
Cyclone	1.1	g/ml	51.2	oz. (volume)/ac	29.57	ml/oz.	1513.98	ml/ac	1665.38	grams/ac	30.1	501.2801	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac

Table. B-22. RTF-WW-SB rotation conversions of pesticides from fluid ounce to grams

	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	units
RTF													
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/ac	1797.00	grams/ac	48.7	875.1411	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.839	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac

Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/ac	29.57	ml/oz.	10.65	ml/ac	10.65	grams/ac	12.5	1.33065	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac
SB													
Round Up powemax	1.3565	g/ml	31.2	oz. (volume)/ac	29.57	ml/oz.	922.58	ml/ac	1251.49	grams/ac	48.7	609.4733	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	grams/ac
Vendetta	1.14	g/ml	5	oz. (volume)/ac	29.57	ml/oz.	147.85	ml/ac	168.55	grams/ac	100	168.549	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.12	oz. (volume)/ac	29.57	ml/oz.	3.55	ml/ac	4.29	grams/ac	50	2.146782	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac

Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac
Brox-M	1.13	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz.	94.62	ml/ac	106.93	grams/ac	65.7	70.2498	grams/ac
Liberate	0.98	g/ml	4.48	oz. (volume)/ac	29.57	ml/oz.	132.47	ml/ac	129.82	grams/ac	100	129.8241	grams/ac
Unfoamer	1	g/ml	0.66	oz. (volume)/ac	29.57	ml/oz.	19.52	ml/ac	19.52	grams/ac	12.5	2.439525	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Huskie	1.14	g/ml	3	oz. (volume)/ac	29.57	ml/oz.	88.71	ml/ac	101.13	grams/ac	35	35.39529	grams/ac
WW													
Round Up powemax	1.3565	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	1026.86	grams/ac	48.7	500.0806	grams/ac
Vendetta	1.14	g/ml	6.4	oz. (volume)/ac	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.7427	grams/ac

Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/ac	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.07121	grams/ac
Osprey	0.92475	g/ml	1.9	oz. (volume)/ac	29.57	ml/oz.	56.18	ml/ac	51.96	grams/ac	4.5	2.337985	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/ac	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.60651	grams/ac
Unfoamer	1	g/ml	0.54	oz. (volume)/ac	29.57	ml/oz.	15.97	ml/ac	15.97	grams/ac	12.5	1.995975	grams/ac

Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac
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Table. B-23. RTF-WW-SO rotation conversions of pesticides from fluid ounce to grams

RTF	Bulk Density from MSDS	Units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	units
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/ac	1797.00	grams/ac	48.7	875.1411	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.839	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac

Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/ac	29.57	ml/oz.	10.65	ml/ac	10.65	grams/ac	12.5	1.33065	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac
SO													
Round Up powemax	1.3565	g/ml	24.8	oz. (volume)/ac	29.57	ml/oz.	733.34	ml/ac	994.77	grams/ac	48.7	484.4531	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac
Liberate	0.98	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz.	94.62	ml/ac	92.73	grams/ac	100	92.73152	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac

Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.46	oz. (volume)/ac	29.57	ml/oz.	13.60	ml/ac	13.60	grams/ac	12.5	1.700275	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Wetcit	1.02	g/ml	2	oz. (volume)/ac	29.57	ml/oz.	59.14	ml/ac	60.32	grams/ac	8.15	4.916308	grams/ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/ac	29.57	ml/oz.	45.42	ml/ac	49.96	grams/ac	22.8	11.39122	grams/ac
Landmaster II	1.13	g/ml	10.8	oz. (volume)/ac	29.57	ml/oz.	319.36	ml/ac	360.87	grams/ac	33.5	120.8922	grams/ac
Assure II	1.02	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	72.39	grams/ac	10.3	7.455898	grams/ac
Warrior II	1.1	g/ml	0.768	oz. (volume)/ac	29.57	ml/oz.	22.71	ml/ac	24.98	grams/ac	22.8	5.695608	grams/ac
WW													
Round Up powemax	1.3565	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	1026.86	grams/ac	48.7	500.0806	grams/ac

Vendetta	1.14	g/ml	6.4	oz. (volume)/ac	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.7427	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/ac	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.07121	grams/ac
Osprey	0.92475	g/ml	1.9	oz. (volume)/ac	29.57	ml/oz.	56.18	ml/ac	51.96	grams/ac	4.5	2.337985	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/ac	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.60651	grams/ac

Unfoamer	1	g/ml	0.54	oz. (volume)/ac	29.57	ml/oz.	15.97	ml/ac	15.97	grams/ac	12.5	1.995975	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac

Table. B-24. RTF-WO-SW rotation conversions of pesticides from fluid ounce to grams

RTF	Bulk Density from MSDS	Units	Volume of herbicide applied	Units	Conversion Factor	units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	Units
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/a c	1797.00	grams/ac	48.7	875.1411	gram s/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/a c	2536.55	grams/ac	48.8	1237.839	gram s/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/a c	67.85	grams/ac	80	54.27633	gram s/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/a c	3.58	grams/ac	50	1.788985	gram s/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/a c	19.40	grams/ac	63.4	12.29828	gram s/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/a c	111.28	grams/ac	100	111.2778	gram s/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/a c	38.50	grams/ac	11.4	4.389016	gram s/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/a c	754.92	grams/ac	43.2	326.1263	gram s/ac

Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz .	756.99	ml/a c	832.69	grams/ac	30.1	250.6401	gram s/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz .	283.87	ml/a c	334.97	grams/ac	41	137.3373	gram s/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz .	37.85	ml/a c	42.77	grams/ac	50	21.38502	gram s/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/ac	29.57	ml/oz .	10.65	ml/a c	10.65	grams/ac	12.5	1.33065	gram s/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz .	70.97	ml/a c	85.16	grams/ac	48.2	41.04789	gram s/ac
WO													
Round up RT3	1.3573	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz .	283.87	ml/a c	385.30	grams/ac	48.8	188.0261	gram s/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz .	75.70	ml/a c	90.46	grams/ac	80	72.36844	gram s/ac
Liberate	0.98	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz .	56.77	ml/a c	55.64	grams/ac	100	55.63891	gram s/ac
Paraquat dichloride	1.15	g/ml	12	oz. (volume)/ac	29.57	ml/oz .	354.84	ml/a c	408.07	grams/ac	43.2	176.2845	gram s/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz .	756.99	ml/a c	832.69	grams/ac	30.1	250.6401	gram s/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz .	378.50	ml/a c	423.92	grams/ac	25	105.9789	gram s/ac

Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz .	41.40	ml/a c	38.50	grams/ac	11.4	4.389016	gram s/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz .	18.92	ml/a c	19.40	grams/ac	63.4	12.29828	gram s/ac
Unfoamer	1	g/ml	0.3	oz. (volume)/ac	29.57	ml/oz .	8.87	ml/a c	8.87	grams/ac	12.5	1.108875	gram s/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz .	283.87	ml/a c	334.97	grams/ac	41	137.3373	gram s/ac
Wetcit	1.02	g/ml	2	oz. (volume)/ac	29.57	ml/oz .	59.14	ml/a c	60.32	grams/ac	8.15	4.916308	gram s/ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/ac	29.57	ml/oz .	45.42	ml/a c	49.96	grams/ac	22.8	11.39122	gram s/ac
SW													
Round Up powemax	1.3565	g/ml	31.2	oz. (volume)/ac	29.57	ml/oz .	922.58	ml/a c	1251.49	grams/ac	48.7	609.4733	gram s/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz .	473.12	ml/a c	642.17	grams/ac	48.8	313.3769	gram s/ac
Vendetta	1.14	g/ml	5	oz. (volume)/ac	29.57	ml/oz .	147.85	ml/a c	168.55	grams/ac	100	168.549	gram s/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz .	2.96	ml/a c	3.67	grams/ac	50	1.83334	gram s/ac
Affinity Broadspec	1.21	g/ml	0.12	oz. (volume)/ac	29.57	ml/oz .	3.55	ml/a c	4.29	grams/ac	50	2.146782	gram s/ac

Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz .	656.45	ml/a c	754.92	grams/ac	43.2	326.1263	gram s/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz .	756.99	ml/a c	832.69	grams/ac	30.1	250.6401	gram s/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz .	378.50	ml/a c	423.92	grams/ac	25	105.9789	gram s/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz .	41.40	ml/a c	38.50	grams/ac	11.4	4.389016	gram s/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz .	18.92	ml/a c	19.40	grams/ac	63.4	12.29828	gram s/ac
Huskie	1.14	g/ml	3	oz. (volume)/ac	29.57	ml/oz .	88.71	ml/a c	101.13	grams/ac	35	35.39529	gram s/ac
Liberate	0.98	g/ml	4.48	oz. (volume)/ac	29.57	ml/oz .	132.47	ml/a c	129.82	grams/ac	100	129.8241	gram s/ac
Unfoamer	1	g/ml	0.66	oz. (volume)/ac	29.57	ml/oz .	19.52	ml/a c	19.52	grams/ac	12.5	2.439525	gram s/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz .	75.70	ml/a c	90.46	grams/ac	80	72.36844	gram s/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz .	37.85	ml/a c	42.77	grams/ac	50	21.38502	gram s/ac
Brox-M	1.13	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz .	94.62	ml/a c	106.93	grams/ac	65.7	70.2498	gram s/ac

Table. B-25. RTF-SW-SO rotation conversions of pesticides from fluid ounce to grams

RTF	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	Units
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/ac	1797.00	grams/ac	48.7	875.1411	grams/ac
Round up RT3	1.3573	g/ml	56.8	oz. (volume)/ac	29.57	ml/oz.	1679.58	ml/ac	2279.69	grams/ac	48.8	1112.488	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac

Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/ac	29.57	ml/oz.	10.65	ml/ac	10.65	grams/ac	12.5	1.33065	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac
SO													
Round Up powemax	1.3565	g/ml	24.8	oz. (volume)/ac	29.57	ml/oz.	733.34	ml/ac	994.77	grams/ac	48.7	484.4531	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac
Liberate	0.98	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz.	94.62	ml/ac	92.73	grams/ac	100	92.73152	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac

Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.46	oz. (volume)/ac	29.57	ml/oz.	13.60	ml/ac	13.60	grams/ac	12.5	1.700275	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Wetcit	1.02	g/ml	2	oz. (volume)/ac	29.57	ml/oz.	59.14	ml/ac	60.32	grams/ac	8.15	4.916308	grams/ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/ac	29.57	ml/oz.	45.42	ml/ac	49.96	grams/ac	22.8	11.39122	grams/ac
Landmaster II	1.13	g/ml	10.8	oz. (volume)/ac	29.57	ml/oz.	319.36	ml/ac	360.87	grams/ac	33.5	120.8922	grams/ac
Assure II	1.02	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	72.39	grams/ac	10.3	7.455898	grams/ac
Warrior II	1.1	g/ml	0.768	oz. (volume)/ac	29.57	ml/oz.	22.71	ml/ac	24.98	grams/ac	22.8	5.695608	grams/ac
SW													
Round Up powemax	1.3565	g/ml	31.2	oz. (volume)/ac	29.57	ml/oz.	922.58	ml/ac	1251.49	grams/ac	48.7	609.4733	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	grams/ac

Vendetta	1.14	g/ml	5	oz. (volume)/ac	29.57	ml/oz.	147.85	ml/ac	168.55	grams/ac	100	168.549	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.12	oz. (volume)/ac	29.57	ml/oz.	3.55	ml/ac	4.29	grams/ac	50	2.146782	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Huskie	1.14	g/ml	3	oz. (volume)/ac	29.57	ml/oz.	88.71	ml/ac	101.13	grams/ac	35	35.39529	grams/ac
Liberate	0.98	g/ml	4.48	oz. (volume)/ac	29.57	ml/oz.	132.47	ml/ac	129.82	grams/ac	100	129.8241	grams/ac
Unfoamer	1	g/ml	0.66	oz. (volume)/ac	29.57	ml/oz.	19.52	ml/ac	19.52	grams/ac	12.5	2.439525	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac

Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Brox-M	1.13	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz.	94.62	ml/ac	106.93	grams/ac	65.7	70.2498	grams/ac

Table. B-26. RTF-WO-ST rotation conversions of pesticides from fluid ounce to grams

RTF	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	Units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	Units
Round Up powemax	1.3565	g/ml	64	oz. (volume)/ac	29.57	ml/oz.	1892.48	ml/ac	2567.15	grams/ac	48.7	1250.202	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.839	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.27633	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.2778	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac

Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/ac	29.57	ml/oz.	10.65	ml/ac	10.65	grams/ac	12.5	1.33065	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/ac	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.04789	grams/ac
WO													
Round up RT3	1.3573	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	385.30	grams/ac	48.8	188.0261	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac
Liberate	0.98	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	55.64	grams/ac	100	55.63891	grams/ac
Paraquat dichloride	1.15	g/ml	12	oz. (volume)/ac	29.57	ml/oz.	354.84	ml/ac	408.07	grams/ac	43.2	176.2845	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac

Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Unfoamer	1	g/ml	0.3	oz. (volume)/ac	29.57	ml/oz.	8.87	ml/ac	8.87	grams/ac	12.5	1.108875	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/ac	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.3373	grams/ac
Wetcit	1.02	g/ml	2	oz. (volume)/ac	29.57	ml/oz.	59.14	ml/ac	60.32	grams/ac	8.15	4.916308	grams/ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/ac	29.57	ml/oz.	45.42	ml/ac	49.96	grams/ac	22.8	11.39122	grams/ac
ST													
Round Up powemax	1.3565	g/ml	31.2	oz. (volume)/ac	29.57	ml/oz.	922.58	ml/ac	1251.49	grams/ac	48.7	609.4733	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/ac	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.3769	grams/ac
Vendetta	1.14	g/ml	5	oz. (volume)/ac	29.57	ml/oz.	147.85	ml/ac	168.55	grams/ac	100	168.549	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.12	oz. (volume)/ac	29.57	ml/oz.	3.55	ml/ac	4.29	grams/ac	50	2.146782	grams/ac

Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/ac	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.1263	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/ac	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.6401	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/ac	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.9789	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.389016	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828	grams/ac
Huskie	1.14	g/ml	3	oz. (volume)/ac	29.57	ml/oz.	88.71	ml/ac	101.13	grams/ac	35	35.39529	grams/ac
Liberate	0.98	g/ml	4.48	oz. (volume)/ac	29.57	ml/oz.	132.47	ml/ac	129.82	grams/ac	100	129.8241	grams/ac
Unfoamer	1	g/ml	0.66	oz. (volume)/ac	29.57	ml/oz.	19.52	ml/ac	19.52	grams/ac	12.5	2.439525	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/ac	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.36844	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/ac	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.38502	grams/ac
Brox-M	1.13	g/ml	3.2	oz. (volume)/ac	29.57	ml/oz.	94.62	ml/ac	106.93	grams/ac	65.7	70.2498	grams/ac

Table. B-27. RTF-SO-WT rotation conversions of pesticides from fluid ounce to grams

RTF	Bulk Density from MSDS	units	Volume of herbicide applied	Units	Conversion Factor	units	Volume	units	Mass Herbicide applied	units	% Active gradient in Herbicide	Mass of active gradient	Units
Round Up powemax	1.3565	g/ml	44.8	oz. (volume)/ac	29.57	ml/oz.	1324.74	ml/ac	1797.00	grams/ac	48.7	875.141135	grams/ac
Round up RT3	1.3573	g/ml	63.2	oz. (volume)/ac	29.57	ml/oz.	1868.82	ml/ac	2536.55	grams/ac	48.8	1237.83875	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/ac	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.2763264	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/ac	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/ac	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.29828128	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/ac	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.277824	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/ac	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.38901596	grams/ac

Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/a c	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.126347 2	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/a c	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.640051 2	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/a c	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.337273 6	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/a c	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.385024	grams/ac
Unfoamer	1	g/ml	0.36	oz. (volume)/a c	29.57	ml/oz.	10.65	ml/ac	10.65	grams/ac	12.5	1.33065	grams/ac
Rifle	1.2	g/ml	2.4	oz. (volume)/a c	29.57	ml/oz.	70.97	ml/ac	85.16	grams/ac	48.2	41.0478912	grams/ac
SO													
Round Up powemax	1.3565	g/ml	24.8	oz. (volume)/a c	29.57	ml/oz.	733.34	ml/ac	994.77	grams/ac	48.7	484.453128 3	grams/ac
Round up RT3	1.3573	g/ml	16	oz. (volume)/a c	29.57	ml/oz.	473.12	ml/ac	642.17	grams/ac	48.8	313.376898 7	grams/ac
Gunsmoke	1.195	g/ml	2.56	oz. (volume)/a c	29.57	ml/oz.	75.70	ml/ac	90.46	grams/ac	80	72.3684352	grams/ac

Liberate	0.98	g/ml	3.2	oz. (volume)/a c	29.57	ml/oz.	94.62	ml/ac	92.73	grams/ac	100	92.73152	grams/ac
Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/a c	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.126347 2	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/a c	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.640051 2	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/a c	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.97888	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/a c	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.38901596	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/a c	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.2982812 8	grams/ac
Choice	1.13	g/ml	1.28	oz. (volume)/a c	29.57	ml/oz.	37.85	ml/ac	42.77	grams/ac	50	21.385024	grams/ac
Unfoamer	1	g/ml	0.46	oz. (volume)/a c	29.57	ml/oz.	13.60	ml/ac	13.60	grams/ac	12.5	1.700275	grams/ac
Glystar plus	1.18	g/ml	9.6	oz. (volume)/a c	29.57	ml/oz.	283.87	ml/ac	334.97	grams/ac	41	137.337273 6	grams/ac

Wetcit	1.02	g/ml	2	oz. (volume)/a c	29.57	ml/oz.	59.14	ml/ac	60.32	grams/ac	8.15	4.9163082	grams/ac
Warrior II	1.1	g/ml	1.536	oz. (volume)/a c	29.57	ml/oz.	45.42	ml/ac	49.96	grams/ac	22.8	11.3912156 2	grams/ac
Landmaster II	1.13	g/ml	10.8	oz. (volume)/a c	29.57	ml/oz.	319.36	ml/ac	360.87	grams/ac	33.5	120.892213 8	grams/ac
Assure II	1.02	g/ml	2.4	oz. (volume)/a c	29.57	ml/oz.	70.97	ml/ac	72.39	grams/ac	10.3	7.45589808	grams/ac
Warrior II	1.1	g/ml	0.768	oz. (volume)/a c	29.57	ml/oz.	22.71	ml/ac	24.98	grams/ac	22.8	5.69560780 8	grams/ac
WT													
Round Up powemax	1.3565	g/ml	25.6	oz. (volume)/a c	29.57	ml/oz.	756.99	ml/ac	1026.86	grams/ac	48.7	500.080648 6	grams/ac
Vendetta	1.14	g/ml	6.4	oz. (volume)/a c	29.57	ml/oz.	189.25	ml/ac	215.74	grams/ac	100	215.74272	grams/ac
Harmony extra	1.24	g/ml	0.1	oz. (volume)/a c	29.57	ml/oz.	2.96	ml/ac	3.67	grams/ac	50	1.83334	grams/ac
Affinity Broadspec	1.21	g/ml	0.1	oz. (volume)/a c	29.57	ml/oz.	2.96	ml/ac	3.58	grams/ac	50	1.788985	grams/ac

Paraquat dichloride	1.15	g/ml	22.2	oz. (volume)/a c	29.57	ml/oz.	656.45	ml/ac	754.92	grams/ac	43.2	326.126347 2	grams/ac
Cyclone	1.1	g/ml	25.6	oz. (volume)/a c	29.57	ml/oz.	756.99	ml/ac	832.69	grams/ac	30.1	250.640051 2	grams/ac
Gramoxone	1.12	g/ml	12.8	oz. (volume)/a c	29.57	ml/oz.	378.50	ml/ac	423.92	grams/ac	25	105.97888	grams/ac
Silencer	0.93	g/ml	1.4	oz. (volume)/a c	29.57	ml/oz.	41.40	ml/ac	38.50	grams/ac	11.4	4.38901596	grams/ac
Tactic	1.025	g/ml	0.64	oz. (volume)/a c	29.57	ml/oz.	18.92	ml/ac	19.40	grams/ac	63.4	12.2982812 8	grams/ac
Huskie	1.14	g/ml	5.6	oz. (volume)/a c	29.57	ml/oz.	165.59	ml/ac	188.77	grams/ac	35	66.071208	grams/ac
Liberate	0.98	g/ml	3.84	oz. (volume)/a c	29.57	ml/oz.	113.55	ml/ac	111.28	grams/ac	100	111.277824	grams/ac
Unfoamer	1	g/ml	0.54	oz. (volume)/a c	29.57	ml/oz.	15.97	ml/ac	15.97	grams/ac	12.5	1.995975	grams/ac
Gunsmoke	1.195	g/ml	1.92	oz. (volume)/a c	29.57	ml/oz.	56.77	ml/ac	67.85	grams/ac	80	54.2763264	grams/ac

Osprey	0.92475	g/ml	0.95	oz. (volume)/a c	29.57	ml/oz.	28.09	ml/ac	25.98	grams/ac	4.5	1.16899265 8	grams/ac
Fitness	1.04	g/ml	1.2	oz. (volume)/a c	29.57	ml/oz.	35.48	ml/ac	36.90	grams/ac	45	16.606512	grams/ac

B.2 Eco profiles in SimaPro

B.2.1 Inventory of materials and processes to SimaPro on an acre basis

Section B.2.1 contains the all the eco profiles used and created to carry out the analysis using SimaPro. Tables B-8-B-27 are the inputs used in SimaPro on per acre basis using the information from sections B.1.2 and B.1.3.

Table. B-28. Inputs to Simapro for the rotation SF-WW based on per acre

Materials/Assemblies	Calculations	Unit	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	114.75	lb.	Average seed rate 114.75 lb. /acre per year;
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN in 196 lb. /acre applied every year and on an average of 55 lb. as N per year;
Glyphosate {GLO} market for Alloc Def, S	1313.54	g	48.7% glyphosate in Roundup powermax; 48.8% glyphosate in Round up RT3; average round up powermax per year is 51.2 oz./acre and average roundup RT3 is 16 oz./acre per year;
Pesticide, unspecified {GLO} market for Alloc Def, S	215.75	g	100% Active; Average Vendetta applied per year is 6.4 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	50% Active; Average Harmony is 0.1 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	72.37	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre;

Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	g	50% active; Average Affinity broad spec applied per year is 0.1 oz./ acre;
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	148.37	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied per year is 5.12 oz./ acre;
Pesticide, unspecified {GLO} market for Alloc Def, S	2.33	g	Osprey- 4.5% Meso-sulfuron; Average Osprey applied per year is 1.9 oz./ acre;
Pesticide, unspecified {GLO} market for Alloc Def, S	16.6	g	Fitness - 45% propiconazole; Average Fitness applied per year is 1.2 oz./ acre;
Diesel, low-sulfur {RoW} market for Alloc Def, S	20.31	kg	24.42 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	52.14	lb.	Average of 41.16 lb./acre thiosulfate per year; thiosulfate Mol. wt. - 112.128; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions_N2O-2A	55	lb.	55 lbs. N per year on average
Dry_land_field_emissions_CO2	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	g	35% active pesticide; Average Huskie per year is 5.6 oz./acre;
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	1134.19	g	43.2% Paraquat dichloride in Paraquat concentrated (PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 44.4 oz./acre; Average Cyclone per year is 38.4 oz./acre; Average Gram Oxone per year is 12.8 oz./acre;

Pesticide, unspecified {GLO} market for Alloc Def, S	8.77	g	Silencer- 11.4% is pesticide; Average Silencer per year is 2.8 oz./acre;
Latex {GLO} market for Alloc Def, S	24.59	g	63.4% active in Tactic; average application-1.28 oz./acre;
Gasoline {RoW} market for Alloc Def, S	0.29	kg	0.38658 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.29	kg	0.38658 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of Choice is active pesticide; average choice per year is 1.28 oz./acre;
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.256	lb.	Average Solution 32 per year is 0.256 lb./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.587	g	Average Unfoamer per year 0.7 oz./acre; Unfoamer- 12.5% active pesticide;
Dry land field emissions CH ₄ -2A	55	lb.	55 lbs. N is applied per year on average
Processes			
Diesel Combustion Emissions	20.31744	kg	24.42 liter/acre; Density 0.832 kg/liter

Table. B-29. Inputs to Simapro for the rotation RTF-WW based on per acre

Materials/Assemblies	Calculations	Unit	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	114.75	lb.	Average seed rate 114.75 lb./acre per year

Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	2612.8	g	48.7% glyphosate in Roundup powermax; 48.8% glyphosate in Round up RT3; average round up powermax per year is 70.4 oz./ acre and average roundup RT3 is 63.2 oz./acre.
Pesticide, unspecified {GLO} market for Alloc Def, S	215.74	g	100% active; Average Vendetta applied per year is 6.4 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	50% active; Average Harmony per year is 0.1 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	108.55	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 3.84 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	19.67	g	50% active; Average Affinity broad spec applied per year is 1.1 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	222.55	g	Liberate - 100% Ethoxylated Alcohol; Average Liberate applied per year is 7.68 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.33	g	Osprey- 4.5% Meso-sulfuron; Average Osprey applied per year is 1.9 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	16.60	g	Fitness - 45% propiconazole; Average Fitness applied per year is 1.2 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	15.04	kg	18.077 liter/acre; 0.832 kg/liter

Sodium sulfate, anhydrite {RER} market for Alloc Def, S	52.14	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.128; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions_N2O-2B	55	lb.	55lbs N per year on average
Dry_land_field_emissions_CO2	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	g	35% active pesticide; Average Huskie per year is 5.6 oz./acre
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	1259.51	g	43.2% Paraquat dichloride in Paraquat concentrated (PC) and 30.1% paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 44.4 oz./acre; Average Cyclone per year is 51.2 oz./acre; Average Gram Oxone per year is 12.8 oz./acre;
Pesticide, unspecified {GLO} market for Alloc Def, S	8.778032	g	Silencer- 11.4% is pesticide; Average Silencer per year is 2.8 oz./acre
Latex {GLO} market for Alloc Def, S	24.59656	g	Tactic - 63.4% latex, Average Tactic per year is 1.28 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.36883	kg	0.479 liter/acre avgas, 0.77 density of Gasoline
CO2 combustion emissions from Gasoline	0.36883	kg	0.479 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38502	g	50% of choice is active pesticide; average choice per year is 1.28 oz/acre

Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.256	lb.	Average solution 32 per year is 12.8 oz./acre; 1.28 lb./64 oz.; 0.256 lb./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	3.326625	g	Average Unfoamer per year is 0.9 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.3373	g	9.6 oz./ac of Glystar plus and 41% of glystar is glyphosate
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04789	g	48.2% active dicamba; average Rifle per year is 2.4 oz./acre
Dry land field emissions CH ₄ -2B	55	lb.	55 lbs. N per year on average
Processes			
Diesel Combustion Emissions	15.040064	kg	18.077 liter/acre; 0.832 kg/liter

Table. B-30. Inputs to Simapro for the rotation RTF-WW (RTF-WW-RTF-WO) based on per acre

Materials/Assemblies	Calculations	Units	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	114.75	lb.	Average seed rate 114.75 lbs. /acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	2613.06	g	48.7% glyphosate in Roundup powermax 48.8% glyphosate in Round up RT3; average round up powermax per year is 70.4 oz./acre and average roundup RT3 per year is 63.2 oz./acre.

Pesticide, unspecified {GLO} market for Alloc Def, S	215.74	g	100% Average Vendetta applied per year is 6.4 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	50% Average Harmony per year is 0.1 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	108.55	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 3.84 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	3.57	g	50% Average Affinity broad spec applied per year is 0.2 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	222.55	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied per year is 7.68 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.33	g	Osprey- 4.5% Meso-sulfuron; Average Osprey applied per year is 1.9 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	16.6	g	Fitness - 45% propiconazole; Average Fitness applied per year is 1.2 oz./ acre
Diesel, low sulfur {RoW} market for Alloc Def, S	15.04	kg	18.077 liter/acre; 0.832 kg/ liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	52.14	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.128; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions_N2O-2C1	55	lb.	55 lbs. N per year on average
Dry_land_field_emissions_CO2	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.

Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	g	35% active pesticide; Average Huskie per year is 5.6 oz./acre
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	1259.51	g	43.2% Paraquat dichloride in Paraquat concentrated (PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 44.4 oz./acre; Average Cyclone per year is 51.2 oz./acre; Average Gram Oxone is 12.8 Oz/acre
Pesticide, unspecified {GLO} market for Alloc Def, S	8.77	g	Silencer- 11.4% is pesticide; Average Silencer per year is 2.8 oz./acre
Latex {GLO} market for Alloc Def, S	24.59	g	Tactic - 63.4% latex, Average Tactic per year is 1.28 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.35	kg	0.458 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.35	kg	0.458 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.25	lb.	Average solution 32 per year 12.8 oz. /acre; 1.28 lb. /64 oz.; 0.256 lb. /acre.
Pesticide, unspecified {GLO} market for Alloc Def, S	3.32	g	Average Unfoamer per year 0.9 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and 41% of glystar is glyphosate

Dicamba, at regional storehouse/US- US-EI U	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year
Dry land field emissions CH ₄ -2C ₁	55	lb.	55 lbs. N per year on average
Processes			
Diesel Combustion Emissions	15.04	kg	18.077 liter/acre; 0.832 kg/liter

Table. B-31. Inputs to Simapro for the rotation RTF-WO (RTF-WO-RTF-WW) based on per acre

Materials/Assemblies	Calculations	Units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.46	lb.	Average seed rate 5.464 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	2050.30	g	48.7% glyphosate in Roundup powermax 48.8% glyphosate in Round up RT3; average round up powermax per year 44.8 oz./acre and average roundup RT3 is 60 oz./acre per year.
Pesticide, unspecified {GLO} market for Alloc Def, S	126.64	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 4.48 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.788	g	50% active; Average Affinity broad spec applied per year is 0.1 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	166.91	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied per year is 5.76 oz./ acre

Diesel, low-sulfur {RoW} market for Alloc Def, S	13.93	kg	16.752 liter/acre; 0.832 kg/ liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	52.14	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions_N ₂ O-2C ₂	55	lb.	55 lbs. N on average per year
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	858.9	g	43.2% Paraquat dichloride in Paraquat concentrated(PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Ozone; Average PC per year is 34.2 oz./acre; Average Cyclone per year is 25.6 oz./acre; Average Gram Ozone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer- 11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic - 63.4% latex, Average Tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.13	kg	0.172 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.13	kg	0.172 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	6.87	g	Average Unfoamer per year 1.86 oz./acre; Unfoamer- 12.5% active pesticide

Glyphosate {GLO} market for Alloc Def, S	274.67	g	19.2 oz./ac of Glystar plus per year and 41% of glystar is glyphosate
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year
Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.91	g	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	g	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Dry land field emissions CH ₄ -2C ₂	55	lb.	55 lbs. N per year on average
Processes			
Diesel Combustion Emissions	13.937664	kg	16.752 liter/acre; 0.832 kg/liter

Table. B-32. Inputs to Simapro for reduced tillage fallow (RTF-WW-SB) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	875.14+1237.83	g	48.7% glyphosate in 44.8 oz./acre Roundup Powermax on average per year; 48.8% glyphosate in 63.2 oz./acre Round up RT3 on average per year;
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of Gun smoke is pesticide, 1.92 oz./acre on average per year;
Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	g	50% active; Affinity broad spec .1 oz./acre on average per year;
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic 0.64 oz./acre on average per year; 63.4% latex

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.27	g	Liberate 3.84 oz./acre on average per year; 100% ethoxylated alcohol
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre on average per year; 11.4% lambda cyhalothrin
Diesel {RoW} market for Alloc Def, S	7.596*0.832	kg	7.596 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.6 4	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrate on average per year and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone on average per year;
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	.229 liter/acre and .77 kg/liter
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	.229 liter/acre and .77 kg/liter
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./acre of Glystar plus on average per year and it contains 41% of glyphosate and 59% inert;
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice in 5 years is 1.28 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	g	Average Unfoamer in 5 years 0.36 oz./acre; Unfoamer-12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year
Dry land field emissions-3A-RTF CH ₄ & N ₂ O	55	lb.	55lbs N per year on average
Processes			
Diesel Combustion Emissions	7.596*.832	kg	7.596 liter/acre, 0.832 kg/liter

Table. B-33. Inputs to Simapro for spring barley (RTF-WW-SB) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Barley seed, for sowing {GLO} market for Alloc Def, S	109.2	lb.	Average seed rate 109.2 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	55 lb. Urea ammonium nitrate (UAN) as N applied on average per year
Glyphosate {GLO} market for Alloc Def, S	$609.47 + 313.37$	G	48.7% glyphosate in 31.2 oz./acre Roundup Powermax and 48.8% glyphosate in RT3 16 oz./acre per year on average
Pesticide, unspecified {GLO} market for Alloc Def, S	168.54	G	100% active; Average Vendetta 5 oz./ acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	G	50% active; Average Harmony 0.1 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	2.14	G	50% active; Average Affinity broad spec 0.12 Oz/acre per year
Diesel, low-sulfur {RoW} market for Alloc Def, S	$10.696 * 0.832$	kg	10.696 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	$41.16 / 112.12 * 142.04$	lb.	41.16 lb./acre average thiosulfate per year; Mol. wt. - 112.12; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions-3A-SB CH ₄ & N ₂ O	55	lb.	55lbs N per year on average
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	$326.12 + 250.64 + 105.97$	G	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrate and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Oxone; Average Gram Oxone is 12.8 oz./acre per year;

Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	G	11.4% active; Average Silencer 1.4 oz./acre per year
Latex {GLO} market for Alloc Def, S	12.29	G	Average Tactic 0.64 oz./acre per year and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	G	80% of gun smoke is active pesticide; Average Gun smoke applied per year is 2.56 oz./ acre;
Pesticide, unspecified {GLO} market for Alloc Def, S	70.24	G	65.7 % active in Brox-M; 3.2 oz. /acre is applied on average per year.
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	129.82	G	Liberate - 100% ethoxylated alcohol; Average Liberate applied per year is 4.48 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.43	G	Average Unfoamer per year is 0.66 oz./acre; Unfoamer-12.5% active pesticide;
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	G	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	35.39	G	35% active pesticide; Average Huskie per year is 3 oz./acre
Processes			
Diesel Combustion Emissions	10.696*0.832	kg	10.696 liter/acre a, 0.832 kg/liter

Table. B-34. Inputs to Simapro for winter wheat (RTF-WW-SB) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	114.75	lb.	Average seed rate per year is 114.75 lb./acre
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	55 lb. Urea ammonium nitrate (UAN) as N applied on average per year
Glyphosate {GLO} market for Alloc Def, S	500.08	g	48.7% glyphosate in 25.6 oz./acre Roundup Powermax
Pesticide, unspecified {GLO} market for Alloc Def, S	215.74	g	active 100%; Vendetta; 6.4 oz./ acre on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	active 50%; Harmony; 0.1 oz./acre on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	g	active 50%; Affinity broad spec 0.1 oz./acre on average per year
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.4815×0.832	kg	10.4815 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	$41.16/112.128 \times 142.04$	lb.	Average 41.16 lb./acre thiosulfate per year, Mol. wt. - 112.128; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions-3A-WW_CH4 & N ₂ O	55	lb.	55 lbs. N per year on average
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	$326.126 + 250.64 + 105.978$	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrate and 31.0 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Oxone; Average Gram Oxone is 12.8 oz./acre

Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre on average per year, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.29	g	tactic 0.64 oz./acre on average per year and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	Kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	0.229*.77	Kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	G	35% active pesticide; Average Huskie per year is 5.6 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.33	G	1.9 oz./ac Osprey on average per year ;4.5% Meso-sulfuron
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.27	G	3.84 oz./ac liberate on average per year (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	16.60	G	Fitness - 45% propiconazole; Average Fitness applied per year is 1.2 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.99	G	Average Unfoamer per year is 0.54 oz./acre; Unfoamer-12.5% active pesticide
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.25	lb.	Average solution 32 per year is 12.8 oz./acre; 1.28 lb./64 oz.; 0.256 lb./acre UAN
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	G	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 1.92 oz./ acre
Processes			
Diesel Combustion Emissions	10.4815*0.83 2	Kg	10.4815 liter/acre a, 0.832 kg/liter

Table. B-35. Inputs to Simapro for reduced tillage fallow based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	$875.14 + 1237.83$	G	48.7% glyphosate in 44.8 oz./acre Roundup Powermax 48.8% glyphosate in 63.2 oz./acre Round up RT3
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	G	80% of Gun smoke is pesticide, 1.92 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	G	Affinity broad spec 0.1 oz./acre; 50% active
Latex {GLO} market for Alloc Def, S	12.29	G	tactic 0.64 oz./acre; 63.4% latex a
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.27	G	Liberate 3.84 oz./acre; 100% ethoxylated alcohol
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	G	Silencer 1.4 oz./acre; 11.4% lambda cyhalothrin
Diesel {RoW} market for Alloc Def, S	$7.8253 * 0.832$	Kg	7.8253 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	$326.1 + 250.64$	G	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 31.0 % paraquat dichloride in 25.6 oz./acre cyclone
Gasoline {RoW} market for Alloc Def, S	$0.229 * .77$	Kg	.229 liter/acre and 0.77 kg/liter
CO ₂ combustion emissions from Gasoline	$0.229 * .77$	Kg	.229 liter/acre and 0.77 kg/liter
Glyphosate {GLO} market for Alloc Def, S	137.33	G	9.6 oz./acre of Glystar plus and it contains 41% of glyphosate and 59% inert

Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	G	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	G	Average Unfoamer per year 0.36 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	G	48.2% active dicamba; average Rifle 2.4 oz./acre
Dry land field emissions-3B-RTF CH ₄ & N ₂ O	55	lb.	55lbs N per year on average
Processes			
Diesel Combustion Emissions	7.8253*.832	kg	7.8253 liter/acre, 0.832 kg/liter

Table. B-36. Inputs to Simapro for spring oilseed (RTF-WW-SO) based on per acre

Materials/Assemblies	Calculation	units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.40	lb.	Average seed rate 5.406 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	$484.45 + 313.37$	G	48.7% glyphosate in Roundup Powermax 48.8% glyphosate in Round up RT3; average round up powemax per year 24.8oz/acre and average roundup RT3 is 16 oz./acre per year.
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	G	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	92.73	G	Liberate - 100% ethoxylated alcohol; Average Liberate applied in per year is 3.2 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.624*0.832	Kg	10.624 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128 *142.04	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3B-SO CH ₄ & N ₂ O	55	lb.	55 lbs. N per year on average
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.6 4+105.978	g	43.2% Paraquat dichloride in Paraquat concentrated(PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 22.2 oz./acre; Average Cyclone per year is 25.6 oz./acre; Average Gram Oxone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer- 11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.29	g	tactic - 63.4% latex, Average tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.401*.77	kg	0.401 liter/acre avgas, 0.77 density of Gasoline
CO ₂ _ combustion emissions from Gasoline	0.401*.77	kg	0.401 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.7	g	Average Unfoamer per year 0.46 oz./acre; Unfoamer- 12.5% active pesticide

Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year on average and 41% of glystar is glyphosate
Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.91	g	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	g	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Isopropylamine {GLO} market for Alloc Def, S	120.89	g	33.5 % of Isopropyl amine, 10.8 oz./acre Land master
Pesticide, unspecified {GLO} market for Alloc Def, S	7.45	g	10.3% Assure II active ingredients and 2.4 oz./ac is applied
Pesticide, unspecified {GLO} market for Alloc Def, S	5.69	g	22.8% warrior II is active, and .768 oz./ac is applied
Processes			
Diesel Combustion Emissions	10.624*0.832	kg	10.624 liter/acre; 0.832 kg/liter

Table. B-37. Inputs to Simapro for winter wheat (RTF-WW-SO) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	114.75	lb	average seed rate 114.75 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb	79% UAN of 196 lb./acre every year and 55 as N per year
Glyphosate {GLO} market for Alloc Def, S	500.08	g	48.7% glyphosate in 25.6 oz./acre Roundup Powermax

Pesticide, unspecified {GLO} market for Alloc Def, S	215.74	g	100% active; Vendetta 6.4 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	50% active; Harmony 0.1 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	g	50% active; Affinity broad spec 0.1 oz./acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.624×0.832	kg	10.624 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	$41.16/112.128 \times 142.04$	lb.	41.16 lb./acre thiosulfate on average per year, Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3B-WW CH ₄ & N ₂ O	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	$326.12+250.64+105.978$	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Oxone; Average Gram Oxone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.29	g	tactic 0.64 oz./acre and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	$0.229 \times .77$	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	$0.229 \times .77$	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	g	35% active pesticide; Average Huskie per year is 5.6 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.33	g	1.9 oz./ac Osprey 4.5% Meso-sulfuron

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.278	g	3.84 oz./ac liberate (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	16.6	g	Fitness - 45% propiconazole; Average Fitness applied per year is 1.2 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.99	g	Average Unfoamer per year is 0.54 oz./acre; Unfoamer- 12.5% active pesticide
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.25	lb.	Average solution 32 per year is 12.8 oz./acre; 1.28 lb./64 oz.; 0.256 lb./acre UAN
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 1.92 oz./ acre
Processes			
Diesel Combustion Emissions	10.624×0.832	kg	10.624 liter/acre a, 0.832 kg/liter

Table. B-38. Inputs to Simapro for reduced tillage fallow (RTF-WO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	$875.14 + 1237.839$	g	48.7% glyphosate in 44.8 oz./acre Roundup Powermax 48.8% glyphosate in 63.2 oz./acre Round up RT3
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of Gun smoke is pesticide, 1.92 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.78	g	50% active; Affinity broad spec 0.1 oz./acre
Latex {GLO} market for Alloc Def, S	12.29	g	tactic 0.64 oz./acre 63.4% latex

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.27	g	Liberate 3.84 oz./acre 100% ethoxylated alcohol
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre, 11.4% lambda cyhalothrin
Diesel {RoW} market for Alloc Def, S	7.596*0.832	kg	7.596 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.1263+250 .6401	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	.229 liter/acre and .81 kg/liter
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	.229 liter/acre and .81 kg/liter
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus and it contains 41% of glyphosate and 59% inert
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	g	Average Unfoamer per year 0.36 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year
Dry land field emissions-3C-RTF CH ₄ & N ₂ O	55	lb.	55 lb./acre N applied on average per year
Processes			
Diesel Combustion Emissions	7.596*.832	kg	7.596 liter/acre, 0.832 kg/liter

Table. B-39. Inputs to Simapro for spring wheat (RTF-WO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	117.6	lb.	average seed rate 117.6 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Glyphosate {GLO} market for Alloc Def, S	609.47+313.376	g	48.7% glyphosate in 31.2 oz./acre Roundup Powermax; 48.8% glyphosate in Round up RT3; Round up RT3 16 oz./ac
Pesticide, unspecified {GLO} market for Alloc Def, S	168.54	g	100% active; Vendetta 5 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.83	g	50% active; Harmony 0.1 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	2.14	g	50% active; Affinity broad spec 0.12 oz./acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.696*0.832	kg	10.696 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	41.16 lb./acre thiosulfate on average per year, Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3C-SW CH ₄ & N ₂ O	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Oxone; Average Gram Oxone is 12.8 oz./acre

Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.29	g	tactic 0.64 oz./acre and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	35.39	g	35% active pesticide; Average Huskie per year is 3 oz./acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	129.82	g	4.48 oz./ac liberate (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	2.43	g	Average Unfoamer per year is 0.66 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	70.24	g	65.7 % active in Brox-M, 3.2 oz./ac per year
Processes			
Diesel Combustion Emissions	10.696*0.832	kg	10.696 liter/acre a, 0.832 kg/liter

Table. B-40. Inputs to Simapro for winter oilseed (RTF-WO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.08	lb.	Average seed rate 5.0833 lb./acre in 5 years
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	188.02	g	48.8% glyphosate in Round up RT3; average roundup RT3 is 9.6 oz./acre per year.
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	55.63	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied in per year is 1.92 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	$\frac{10.1955 \times 0.83}{2}$	kg	10.1955 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	$\frac{41.16}{112.128} \times 142.04$	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3C-WO CH ₄ & N ₂ O	55	lb.	55 lbs. N per year on average
Dry_land_field_emissions_CO ₂	54.19	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	$176.28 + 250.64 + 105.97$	g	43.2% Paraquat dichloride in Paraquat concentrated(PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 12 oz./acre; Average 5 years Cyclone is 25.6 oz./acre; Average Gram Oxone is 12.8 oz./acre

Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer- 11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.29	g	tactic - 63.4% latex, Average Tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.315*.77	kg	0.315 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.315*.77	kg	0.315 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	1.108	G	Average Unfoamer per year is 0.3 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.33	G	9.6 oz./ac of Glystar plus and 41% of glystar is glyphosate
Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.91	G	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	G	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Processes			
Diesel Combustion Emissions	10.1955×0.832	kg	10.1955 liter/acre; 0.832 kg/liter

Table. B-41. Inputs to Simapro for reduced tillage fallow (RTF-SO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	875.1411+1112.488	g	48.7% glyphosate in 44.8 oz./acre Roundup Powermax; 48.8% glyphosate in 56.8 oz./acre Round up RT3

Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of Gun smoke is pesticide, 1.92 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.788	g	50% active; Affinity broad spec .1 oz./acre
Latex {GLO} market for Alloc Def, S	12.298	g	Tactic 0.64 oz./acre 63.4% latex
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.278	g	Liberate 3.84 oz./acre 100% ethoxylated alcohol
Pesticide, unspecified {GLO} market for Alloc Def, S	4.389	g	Silencer 1.4 oz./acre, 11.4% lambda cyhalothrin
Diesel {RoW} market for Alloc Def, S	7.596*0.832	kg	7.596 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.1+250.6	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	.229 liter/acre and .77 kg/liter
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	.229 liter/acre and .77 kg/liter
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus and it contains 41% of glyphosate and 59% inert
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	g	Average Unfoamer per year 0.36 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.047	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year

Dry land field emissions-3D-RTF CH ₄ & N ₂ O	55	lb.	55 lb. /acre N applied on average per year
Processes			
Diesel Combustion Emissions	7.596*.832	kg	7.596 liter/acre, 0.832 kg/liter

Table. B-42. Inputs to Simapro for spring oilseed (RTF-SO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.406	lb.	Average seed rate 5.406 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	484.45+313.37	g	48.8% glyphosate in Roundup Powermax 48.8% glyphosate in Round up RT3; average round up powemax per year 24.8oz/acre and average roundup RT3 is 16 oz./acre per year.
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	92.73	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied per year is 3.2 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.624*0.832	kg	10.624 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;

Dry_land_field_emissions-3D-SO ₂ CH ₄ & N ₂ O	55	lb.	N per year on average per year
Dry_land_field_emissions_CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in Paraquat concentrated (PC) and 30.1 % paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 22.2 oz./acre; Average Cyclone per year is 25.6 oz./acre; Average Gram Oxone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer-11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic - 63.4% latex, Average Tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.401*.77	kg	0.401 lit/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.401*.77	kg	0.401 lit/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.7	g	Average Unfoamer in per year is 0.46 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and 41% of glystar is glyphosate

Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.91	g	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	g	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Isopropylamine {GLO} market for Alloc Def, S	120.89	g	33.5 % of Isopropyl amine, 10.8 oz./acre Land master
Pesticide, unspecified {GLO} market for Alloc Def, S	7.45	g	10.3% Assure II active ingredients and 2.4 oz./ac is applied
Pesticide, unspecified {GLO} market for Alloc Def, S	5.69	g	22.8% warrior II is active, and .768 oz./ac is applied
Processes			
Diesel Combustion Emissions	10.624*0.832	kg	10.624 liter/acre; 0.832 kg/liter

Table. B-43. Inputs to Simapro for spring wheat (RTF-SO-SW) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Wheat seed, for sowing {GLO} market for Alloc Def, S	117.6	lb.	average seed rate 117.6 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Glyphosate {GLO} market for Alloc Def, S	609.47+313.37	g	48.7% glyphosate in 31.2 oz./acre Roundup Powermax; 48.8% glyphosate in Round up RT3; Round up RT3 16 oz./ac
Pesticide, unspecified {GLO} market for Alloc Def, S	168.54	g	100% active; Vendetta 5 oz./ acre per year

Pesticide, unspecified {GLO} market for Alloc Def, S	1.833	g	50% active; Harmony .1 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	2.146	g	50% active; Affinity broad spec 0.12 oz./acre per year
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.696*0.832	kg	10.696 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	41.16 lb./acre thiosulfate per year, Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions-3D-SW_CH ₄ & N ₂ O	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Dry_land_field_emissions_CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Oxone; Average Gram Oxone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.389	g	Silencer 1.4 oz./acre per year, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.298	g	Tactic 0.64 oz./acre per year and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	35.395	g	35% active pesticide; Average Huskie per year is 3 oz./acre

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	129.82	g	4.48 oz./ac liberate per year (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	2.439	g	Average Unfoamer per year 0.66 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	70.249	g	65.7 % active in Brox-M, 3.2 oz./ac per year
Processes			
Diesel Combustion Emissions	10.696*0.832	kg	10.696 liter/acre a, 0.832 kg/liter

Table. B-44. Inputs to Simapro for reduced tillage fallow (RTF-WO-ST) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	1250.202+1237.839	g	48.7% glyphosate in 64 oz./acre Roundup Powermax 48.8% glyphosate in 63.2 oz./acre Round up RT3
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of Gun smoke is pesticide, 1.92 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.788	g	50% active; Affinity broad spec .1 oz./acre per year
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic 0.64 oz./acre per year; 63.4% latex

Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.2778	g	Liberate 3.84 oz./acre per year; 100% ethoxylated alcohol
Pesticide, unspecified {GLO} market for Alloc Def, S	4.389	g	Silencer 1.4 oz./acre per year, 11.4% lambda cyhalothrin
Diesel {RoW} market for Alloc Def, S	7.739*0.832	kg	7.739 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	.229 liter/acre and .77 kg/liter
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	.229 liter/acre and .77 kg/liter
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and it contains 41% of glyphosate and 59% inert
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	g	Average Unfoamer per year 0.36 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre per year
Dry land field emissions-3E-RTF CH ₄ & N ₂ O	55	lb.	55 lb./ acre N applied on average per year
Processes			

Diesel Combustion Emissions	7.739*.832	kg	7.739 liter/acre, 0.832 kg/liter
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Table. B-45. Inputs to Simapro for spring triticale (RTF-WO-ST) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Rye seed, for sowing {GLO} market for Alloc Def, S	100.6	lb.	average seed rate 100.6 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Glyphosate {GLO} market for Alloc Def, S	609.47+313.37	g	48.7% glyphosate in 31.2 oz./acre Roundup Powermax; 48.8% glyphosate in Round up RT3 ; Round up RT3 16 oz./ac per year
Pesticide, unspecified {GLO} market for Alloc Def, S	168.54	g	100% active; Vendetta 5 oz./ acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.833	g	50% active; Harmony .1 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	2.146	g	50% active; Affinity broad spec 0.12 oz./acre per year
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.481*0.832	kg	10.481 liter/acre, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	41.16 lb./acre thiosulfate per year, Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions-3E-ST_CH ₄ & N ₂ O	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Dry_land_field_emissions_CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.

Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Ozone; Average Gram Ozone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre per year, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic 0.64 oz./acre per year and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	35.39	g	35% active pesticide; Average Huskie per year is 3 oz./acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	129.82	g	4.48 oz./ac liberate per year (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	2.439	g	Average Unfoamer per year 0.66 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	72.368	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	21.385	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	70.249	g	65.7 % active in Brox-M, 3.2 oz./ac in use per year on average
Processes			

Diesel Combustion Emissions	10.481*0.832	kg	10.481 liter/acre a, 0.832 kg/liter
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Table. B-46. Inputs to Simapro for winter oilseed (RTF-WO-ST) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.464	lb.	Average seed rate 5.464 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	188.02	g	48.8% glyphosate in Round up RT3; average roundup RT3 is 9.6 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	55.63	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied in per year is 1.92 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.2815*0.832	kg	10.2815 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3E-WO CH ₄ & N ₂ O	55	lb.	55lbs N per year on average per year
Dry land field emissions CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.

Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	176.28+250.64+105.97	g	43.2% Paraquat dichloride in Paraquat concentrated (PC) and 30.1% paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 12 oz./acre; Average 5 years Cyclone is 25.6 oz./acre; Average Gram Oxone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.389	g	Silencer- 11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.298	g	Tactic - 63.4% latex, Average tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline
Pesticide, unspecified {GLO} market for Alloc Def, S	1.108	g	Average Unfoamer per year 0.3 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and 41% of glystar is glyphosate
Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.91	g	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	g	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Processes			
Diesel Combustion Emissions	10.2815*0.832	kg	10.2815 liter/acre; 0.832 kg/liter

Table. B-47. Inputs to Simapro for reduced tillage fallow (RTF-WT-SO) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Glyphosate {GLO} market for Alloc Def, S	875.14+1237.83	g	48.7% glyphosate in 44.8 oz./acre Roundup Powermax 48.8% glyphosate in 63.2 oz./acre Round up RT3
Pesticide, unspecified {GLO} market for Alloc Def, S	54.27	g	80% of Gun smoke is pesticide, 1.92 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.788	g	50% active; Affinity broad spec .1 oz./acre per year
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic 0.64 oz./acre per year; 63.4% latex
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.277	g	Liberate 3.84 oz./acre 100% ethoxylated alcohol per year
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre, 11.4% lambda cyhalothrin per year
Diesel {RoW} market for Alloc Def, S	7.682*0.832	kg	7.682 liter/acre, 0.832 kg/liter
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1 % paraquat dichloride in 25.6 oz./acre cyclone
Gasoline {RoW} market for Alloc Def, S	0.229*.81	kg	.229 liter/acre and .81 kg/liter
CO ₂ _combustion emissions from Gasoline	0.229*.77	kg	0.77 kg/liter and 0.229 liter/acre

Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and it contains 41% of glyphosate and 59% inert
Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.33	g	Average Unfoamer per year 0.36 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	41.04	g	48.2% active dicamba; average Rifle 2.4 oz./acre
Dry land field emissions-3F-RTF CH ₄ & N ₂ O	55	lb.	55 lb./acre N applied on average per year
Processes			
Diesel Combustion Emissions	7.682*.832	kg	7.682 liter/acre, 0.832 kg/liter

Table. B-48. Inputs to Simapro for spring oilseed (RTF-WT-SO) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Sunflower seed, for sowing {GLO} market for Alloc Def, S	5.406	lb.	Average seed rate 5.406 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre applied every year and on an average of 55 lb. as N per year
Glyphosate {GLO} market for Alloc Def, S	484.45+72.36	g	48.7% glyphosate in Roundup Powermax 48.8% glyphosate in Round up RT3; average round up powemax per year 24.8oz/acre and average roundup RT3 is 16 oz. /acre per year.

Pesticide, unspecified {GLO} market for Alloc Def, S	72.36	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 2.56 oz./ acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	92.73	g	Liberate - 100% ethoxylated alcohol; Average Liberate applied in 5years is 3.2 oz./ acre
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.624*0.832	kg	10.624 liter/acre; 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	Average of 41.16 lb./acre thiosulfate per year; Thiosulfate Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry land field emissions-3F-SO ₂ CH ₄ & N ₂ O	55	lb.	55lbs N per year on average per year
Dry land field emissions CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.
Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in Paraquat concentrated(PC) and 30.1% paraquat dichloride in cyclone and 25% Paraquat dichloride in Gram Oxone; Average PC per year is 22.2 oz./acre; Average Cyclone per year is 25.6 oz./acre; Average Gram Oxone is 12.8 Oz/acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.389	g	Silencer-11.4% is pesticide; Average Silencer per year is 1.4 oz./acre
Latex {GLO} market for Alloc Def, S	12.298	g	Tactic - 63.4% latex, Average Tactic per year is 0.64 oz./acre
Gasoline {RoW} market for Alloc Def, S	0.401*.77	kg	0.401 liter/acre avgas, 0.77 density of Gasoline
CO ₂ combustion emissions from Gasoline	0.401*.77	kg	0.401 liter/acre avgas, 0.77 density of Gasoline

Pesticide, unspecified {GLO} market for Alloc Def, S	21.38	g	50% of choice is active pesticide; average choice per year is 1.28 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.7	g	Average Unfoamer per year 0.46 oz./acre; Unfoamer- 12.5% active pesticide
Glyphosate {GLO} market for Alloc Def, S	137.33	g	9.6 oz./ac of Glystar plus per year and 41% of glystar is glyphosate
Ethoxylated alcohol (AE11) {GLO} market for Alloc Def, S	4.916	g	8.15% active ethoxylated alcohol in Wetcit; 2 oz./ac applied on average per year
Pesticide, unspecified {GLO} market for Alloc Def, S	11.39	g	22.8% active in Warrior II (Lambda-CY); 1.536 oz./ac applied on average per year
Isopropylamine {GLO} market for Alloc Def, S	120.89	g	33.5 % of Isopropyl amine, 10.8 oz./acre Land master per year
Pesticide, unspecified {GLO} market for Alloc Def, S	7.455	g	10.3% Assure II active ingredients and 2.4 oz./ac is applied per year
Pesticide, unspecified {GLO} market for Alloc Def, S	5.695	g	22.8% warrior II is active, and .768 oz./ac is applied per year
Processes			
Diesel Combustion Emissions	10.624*0.832	kg	10.624 liter/acre; 0.832 kg/liter

Table. B-49. Inputs to Simapro for winter triticale (RTF-WT-SO) based on per acre

Materials/Assemblies	Calculation	Units	Remarks
Rye seed, for sowing {GLO} market for Alloc Def, S	115.5	lb.	average seed rate 115.5 lb./acre per year
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Glyphosate {GLO} market for Alloc Def, S	500.08	g	48.7% glyphosate in 25.6 oz./acre Roundup Powermax per year;
Pesticide, unspecified {GLO} market for Alloc Def, S	215.74	g	100% active; Vendetta 6.4 oz./ acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.833	g	50% active; Harmony .1 oz./acre per year
Pesticide, unspecified {GLO} market for Alloc Def, S	1.788	g	Affinity broad spec 0.1 oz./acre per year; 50% active
Diesel, low-sulfur {RoW} market for Alloc Def, S	10.481*0.832	kg	10.481 liter/acre a, 0.832 kg/liter
Sodium sulfate, anhydrite {RER} market for Alloc Def, S	41.16/112.128*142.04	lb.	41.16 lb./acre thiosulfate on average per year, Mol. wt. - 112.1282; Mol. wt. sodium sulfate- 142.04;
Dry_land_field_emissions-3F-WT_CH ₄ & N ₂ O	55	lb.	79% UAN of 196 lb./acre every year and 55 as N per year
Dry_land_field_emissions_CO ₂	54.194	lb.	54.194 lbs. of urea/acre; 196 lbs. /acre of fertilizer; 71% UAN=154.84 lbs.; 35% Urea by weight=54.194 lbs.

Pesticide, unspecified {GLO} dichloropropene to generic market for Alloc Def, S	326.12+250.64+105.97	g	43.2% Paraquat dichloride in 22.2 oz./acre Paraquat concentrated and 30.1% paraquat dichloride in 25.6 oz./acre cyclone; 25% Paraquat dichloride in Gram Ozone; Average Gram Ozone is 12.8 oz./acre
Pesticide, unspecified {GLO} market for Alloc Def, S	4.38	g	Silencer 1.4 oz./acre per year, 11.4% main ingredients
Latex {GLO} market for Alloc Def, S	12.29	g	Tactic 0.64 oz./acre per year and 63.4% latex,
Gasoline {RoW} market for Alloc Def, S	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
CO ₂ combustion emissions from Gasoline	0.229*.77	kg	0.229 liter/acre avgas, 0.77 density of Gasoline,
Pesticide, unspecified {GLO} market for Alloc Def, S	66.07	g	35% active pesticide; Average Huskie per year is 5.6 oz./acre
Ethoxylated alcohol (AE3) {GLO} market for Alloc Def, S	111.277	g	3.84 oz./ac liberate per year (100% ethoxylated alcohol)
Pesticide, unspecified {GLO} market for Alloc Def, S	1.995	g	Average Unfoamer per year is 0.54 oz./acre; Unfoamer- 12.5% active pesticide
Pesticide, unspecified {GLO} market for Alloc Def, S	54.276	g	80% of gun smoke is Pesticide; Average Gun smoke applied per year is 1.92 oz./ acre
Pesticide, unspecified {GLO} market for Alloc Def, S	1.1689	g	0.95 oz./ac Osprey per year; 4.5% Meso-sulfuron
Pesticide, unspecified {GLO} market for Alloc Def, S	16.6	g	Fitness - 45% propiconazole per year; Average Fitness applied per year is 1.2 oz./ acre
Nitrogen fertiliser, as N {RER} urea ammonium nitrate production Alloc Def, S	0.256	lb.	Average solution 32 per year 12.8 oz./acre; 1.28 lb./64 oz.; 0.256 lb./acre UAN

Processes			
Diesel Combustion Emissions	10.481*0.832	kg	10.481 liter/acre a, 0.832 kg/liter

B.2.2 Eco profiles for field emissions in SimaPro

This section gives the information on different ecoprofiles created in SimaPro for the field emissions per lb N applies and combustion emissions. A detailed description of calculations of allocation factors for mass, market and energy are tabulated.

Table. B-50. Dry land field emissions CH₄-SF-WW (1 lb. N applied)

Methane	-0.829/55	kg	Undefined	Emissions from WW using EF of -0.829 kg CH ₄ /acre/year; Total N 55 lbs.
Methane	-0.641/55	kg	Undefined	Emissions from SF using EF of -0.641 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-51. Dry land field emissions N₂O- SF-WW (1 lb. N applied)

Dinitrogen monoxide	0.11/55	kg		Emissions from WW using EF of 0.110 kg N ₂ O/acre/year; Total N 55 lbs.
Dinitrogen monoxide	0.2/55	kg		Emissions from SF using EF of 0.2 kg N ₂ O/acre/year; Total N 55 lbs.

Table. B-52. Dry land field emissions CH₄- RTF-WW (1 lb. N applied)

Methane	-0.625/55	kg		Emissions from WW using EF of -0.625 kg CH ₄ /acre/year; Total N 55 lbs.
Methane	-0.641/55	kg		Emissions from RTF using EF of -0.641 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-53. Dry land field emissions N₂O- RTF-WW (1 lb. N applied)

Dinitrogen monoxide	0.258/55	Kg		Emissions from WW using EF of 0.258 kg N ₂ O/acre/year; Total N 55 lbs.
Dinitrogen monoxide	0.368/55	Kg		Emissions from RTF using EF of 0.368 kg N ₂ O/acre/year; Total N 55 lbs.

Table. B-54. Dry land field emissions CH₄- RTF-WW -WO-RTF (1 lb. N applied)

Methane	-0.779/55	Kg		Emissions from WW using EF of -0.779 kg CH ₄ /acre/year; Total N 55 lbs.
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Methane	-0.641/55	Kg	Emissions from RTF using EF of -0.641 kg CH ₄ /acre/year; Total N 55 lbs.
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Table. B-55. Dry land field emissions N₂O- RTF-WW -WO-RTF (1 lb. N applied)

Dinitrogen monoxide	0.301/55	Kg	Emissions from WW using EF of 0.301 kg N ₂ O/acre/year; Total N 55 lbs.
Dinitrogen monoxide	0.368/55	Kg	Emissions from RTF using EF of 0.368 kg N ₂ O/acre/year; Total N 55 lbs.

Table. B-56. Dry land field emissions CH₄- RTF-WO -WW-RTF (1 lb. N applied)

Methane	-0.779/55	Kg	Emissions from WO using EF of -0.640 kg CH ₄ /acre/year; Total N 55 lbs.
Methane	-0.514/55	Kg	Emissions from RTF using EF of -0.742 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-57. Dry land field emissions N₂O- RTF-WO- WW-RTF (1 lb. N applied)

Dinitrogen monoxide	0.206/55	kg	Emissions from WO using EF of 0.206 kg N ₂ O/acre/year; Total N 55 lbs.
Dinitrogen monoxide	0.159/55	kg	Emissions from RTF using EF of 0.159 kg N ₂ O/acre/year; Total N 55 lbs.

Table. B-58. Dry land field emissions-RTF (RTF-WW-SB) _CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.237/55	kg	Emissions from RTF using EF of 0.237 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.691/55	kg	Emissions from RTF using EF of -0.691 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-59. Dry land field emissions-SB (RTF-WW-SB) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.303/55	kg	Emissions from RTF using EF of 0.303 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.438/55	kg	Emissions from RTF using EF of -0.438 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-60. Dry_land_field_emissions--WW (RTF-WW-SB) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.172/55	kg	Emissions from RTF using EF of 0.172 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	- 0.705/55	kg	Emissions from RTF using EF of -0.705 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-61. Dry_land_field_emissions-SO (RTF-WW-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.323/55	kg	Emissions from RTF using EF of 0.323 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.542/55	kg	Emissions from RTF using EF of -0.542 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-62. Dry_land_field_emissions--WW (RTF-WW-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.209/55	kg	Emissions from RTF using EF of 0.209 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.684/55	kg	Emissions from RTF using EF of -0.684 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-63.Dry_land_field_emissions--RTF (RTF-WW-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.268/55	kg	Emissions from RTF using EF of 0.268 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	- 0.616/55	kg	Emissions from RTF using EF of -0.616 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-64. Dry_land_field_emissions--RTF (RTF-WO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.159/55	kg	Emissions from RTF using EF of 0.159 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.640/55	kg	Emissions from RTF using EF of -0.640 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-65. Dry_land_field_emissions--SW (RTF-WO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.303/55	kg	Emissions from RTF using EF of 0.303 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	- 0.438/55	kg	Emissions from RTF using EF of -0.438 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-66. Dry_land_field_emissions--WO (RTF-WO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.206/55	kg	Emissions from RTF using EF of 0.206 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.640/55	kg	Emissions from RTF using EF of -0.640 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-67. Dry_land_field_emissions-3D-RTF (RTF-SO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.368/55	kg	Emissions from RTF using EF of 0.368 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.514/55	kg	Emissions from RTF using EF of -0.514 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-68. Dry_land_field_emissions--SO (RTF-SO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.206/55	kg	Emissions from RTF using EF of 0.206 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.533/55	kg	Emissions from RTF using EF of -0.533 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-69. Dry_land_field_emissions--SW (RTF-SO-SW) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.303/55	kg	Emissions from RTF using EF of 0.303 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.438/55	kg	Emissions from RTF using EF of -0.438 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-70. Dry_land_field_emissions--RTF (RTF-WO-ST) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.2/55	kg	Emissions from RTF using EF of 0.200 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.641/55	kg	Emissions from RTF using EF of -0.641 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-71. Dry_land_field_emissions--ST (RTF-WO-ST) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.303/55	kg	Emissions from RTF using EF of 0.303 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.438/55	kg	Emissions from RTF using EF of -0.438 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-72. Dry_land_field_emissions--WO (RTF-WO-ST) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.274/55	kg	Emissions from RTF using EF of 0.274 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.721/55	kg	Emissions from RTF using EF of -0.721 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-73. Dry_land_field_emissions-RTF (RTF-WT-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.268/55	kg	Emissions from RTF using EF of 0.268 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.616/55	kg	Emissions from RTF using EF of -0.616 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-74. Dry_land_field_emissions--SO (RTF-WT-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.474/55	kg	Emissions from RTF using EF of 0.474 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.485/55	kg	Emissions from RTF using EF of -0.485 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-75. Dry_land_field_emissions--WT (RTF-WT-SO) CH₄ & N₂O (1 lb. N applied)

Dinitrogen monoxide	0.172/55	kg	Emissions from RTF using EF of 0.172 kg N ₂ O/acre/year; Total N 55 lbs.
Methane	-0.705/55	kg	Emissions from RTF using EF of -0.705 kg CH ₄ /acre/year; Total N 55 lbs.

Table. B-76. Dry land field emissions CO₂ (1 kg Urea)

Carbon dioxide	0.1998*44/12	kg	0.1998 kg C/kg Urea;44/12=3.6667 kg CO ₂ /kg C;0.733 kg CO ₂ /kg Urea;
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Table. B-77. Gasoline combustion emissions (1 kg gasoline)

Carbon dioxide	(8.31/3.78541)/.77	Kg	3.78541 lit/gallon; 8.31 kg CO ₂ / gallon [1]; 0.77 kg/li density [2]
Methane	(.00047/3.78541)/.77	Kg	.47 g CH ₄ / gallon gasoline [1]
Dinitrogen monoxide	(0.00009/3.78541)/.77	Kg	.09 g N ₂ O / gallon gasoline [1]

Table. B-78. Diesel combustion emissions (1 kg diesel)

Carbon dioxide	(10.21/3.78541)/.8321	Kg	3.78541 lit/gallon;10.21 kg CO ₂ / gallon [1]; 0.8321 kg/lit density [3]
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B.3 GHG emissions of 3-year and 2-year crop rotations

B.3.1 Gives information on market value allocation (MVA) of different 2-yr and 3-yr cropping systems:

Figures B-1, B-2, and B-3 show emission intensity results similar to Figures 3-5 in the main manuscript except for using MVA for the 3-yr rotations. Greenhouse gas emissions increase slightly for WW in RTF-WW-SB because the market value of SB is much less than that of WW so most of emissions from RTF are allocated to WW (Figure B-1).

Emissions from wheat in the RTF-WW-SO, RTF-WO-SW, and RTF-SO-SW rotations are decreased when expressed on a mass allocation basis because the unit price for the oilseed crop is double that for the wheat crop, making the allocation less to wheat and decreases emission intensity. Among all wheat crops, RTF-WW-SB stands out to be the lowest in GHG emissions with 0.30 kg CO₂ eq./kg grain whereas RTF-SO-SW is highest with 1.02 kg CO₂ eq./kg grain. The least emissions of RTF-WW-SB is because of high yield and lower input load of winter wheat, which over weights the unit value allocation due to low yield of SB compared to WW.

Figure. B-1. Greenhouse gas emissions of winter wheat (WW) and spring wheat (SW) in different crop rotations based on market value allocation.

Greenhouse gas emissions increase for all the rotations compared to mass allocation, due to high percentage distribution of RTF based on higher oilseed prices compared to other food crops (Figure B-2). Among all rotations, winter oilseed in RTF-WO-SW has the least emissions with 0.77 kg CO₂ eq./kg oilseed and spring oilseed in RTF-WT-SO has the highest emissions with 1.90 kg CO₂ eq./kg oilseed.

Figure. B-2. Greenhouse gas emissions of different oilseed crop rotation based on market value allocation.

Emissions are lower with market value allocation compared to mass allocation for spring barley, spring triticale, and winter triticale due to their low yields and allocation for winter wheat in RTF-WW-SB dominated by price because of high yield and less allocation to spring barley, thereby decreasing its emissions compared to mass allocation (Figure B-3). Similarly, for other crops with relatively low yields, the oilseed price dominates the triticale price and RTF is allocated less to triticale which leads to lower emissions. The least emissions out of all other crops is from spring barley in RTF-WW-SB with 0.79 kg CO₂ eq./kg barley and highest emissions are from spring triticale in RTF-WO-ST with 1.79 kg CO₂ eq./kg triticale.

Figure. B-3. Greenhouse gas emissions of spring barley (SB), spring triticale (ST), and winter triticale (WT) in other crop rotations based on market value allocation.

B.4 References

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C Supporting Information for Chapter 4

Synergistic Effects Between Hydrolysis Time and Microporous Structure in Poplar

C.1 Cryoporometry Materials and Methods:

The NMR Cryoporometry measurements were performed on a purpose-built NMR Scanning Cryoporometer with 25 years of development and optimization, at the Lab-Tools NMR Laboratory in Kent. This Mk2b Lab-Tools NMR Cryoporometer is now mainly digital and is based on 3 credit-card sized modules, Figure C-1: The RF hardware for the Lab-Tools NMR Cryoporometer v2b employs: A Red Pitaya STEMLab 125-14 Linux computer (Dual Core ARM CORTEX A9) with tightly coupled Field Programmable Gate Array (FPGA Xilinx Zynq 7010 SOC) module. Plugged into it is a Lab-Tools Mk2 NMR Low-Noise Pre-Amplifier module. The NMR probe is connected to the Lab-Tools Mk1 NMR Linear Amplifier Transmitter module,¹ and joining these items is a probe tuning box with variable capacitor. The thermally insulated tubes carrying the cooling water for the Peltier units can also be seen, as can the thermocouples that monitor the sample and probe temperatures.

Figure. C-1. NMR Cryoporometer – v2b NMR RF hardware, which has recently been developed by Lab-Tools.

Originating in 1993, NMR Cryoporometry (NMRC) is now an important method for determining pore sizes and volumes in porous media.² Josiah Willard Gibbs and three different Thomsons applied thermodynamics, generalized dynamics and experiments to produce an equation that well describes the phase-change behavior of liquids in confined geometry. A development of the Gibbs-Thomson equation has been discussed that relates these phase changes so that the pore area a_p and volume v_p are related to the melting point depression.³

For many purposes this may be simplified so that the pore diameter x is related to a melting point depression $[K] = \Delta T_m = k_{GT} / x$, where we are grouping all the thermodynamic terms into a single constant, k_{GT} $[K \cdot \text{\AA}]$ the Gibbs-Thomson coefficient usually established by experiment. It is important to note that k_{GT} includes a term dependent on pore geometry, however for these biomass samples the conventional “4” can be expected to apply for the geometric term. In Figure C-2, the Gibbs-Thomson Coefficients k_{GT} are calculated from the slopes of the plotted lines of melting point depression vs inverse nominal pore diameter.⁴ The Sol-Gel case of pore geometry being spherical/oblate/prolate is expected to apply to these biomass samples, as opposed to the linear cylinder pores typical of templated pores as in SBA-15 or MCM-41, for which a different geometric term applies.^{4,5}

Figure. C-2. Melting point depressions, for different pore geometries: Sol-Gel (spherical), SBA-15 (hexagonal) and MCM-41 (hexagonal), plotted against inverse pore diameter, as determined by gas adsorption.⁴

The Figure C-3 shows the Software and firmware control for the NMR Cryoporometer, which is provided by multi-tasking AplX programs, running on a Windows 10 PC, a Windows 7 PC and the Red Pitaya Linux core. Data is transferred between these 3 computers over an Ethernet LAN network. USB is also used to program, control and read a Lab-Tools 24-bit 5 channel precision FPGA based DVM, to acquire and average the thermocouple microvolt signals. The left screen shows the AplX Graphical User Interface (GUI) controlling the firmware in the Red Pitaya, generating the RF pulses, and capturing, averaging and peak-fitting the NMR echo. The middle screen shows a set of 10 multi-tasking AplX programs that comprise the core of the NMR cryoporometer. The right screen shows the GUI capturing and averaging the thermocouple signals, and plots temperature and amplitude graphs that monitor the progress of the cryoporometric run.

Figure. C-3. The 3 screens show the multitasking and cooperating ApIX programs generating and controlling Graphical User Interfaces (GUIs) controlling the firmware in the red pitaya and the ApIX software in the 2 windows PCs, and generating the output graphs and di

The Figure C-4 shows the NMR RF pulses. Ch1: RF pulse output by Red Pitaya and input to NMR Linear Amplifier. Ch2: RF Pulse across NMR Probe, as monitored at a 1/100 attenuator followed by 1/10 Scope Probe. The slightly ragged shape is due to aliasing between the 20.7 MHz RF pulse and the Tektronix oscilloscope sampling. Ch4: Transmitter Enable pulse generated by the Red Pitaya. This section shows the calibration curves used for determining the Concentrations of glucose, xylose and furfural using HPLC.

Figure. C-4. Ch1: RF pulse output by red pitaya and input to NMR linear amplifier. Ch2: RF pulse across NMR probe, as monitored at a 1/100 attenuator followed by 1/10 Scope Probe. Ch4: transmitter enable pulse generated by the red pitaya.

Table. C-1. Weights of the severity pretreatment and enzyme hydrolysis poplar biomass samples after wetting (in grams)

Pretreatment (Min) Hydrolysis (Hours)	Tube	Tube + Wet Poplar	Tube+ Wet Poplar+Water	Wet Poplar	Water
8 Min 0 Hours	0.441	0.452	0.479	0.011	0.027
8 Min 4 Hours	0.417	0.425	0.461	0.008	0.036
8 Min 24 Hours	0.431	0.439	0.472	0.008	0.032
13 Min 0 Hours	0.455	0.463	0.493	0.008	0.031
13 Min 24 Hours	0.450	0.459	0.490	0.009	0.031
15 Min 0 Hours	0.445	0.454	0.483	0.009	0.029
15 Min 4 Hours	0.432	0.440	0.465	0.007	0.026
15 Min 24 Hours	0.446	0.454	0.493	0.008	0.039
21 Min 0 Hours	0.455	0.466	0.503	0.011	0.037
21 Min 4 Hours	0.447	0.455	0.491	0.008	0.036
21 Min 24 Hours	0.460	0.469	0.510	0.010	0.041
40 Min 0 Hours	0.432	0.442	0.481	0.010	0.040
40 Min 4 Hours	0.432	0.442	0.478	0.010	0.036
40 Min 24 Hours	0.428	0.445	0.465	0.016	0.020

C.2 HPLC standards calibration figures:

Figures from C-5 to C-7 shows the calibration graphs for glucose, xylose and furfural respectively.

Figure. C-5. HPLC glucose calibration standards

Figure. C-6. HPLC xylose calibration standards

Figure. C-7. HPLC furfural calibration standards

C.3 Compositional Analysis Method for Pretreated Biomass⁶:

20 mg of dried pretreated biomass samples (8, 13, 15, 21, 40 mins) were weighed and transferred into hungate vials. Then a 0.2 mL of 72% (w/w) concentrated sulfuric acid was added to each hungate vial. The samples were then incubated for 1 hour at room temperature, vortexing every 15 minutes for 10 seconds. At the end, 5.6 mL deionized water was added in each vial, and the vials were vortexed for 10 seconds. The sugar recovery standards (SRS) were prepared in hungate vials containing 20 mg glucose in 5.6 mL of deionized water and 0.2 mL of 72% (w/w) diluted sulfuric acid. Both the sample and SRS vials were vortexed for 10 seconds and autoclaved for 60 minutes at 121 °C. After 60 minutes, the vials were taken out and let cooled to room temperature. After cooling, the samples were refrigerated overnight, and a supernatant was filtered using 0.2 micron nitrocellulose filter and analyzed by HPLC.

C.3.1 Composition Analysis Calculations:

Peak areas for glucose, xylose, arabinose, cellobiose, galactose, and mannose were measured for pretreated DN34 hybrid poplar samples (8, 13, 15, 21, 40 mins) using HPLC. The peak areas were then converted to concentrations by using calibration standards. The concentrations were multiplied by the volume (10 mL used for EH experiments) to obtain the mass of each component. The mass of glucose and cellobiose were added up as glucan, and xylose, galactose, mannose as xylan. These parameters were then divided by their respective conversion factors (0.9 and 0.88) accounting for the effect of hydrolysis of water. Finally, the converted mass was divided by the initial mass of biomass (20 mg) to get the percent composition.

Table. C-2. Peak area of sugars in pretreated DN34 hybrid poplar samples

DAP time	Glucose	Xylose	Mannose	Cellobiose	Galactose	Arabinose
8 min 1	2.78E+05	3.21E+04	2.03E+04	0.00E+00	3.08E+03	0.00E+00
8 min 2	2.75E+05	3.14E+04	1.77E+04	5.19E+01	2.71E+03	0.00E+00
13 min 1	2.97E+05	1.53E+04	1.47E+04	8.47E+01	4.22E+03	0.00E+00
13 min 2	2.89E+05	1.47E+04	1.32E+04	1.98E+03	5.02E+03	0.00E+00
15 min 1	2.80E+05	1.17E+04	1.49E+04	1.91E+03	4.67E+03	0.00E+00
15 min 2	3.04E+05	1.29E+04	1.18E+04	5.55E+03	4.73E+03	1.65E+03
21 min 1	3.18E+05	1.37E+04	1.55E+04	2.00E+03	4.33E+03	1.28E+03
21 min 2	3.13E+05	1.39E+04	1.01E+04	1.92E+03	3.96E+03	0.00E+00
40 min 1	3.30E+05	8.58E+03	5.81E+03	3.03E+03	8.62E+03	1.39E+03
40 min 2	3.13E+05	7.77E+03	7.51E+03	1.12E+04	3.25E+03	0.00E+00

Table. C-3. Concentration (g/L) of sugars in pretreated DN34 hybrid poplar samples

Concentration, g/L						
DAP time	[Glucose]	[Xylose]	[Mannose]	[Cellobiose]	[Arabinose]	[Galactose]
8 min 1	1.82E+00	2.67E-01	1.35E-01	0.00E+00	0.00E+00	2.16E-02
8 min 2	1.81E+00	2.61E-01	1.17E-01	3.41E-04	0.00E+00	1.89E-02

13 min 1	1.95E+0 0	1.28E-01	9.72E-02	5.57E-04	0.00E+00	2.95E-02
13 min 2	1.90E+0 0	1.22E-01	8.75E-02	1.30E-02	0.00E+00	3.52E-02
15 min 1	1.84E+0 0	9.71E-02	9.85E-02	1.26E-02	0.00E+00	3.27E-02
15 min 2	2.00E+0 0	1.08E-01	7.84E-02	3.64E-02	1.11E-02	3.31E-02
21 min 1	2.09E+0 0	1.14E-01	1.02E-01	1.31E-02	8.67E-03	3.03E-02
21 min 2	2.05E+0 0	1.15E-01	6.66E-02	1.26E-02	0.00E+00	2.77E-02
40 min 1	2.17E+0 0	7.14E-02	3.85E-02	1.99E-02	9.38E-03	6.03E-02
40 min 2	2.05E+0 0	6.47E-02	4.97E-02	7.35E-02	0.00E+00	2.28E-02

Table. C-4. Mass (g) of sugars in pretreated DN34 hybrid poplar samples

Mass, g						
[Glucose]	[Xylose]	[Mannose]	[Cellobiose]	[Arabinose]	[Galactose]	Total
1.06E-02	1.55E-03	7.80E-04	0.00E+00	0.00E+00	1.30E-04	1.30E-02
1.05E-02	1.51E-03	6.80E-04	0.00E+00	0.00E+00	1.10E-04	1.28E-02
1.13E-02	7.40E-04	5.60E-04	0.00E+00	0.00E+00	1.70E-04	1.28E-02
1.10E-02	7.10E-04	5.10E-04	8.00E-05	0.00E+00	2.00E-04	1.25E-02
1.07E-02	5.60E-04	5.70E-04	7.00E-05	0.00E+00	1.90E-04	1.21E-02

1.16E-02	6.20E-04	4.50E-04	2.10E-04	6.00E-05	1.90E-04	1.31E-02
1.21E-02	6.60E-04	5.90E-04	8.00E-05	5.00E-05	1.80E-04	1.37E-02
1.19E-02	6.70E-04	3.90E-04	7.00E-05	0.00E+00	1.60E-04	1.32E-02
1.26E-02	4.10E-04	2.20E-04	1.20E-04	5.00E-05	3.50E-04	1.37E-02
1.19E-02	3.80E-04	2.90E-04	4.30E-04	0.00E+00	1.30E-04	1.31E-02

Table. C-5. Mass of xylan (xylose, galactose, mannose), glucan (glucose, cellobiose), and arabinan (arabinose) in pretreated DN34 hybrid poplar samples

	Not accounting hydrolysis of water			Accounting hydrolysis of water		
DAP time	Xylan	Glucan	Arabinan	Xylan	Glucan	Arabinan
8 min 1	2.46E-03	1.06E-02	0.00E+00	2.79E-03	1.17E-02	0.00E+00
8 min 2	2.30E-03	1.05E-02	0.00E+00	2.62E-03	1.17E-02	0.00E+00
13 min 1	1.48E-03	1.13E-02	0.00E+00	1.68E-03	1.26E-02	0.00E+00
13 min 2	1.42E-03	1.11E-02	0.00E+00	1.61E-03	1.23E-02	0.00E+00
15 min 1	1.32E-03	1.07E-02	0.00E+00	1.50E-03	1.19E-02	0.00E+00
15 min 2	1.27E-03	1.18E-02	6.00E-05	1.44E-03	1.31E-02	7.30E-05
21 min 1	1.43E-03	1.22E-02	5.00E-05	1.63E-03	1.35E-02	5.70E-05
21 min 2	1.22E-03	1.20E-02	0.00E+00	1.38E-03	1.33E-02	0.00E+00
40 min 1	9.90E-04	1.27E-02	5.00E-05	1.12E-03	1.41E-02	6.20E-05
40 min 2	8.00E-04	1.23E-02	0.00E+00	9.04E-04	1.37E-02	0.00E+00

Table. C-6. Percent composition of xylan and glucan in pretreated DN34 hybrid poplar samples

DAP time	Composition %			
	Xylan	Glucan	Average Glucan	Average Xylan
8 min 1	14.0%	58.7%	58.5%	13.5%
8 min 2	13.1%	58.3%		
13 min 1	8.4%	63.0%	62.3%	8.2%
13 min 2	8.1%	61.5%		
15 min 1	7.5%	59.6%	62.6%	7.4%
15 min 2	7.2%	65.5%		
21 min 1	8.1%	67.7%	67.1%	7.5%
21 min 2	6.9%	66.6%		
40 min 1	5.6%	70.4%	69.5%	5.1%
40 min 2	4.5%	68.6%		

C.4 Calculations of % yields for dilute acid pretreated and enzyme hydrolyzed DN34 Hybrid Poplar:

C.4.1 Dilute Acid Pretreatment % Yield (Glucan, Xylan) Calculations:

Table. C-7. Compositions by weight of DN34 hybrid poplar samples before dilute acid pretreatment (in 0.5 g dry biomass)⁷

Component	Mass (g)
Cellulose	0.22
Hemicellulose	0.10
Lignin	0.14
Inerts	0.05

Table. C-8. Concentrations of DN34 hybrid poplar samples after dilute acid pretreatment

Concentration (g/L) (average of triplicates)				Error Bars (standard deviations)		
Time (Min)	Glucose	Xylose	Furfural	Glucose	Xylose	Furfural
8	2.355	8.102	0.033	0.148	0.999	0.002
13	3.160	17.251	0.318	0.117	0.589	0.015
15	3.268	18.141	0.504	0.147	0.546	0.003
21	3.395	19.080	0.811	0.129	0.450	0.055
40	4.006	15.573	2.404	0.177	0.431	0.139

Table. C-9. Mass of sugars in pretreated DN34 hybrid poplar samples

Mass after DAP (g)				Error Bars		
Time	Glucose	Xylose	Furfural	Glucose	Xylose	Furfural
8	1.06E-02	3.65E-02	1.47E-04	6.66E-04	4.50E-03	9.00E-06
13	1.42E-02	7.76E-02	1.43E-03	5.27E-04	2.65E-03	6.75E-05
15	1.47E-02	8.16E-02	2.27E-03	6.62E-04	2.46E-03	1.35E-05
21	1.53E-02	8.59E-02	3.65E-03	5.81E-04	2.03E-03	2.48E-04
40	1.80E-02	7.01E-02	1.08E-02	7.97E-04	1.94E-03	6.26E-04

Table. C-10. Mass of glucan and xylan in pretreated DN34 hybrid poplar samples (accounting the effect of hydrolysis of water)

	Mass (g) After DAP (Accounting Hydrolysis of Water)		Error Bars	
DAP Time (Min)	Glucan	Xylan	Glucan	Xylan
8	9.54E-03	3.23E-02	5.99E-04	3.96E-03
13	1.28E-02	7.03E-02	4.74E-04	2.33E-03

15	1.32E-02	7.50E-02	5.95E-04	2.16E-03
21	1.38E-02	8.06E-02	5.22E-04	1.78E-03
40	1.62E-02	7.66E-02	7.17E-04	1.71E-03

Table. C-11. Percent yield of xylan and glucan with respect to hemicellulose and cellulose in dried DN34 hybrid poplar samples

	Yield (%)		Error Bars	
DAP Time (Min)	Glucan	Xylan	Glucan	Xylan
8	4.37	33.03	0.27	4.06
13	5.86	71.90	0.22	2.48
15	6.06	76.69	0.27	2.23
21	6.30	82.44	0.24	2.17
40	7.43	78.31	0.33	2.63

C.4.2 Enzymatic Hydrolysis % Yield of Glucan Calculations:

Table. C-12. Carbohydrate composition of pretreated DN34 hybrid poplar samples

Time (Hr)	Weight fractions of Cellulose in 0.25 g of Pretreated biomass
8	0.044
13	0.047
15	0.047
21	0.050
40	0.052

Table. C-13. Formulae used for calculating the % yields of glucan

Mass of Glucose After EH	Mass of Glucan After EH	Glucan Yield (%)
Conc. of Glucose* Volume used in EH/1000	Mass of Glucose* (180.156-18)/180.156	Mass of Glucan*100/Mass of Dried Cellulose

Table. C-14. Percent glucan yield with respect to cellulose in 8 Min pretreated DN34 hybrid poplar samples

8 min of DAP (Average values) subjected to EH (time)					
Time (Hr)	Glucose Concentration (g/L)	Mass of Glucose (g)	Mass of Glucan (g)	Glucan Yield (%)	Error bars (%)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.5	1.46E-01	1.46E-03	1.32E-03	3.00E+00	3.11E-01
1	2.76E-01	2.76E-03	2.49E-03	5.67E+00	4.40E-01
2	4.50E-01	4.50E-03	4.05E-03	9.23E+00	1.55E-02
4	7.58E-01	7.58E-03	6.83E-03	1.55E+01	5.27E-01
24	1.80E+00	1.80E-02	1.62E-02	3.69E+01	5.07E-01

Table. C-15. Percent glucan yield with respect to cellulose in 13 min pretreated DN34 hybrid poplar samples

13 min of DAP (Average values) subjected to EH (time)					
Time (Hr)	Glucose Concentration (g/L)	Mass of Glucose (g)	Mass of Glucan (g)	Glucan Yield (%)	Error bars (%)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.5	2.45E-01	2.45E-03	2.21E-03	4.73E+00	3.34E-01
1	5.86E-01	5.86E-03	5.27E-03	1.13E+01	6.48E-01
2	9.39E-01	9.39E-03	8.45E-03	1.81E+01	1.28E-01
4	1.58E+00	1.58E-02	1.42E-02	3.05E+01	1.08E+00

24	3.97E+00	3.97E-02	3.57E-02	7.65E+01	8.20E+00
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Table. C-16. Percent glucan yield with respect to cellulose in 15 min pretreated DN34 hybrid poplar samples

15 min of DAP (Average values) subjected to EH (time)					
Time (Hr)	Glucose Concentration (g/L)	Mass of Glucose (g)	Mass of Glucan (g)	Glucan Yield (%)	Error bars (%)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.5	4.18E-01	4.18E-03	3.76E-03	8.02E+00	8.93E-01
1	4.79E-01	4.79E-03	4.31E-03	9.19E+00	0.00E+00
2	8.94E-01	8.94E-03	8.04E-03	1.71E+01	3.27E-01
4	1.49E+00	1.49E-02	1.34E-02	2.87E+01	3.13E-01
24	3.96E+00	3.96E-02	3.56E-02	7.59E+01	3.45E+00

Table. C-17. Percent glucan yield with respect to cellulose in 21 min pretreated DN34 hybrid poplar samples

21 min of DAP (Average values) subjected to EH (time)					
Time (Hr)	Glucose Concentration (g/L)	Mass of Glucose (g)	Mass of Glucan (g)	Glucan Yield (%)	Error bars (%)
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.5	4.06E-01	4.06E-03	3.65E-03	7.25E+00	2.71E+00
1	8.44E-01	8.44E-03	7.60E-03	1.51E+01	5.25E+00
2	1.08E+00	1.08E-02	9.68E-03	1.92E+01	5.68E-01
4	1.74E+00	1.74E-02	1.57E-02	3.11E+01	5.93E-01
24	4.47E+00	4.47E-02	4.03E-02	8.00E+01	6.85E-01

Table. C-18. Percent glucan yield with respect to cellulose in 40 min pretreated DN34 hybrid poplar samples

40 min of DAP (Average values) subjected to EH (time)					
Time (Hr)	Glucose Concentration (g/L)	Mass of Glucose (g)	Mass of Glucan (g)	Glucan Yield (%)	Error bars (%)
0	2.28E-01	2.28E-03	2.05E-03	3.93E+00	1.20E+00
0.5	6.17E-01	6.17E-03	5.56E-03	1.07E+01	3.40E+00
1	9.77E-01	9.77E-03	8.80E-03	1.69E+01	3.35E+00
2	1.41E+00	1.41E-02	1.27E-02	2.43E+01	1.61E+00
4	2.20E+00	2.20E-02	1.98E-02	3.79E+01	9.44E-01
24	4.92E+00	4.92E-02	4.42E-02	8.49E+01	1.54E+00

C.5 Conversion of porosity for normalized pore volume

This section describes the calculations for converting the raw porosity measurements (Table C-19) to normalized pore volume fractions and absolute pore volumes (Table C-20) as a function of pore size using the MATLAB code. This MATLAB codes integrates the raw porosity data (mL/g*A°) using Trapezoidal rule to calculate the cumulative pore volume (mL/g).

MATLAB code:

```
%import the raw data from excel

X=xlsread('Porosity_raw_data.xlsx','8A0', 'B3:B314');

Y=xlsread('Porosity_raw_data.xlsx','8A0', 'C3:C314');

figure (1)

plot(X,Y)

xlabel('Pore size (A°)');

ylabel('Pore volume mL/A°*g');

set(gca, 'XScale', 'log')

Z=cumtrapz(X,Y);
```

```

figure (2)

plot(X,Z)

xlabel('Pore Size (Å)');

ylabel('Area mL/g');

```

Table. C-19. Raw measurement data of 8 min acid pretreatment and 0-hour enzymatic hydrolysis from NMR cryoporometry.

8 min Acid pretreatment and 0-hour Enzymatic hydrolysis	
Pore size (Å)	Porosity (mL/g*Å)
2.87304	0.0000001
2.94776	0.0000000
3.02453	0.0000000
3.10299	0.0000000
3.18351	0.0000000
3.26546	0.0000000
3.34978	0.0000000
3.43714	0.0000000
3.52602	0.0000000
3.66338	0.0000000
3.71061	0.0000000
3.80685	0.0000000
3.90562	0.0000000
4.0063	0.0000000
4.16234	0.0000000

4.21632	0.0000000
4.38093	0.0000000
4.43676	0.0000000
4.5511	0.0000000
4.72939	0.0000000
4.79039	0.0000000
4.9773	0.0000000
5.04098	0.0000000
5.17178	0.0000000
5.37391	0.0000000
5.4434	0.0000000
5.72943	0.0000000
5.72943	0.0000000
5.87812	0.0000000
6.10683	0.0000000
6.18517	0.0000000
6.50962	0.0000000
6.50962	0.0000000
6.67954	0.0000000
6.85228	0.0000000
7.1198	0.0000001
7.39457	0.0000002
7.48706	0.0000004

7.67633	0.0000008
7.97399	0.0000015
8.07537	0.0000027
8.38392	0.0000078
8.4905	0.0000225
8.70806	0.0000561
8.81755	0.0000617
9.16503	0.0001429
9.53135	0.0004268
9.782	0.0006941
9.91281	0.0007708
10.1757	0.0011690
10.4503	0.0017007
10.8618	0.0025446
11.1432	0.0030789
11.4294	0.0036181
11.5756	0.0037889
11.8648	0.0042381
12.1705	0.0048484
12.4894	0.0050945
12.652	0.0050553
12.9865	0.0051011
13.3264	0.0050281

13.8551	0.0048849
14.2366	0.0046696
14.6125	0.0044211
15.0157	0.0041755
15.4247	0.0039358
15.6369	0.0038499
15.8465	0.0037343
16.318	0.0035595
16.7844	0.0034797
17.0108	0.0034060
17.5745	0.0033427
18.1326	0.0033255
18.7649	0.0033724
19.0648	0.0033846
19.4097	0.0033733
20.2099	0.0035021
20.6544	0.0034751
21.0358	0.0035328
21.486	0.0035732
22.044	0.0034561
23.0282	0.0033126
24.0935	0.0030646
24.7026	0.0028975

25.2457	0.0026659
25.2457	0.0026659
25.826	0.0024291
27.1547	0.0019479
27.1547	0.0019479
27.9067	0.0017441
28.5141	0.0015187
29.9936	0.0011443
30.8607	0.0009431
31.6046	0.0008867
33.2581	0.0007169
33.2581	0.0007169
33.2581	0.0007169
34.9847	0.0006782
34.9847	0.0006782
36.7539	0.0006489
36.7539	0.0006489
38.7078	0.0006276
38.7078	0.0006276
39.7619	0.0006193
42.3453	0.0005900
42.3453	0.0005900
42.3453	0.0005900

45.2557	0.0005985
45.2557	0.0005985
46.7928	0.0006053
46.7928	0.0006053
50.8227	0.0007183
50.8227	0.0007183
52.7174	0.0007758
54.8831	0.0008540
54.8831	0.0008540
56.7226	0.0008595
58.8393	0.0008965
58.8393	0.0008965
58.8393	0.0008965
61.3244	0.0008597
63.4787	0.0008579
63.4787	0.0008579
65.9356	0.0008126
69.5313	0.0007083
69.5313	0.0007083
73.2685	0.0006244
73.2685	0.0006244
77.3998	0.0004985
77.3998	0.0004985

81.7228	0.0003732
85.2944	0.0002928
85.2944	0.0002928
85.2944	0.0002928
92.9684	0.0001836
92.9684	0.0001836
92.9684	0.0001836
96.5359	0.0002162
100.182	0.0002060
100.182	0.0002060
104.123	0.0002668
108.153	0.0003117
108.153	0.0003117
112.512	0.0003669
116.972	0.0004320
116.972	0.0004320
121.81	0.0004647
126.763	0.0005150
126.763	0.0005150
126.763	0.0005150
137.648	0.0005449
137.648	0.0005449
137.648	0.0005449

149.802	0.0005241
149.802	0.0005241
149.802	0.0005241
163.38	0.0004668
163.38	0.0004668
163.38	0.0004668
163.38	0.0004668
178.622	0.0004006
178.622	0.0004006
178.622	0.0004006
186.83	0.0003657
195.745	0.0003485
195.745	0.0003485
205.007	0.0003271
215.093	0.0003186
215.093	0.0003186
215.093	0.0003186
225.56	0.0003077
236.951	0.0003015
236.951	0.0003015
236.951	0.0003015
248.827	0.0002953
261.768	0.0002908

261.768	0.0002908
275.234	0.0002856
275.234	0.0002856
289.928	0.0002866
289.928	0.0002866
305.288	0.0002853
305.288	0.0002853
305.288	0.0002853
322.123	0.0002973
339.669	0.0003050
339.669	0.0003050
339.669	0.0003050
339.669	0.0003050
358.629	0.0003214
387.312	0.0002535
387.312	0.0002535
387.312	0.0002535
387.312	0.0002535
418.289	0.0001857
418.289	0.0001857
452.938	0.0001066
452.938	0.0001066
452.938	0.0001066

452.938	0.0001066
490.456	0.0000274
519.899	0.0000137
519.899	0.0000137
519.899	0.0000137
546.049	0.0000091
546.049	0.0000091
576.166	0.0000000
576.166	0.0000000
576.166	0.0000000
609.084	0.0000000
609.084	0.0000000
640.32	0.0000000
640.32	0.0000000
640.32	0.0000000
680.671	0.0000000
680.671	0.0000000
680.671	0.0000000
757.913	0.0000000
757.913	0.0000000
843.919	0.0000000
843.919	0.0000000
843.919	0.0000000

843.919	0.0000000
843.919	0.0000000
923.415	0.0000000
923.415	0.0000000
923.415	0.0000000
1010.4	0.0000000
1056.77	0.0000000
1056.77	0.0000000
1097.99	0.0000525
1097.99	0.0000525
1097.99	0.0000525
1097.99	0.0000525
1144.6	0.0000788
1144.6	0.0000788
1212.78	0.0000525
1212.78	0.0000525
1270.39	0.0000788
1270.39	0.0000788
1430.28	0.0000000
1466.4	0.0000000
1494.32	0.0000000
1494.32	0.0000000
1494.32	0.0000000

1538.67	0.0000000
1586.44	0.0000000
1586.44	0.0000000
1586.44	0.0000000
1643.6	0.0000153
1680.91	0.0000191
1730.17	0.0000255
1884.35	0.0001536
1884.35	0.0001536
1884.35	0.0001536
2043.3	0.0002041
2096.01	0.0001715
2139.21	0.0001372
2177.77	0.0001143
2239.53	0.0001219
2239.53	0.0001219
2296.45	0.0001016
2350.83	0.0000450
2350.83	0.0000450
2350.83	0.0000450
2474.8	0.0000147
2605.31	0.0000000
2742.7	0.0000000

2887.34	0.0000000
2930.89	0.0000000
2973.25	0.0000243
3078.92	0.0000717
3078.92	0.0000717
3078.92	0.0000717
3137.99	0.0001044
3181.21	0.0001193
3225.98	0.0001392
3365.89	0.0001563
3511.87	0.0001647
3664.17	0.0001647
3823.08	0.0001363
3931.42	0.0000972
3931.42	0.0000972
4030.93	0.0000810
4126.68	0.0000306
4126.68	0.0000306
4126.68	0.0000306
4344.3	0.0000100
4573.39	0.0000000
4814.57	0.0000000
5068.47	0.0000000

5145.05	0.0000000
5219.5	0.0000000
5405.58	0.0000000
5475.17	0.0000000
5545.66	0.0000000
5617.06	0.0000000
5762.62	0.0000000
5911.96	0.0000000
6065.16	0.0000000
6222.34	0.0000000
6383.58	0.0000000
6549.01	0.0000000
6718.72	0.0000000
6892.83	0.0000000
7071.46	0.0000000
7254.71	0.0000000
7442.71	0.0000000
7635.58	0.0000000
7833.46	0.0000000
8036.46	0.0000000
8244.72	0.0000000

Figure. C-8. Porosity distribution of dilute acid pretreatment of 8 min sample (acid concentration (0.5% wt.) and temperature (160°C))

The cumulative pore volume data as a function of pore size was obtained from the MATLAB code mentioned above. The obtained cumulative pore volume is divided into segments (Absolute Pore volume (mL/g)) by using formula $A(i)=C(i)-C(i-1)$ where $A(i)$ is absolute pore volume at pore size i and $C(i)$ is cumulative pore volume at pore size i . Where $i \in 2, 3 \dots n$ where n is the highest pore size of the data. For $i=1$, $C(i)$ is assumed to be zero.

The total pore volume was calculated as sum of the absolute pore volumes, which is given by formula:

$$\text{Total pore volume} = \sum_{i=1}^n A(i) \text{ Where } i \in 1, 2, 3 \dots n$$

The normalized pore volume fraction was calculated as the individual absolute pore volume divided by the total pore volume, which is given by the formula:

$$\text{Normalised pore volume fraction} = A(i) / \sum_{i=1}^n A(i) \text{ Where } i \in 1, 2, 3 \dots n$$

Table. C-20. Integrated porosity data of 8 min of acid pretreatment and 0-hour enzymatic hydrolysis

8 min of acid pretreatment and 0-hour enzymatic hydrolysis						
Pore size (Å)	Cumulative Pore volume (mL/g)	Absolute Pore volume(mL/g)	Normalized pore volume fraction	Range of pore sizes [Å]	Normalized pore volume fraction	Absolute pore volume (mL/g)
2.83568	0.0000000	0.0000000	0.0000000	0-10	0.0008725 84	0.00040 4739
2.9104	0.0000000	0.0000000	0.0000000	10-100	0.2185972 89	0.10139 3941
2.986145	0.0000000	0.0000000	0.0000000	100-1000	0.2364637 45	0.10968 1100
3.06376	0.0000000	0.0000000	0.0000000	1000-10000	0.5440663 81	0.25235 9190
3.14325	0.0000000	0.0000000	0.0000000			
3.224485	0.0000000	0.0000000	0.0000000			
3.30762	0.0000000	0.0000000	0.0000000			
3.39346	0.0000000	0.0000000	0.0000000			
3.48158	0.0000000	0.0000000	0.0000000			
3.5947	0.0000000	0.0000000	0.0000000			
3.686995	0.0000000	0.0000000	0.0000000			
3.75873	0.0000000	0.0000000	0.0000000			
3.856235	0.0000000	0.0000000	0.0000000			
3.95596	0.0000000	0.0000000	0.0000000			
4.08432	0.0000000	0.0000000	0.0000000			
4.18933	0.0000000	0.0000000	0.0000000			

4.298625	0.0000000	0.0000000	0.0000000
4.408845	0.0000000	0.0000000	0.0000000
4.49393	0.0000000	0.0000000	0.0000000
4.640245	0.0000000	0.0000000	0.0000000
4.75989	0.0000000	0.0000000	0.0000000
4.883845	0.0000000	0.0000000	0.0000000
5.00914	0.0000000	0.0000000	0.0000000
5.10638	0.0000000	0.0000000	0.0000000
5.272845	0.0000000	0.0000000	0.0000000
5.408655	0.0000000	0.0000000	0.0000000
5.586415	0.0000000	0.0000000	0.0000000
5.72943	0.0000000	0.0000000	0.0000000
5.803775	0.0000000	0.0000000	0.0000000
5.992475	0.0000000	0.0000000	0.0000000
6.146	0.0000000	0.0000000	0.0000000
6.347395	0.0000000	0.0000000	0.0000000
6.50962	0.0000000	0.0000000	0.0000000
6.59458	0.0000000	0.0000000	0.0000000
6.76591	0.0000000	0.0000000	0.0000000
6.98604	0.0000000	0.0000000	0.0000000
7.257185	0.0000000	0.0000000	0.0000000
7.440815	0.0000001	0.0000001	0.0000001
7.581695	0.0000001	0.0000000	0.0000001

7.82516	0.0000003	0.0000001	0.0000003
8.02468	0.0000007	0.0000005	0.0000010
8.229645	0.0000010	0.0000003	0.0000006
8.43721	0.0000034	0.0000024	0.0000052
8.59928	0.0000058	0.0000024	0.0000052
8.762805	0.0000180	0.0000122	0.0000263
8.99129	0.0000248	0.0000068	0.0000146
9.34819	0.0000744	0.0000496	0.0001070
9.656675	0.0002308	0.0001563	0.0003371
9.847405	0.0004047	0.0001740	0.0003751
10.044255	0.0005056	0.0001008	0.0002174
10.313	0.0008129	0.0003073	0.0006625
10.65605	0.0012799	0.0004670	0.0010069
11.0025	0.0023270	0.0010471	0.0022574
11.2863	0.0031934	0.0008664	0.0018679
11.5025	0.0042289	0.0010355	0.0022325
11.7202	0.0047828	0.0005539	0.0011943
12.01765	0.0060085	0.0012256	0.0026424
12.32995	0.0074906	0.0014821	0.0031954
12.5707	0.0091153	0.0016246	0.0035026
12.81925	0.0099372	0.0008220	0.0017721
13.15645	0.0116436	0.0017063	0.0036787
13.59075	0.0133526	0.0017090	0.0036846

14.04585	0.0159353	0.0025826	0.0055680
14.42455	0.0177167	0.0017814	0.0038407
14.8141	0.0193786	0.0016619	0.0035829
15.2202	0.0210622	0.0016836	0.0036296
15.5308	0.0226719	0.0016097	0.0034705
15.7417	0.0234889	0.0008170	0.0017613
16.08225	0.0242716	0.0007827	0.0016874
16.5512	0.0259499	0.0016783	0.0036183
16.8976	0.0275728	0.0016229	0.0034989
17.29265	0.0283439	0.0007711	0.0016625
17.85355	0.0302282	0.0018843	0.0040624
18.44875	0.0320842	0.0018560	0.0040013
18.91485	0.0342166	0.0021324	0.0045972
19.23725	0.0352316	0.0010150	0.0021884
19.8098	0.0363951	0.0011635	0.0025083
20.43215	0.0391974	0.0028023	0.0060416
20.8451	0.0407421	0.0015447	0.0033303
21.2609	0.0420895	0.0013474	0.0029049
21.765	0.0436981	0.0016086	0.0034681
22.5361	0.0456266	0.0019285	0.0041577
23.56085	0.0488869	0.0032603	0.0070289
24.39805	0.0521516	0.0032647	0.0070385
24.97415	0.0539165	0.0017649	0.0038050

25.2457	0.0553644	0.0014478	0.0031214
25.53585	0.0553644	0.0000000	0.0000000
26.49035	0.0567740	0.0014096	0.0030390
27.1547	0.0593622	0.0025882	0.0055800
27.5307	0.0593622	0.0000000	0.0000000
28.2104	0.0606737	0.0013115	0.0028275
29.25385	0.0615962	0.0009225	0.0019888
30.42715	0.0632893	0.0016931	0.0036501
31.23265	0.0641070	0.0008178	0.0017630
32.43135	0.0647667	0.0006596	0.0014221
33.2581	0.0659520	0.0011853	0.0025555
33.2581	0.0659520	0.0000000	0.0000000
34.1214	0.0659520	0.0000000	0.0000000
34.9847	0.0671229	0.0011710	0.0025245
35.8693	0.0671229	0.0000000	0.0000000
36.7539	0.0682709	0.0011480	0.0024750
37.73085	0.0682709	0.0000000	0.0000000
38.7078	0.0694973	0.0012263	0.0026439
39.23485	0.0694973	0.0000000	0.0000000
41.0536	0.0701500	0.0006528	0.0014073
42.3453	0.0716743	0.0015242	0.0032861
42.3453	0.0716743	0.0000000	0.0000000
43.8005	0.0716743	0.0000000	0.0000000

45.2557	0.0734161	0.0017419	0.0037553
46.02425	0.0734161	0.0000000	0.0000000
46.7928	0.0743466	0.0009304	0.0020060
48.80775	0.0743466	0.0000000	0.0000000
50.8227	0.0772412	0.0028946	0.0062406
51.77005	0.0772412	0.0000000	0.0000000
53.80025	0.0787111	0.0014699	0.0031691
54.8831	0.0805606	0.0018494	0.0039872
55.80285	0.0805606	0.0000000	0.0000000
57.78095	0.0821416	0.0015810	0.0034086
58.8393	0.0840393	0.0018977	0.0040912
58.8393	0.0840393	0.0000000	0.0000000
60.08185	0.0840393	0.0000000	0.0000000
62.40155	0.0861757	0.0021364	0.0046059
63.4787	0.0880238	0.0018481	0.0039844
64.70715	0.0880238	0.0000000	0.0000000
67.73345	0.0900203	0.0019965	0.0043043
69.5313	0.0925670	0.0025467	0.0054904
71.3999	0.0925670	0.0000000	0.0000000
73.2685	0.0949003	0.0023334	0.0050306
75.33415	0.0949003	0.0000000	0.0000000
77.3998	0.0969598	0.0020594	0.0044400
79.5613	0.0969598	0.0000000	0.0000000

83.5086	0.0985729	0.0016131	0.0034778
85.2944	0.0996188	0.0010459	0.0022549
85.2944	0.0996188	0.0000000	0.0000000
89.1314	0.0996188	0.0000000	0.0000000
92.9684	0.1010275	0.0014087	0.0030370
92.9684	0.1010275	0.0000000	0.0000000
94.75215	0.1010275	0.0000000	0.0000000
98.35895	0.1017987	0.0007712	0.0016626
100.182	0.1025497	0.0007510	0.0016191
102.1525	0.1025497	0.0000000	0.0000000
106.138	0.1036012	0.0010515	0.0022670
108.153	0.1048572	0.0012560	0.0027079
110.3325	0.1048572	0.0000000	0.0000000
114.742	0.1064566	0.0015994	0.0034481
116.972	0.1083833	0.0019267	0.0041537
119.391	0.1083833	0.0000000	0.0000000
124.2865	0.1106316	0.0022483	0.0048472
126.763	0.1131822	0.0025506	0.0054989
126.763	0.1131822	0.0000000	0.0000000
132.2055	0.1131822	0.0000000	0.0000000
137.648	0.1191129	0.0059307	0.0127862
137.648	0.1191129	0.0000000	0.0000000
143.725	0.1191129	0.0000000	0.0000000

149.802	0.1254823	0.0063694	0.0137320
149.802	0.1254823	0.0000000	0.0000000
156.591	0.1254823	0.0000000	0.0000000
163.38	0.1318209	0.0063385	0.0136654
163.38	0.1318209	0.0000000	0.0000000
163.38	0.1318209	0.0000000	0.0000000
171.001	0.1318209	0.0000000	0.0000000
178.622	0.1379262	0.0061054	0.0131627
178.622	0.1379262	0.0000000	0.0000000
182.726	0.1379262	0.0000000	0.0000000
191.2875	0.1409280	0.0030017	0.0064715
195.745	0.1440348	0.0031069	0.0066982
200.376	0.1440348	0.0000000	0.0000000
210.05	0.1470648	0.0030300	0.0065324
215.093	0.1502777	0.0032129	0.0069268
215.093	0.1502777	0.0000000	0.0000000
220.3265	0.1502777	0.0000000	0.0000000
231.2555	0.1534987	0.0032209	0.0069441
236.951	0.1569335	0.0034348	0.0074052
236.951	0.1569335	0.0000000	0.0000000
242.889	0.1569335	0.0000000	0.0000000
255.2975	0.1604401	0.0035066	0.0075600
261.768	0.1642040	0.0037639	0.0081146

268.501	0.1642040	0.0000000	0.0000000
275.234	0.1680497	0.0038457	0.0082911
282.581	0.1680497	0.0000000	0.0000000
289.928	0.1722607	0.0042109	0.0090784
297.608	0.1722607	0.0000000	0.0000000
305.288	0.1766425	0.0043818	0.0094468
305.288	0.1766425	0.0000000	0.0000000
313.7055	0.1766425	0.0000000	0.0000000
330.896	0.1816476	0.0050052	0.0107908
339.669	0.1869985	0.0053508	0.0115359
339.669	0.1869985	0.0000000	0.0000000
339.669	0.1869985	0.0000000	0.0000000
349.149	0.1869985	0.0000000	0.0000000
372.9705	0.1930917	0.0060932	0.0131366
387.312	0.2003642	0.0072725	0.0156788
387.312	0.2003642	0.0000000	0.0000000
387.312	0.2003642	0.0000000	0.0000000
402.8005	0.2003642	0.0000000	0.0000000
418.289	0.2061171	0.0057530	0.0124030
435.6135	0.2061171	0.0000000	0.0000000
452.938	0.2098094	0.0036922	0.0079602
452.938	0.2098094	0.0000000	0.0000000
452.938	0.2098094	0.0000000	0.0000000

471.697	0.2098094	0.0000000	0.0000000
505.1775	0.2108375	0.0010281	0.0022165
519.899	0.2112409	0.0004034	0.0008697
519.899	0.2112409	0.0000000	0.0000000
532.974	0.2112409	0.0000000	0.0000000
546.049	0.2114798	0.0002389	0.0005150
561.1075	0.2114798	0.0000000	0.0000000
576.166	0.2114798	0.0000000	0.0000000
576.166	0.2114798	0.0000000	0.0000000
592.625	0.2114798	0.0000000	0.0000000
609.084	0.2114798	0.0000000	0.0000000
624.702	0.2114798	0.0000000	0.0000000
640.32	0.2114798	0.0000000	0.0000000
640.32	0.2114798	0.0000000	0.0000000
660.4955	0.2114798	0.0000000	0.0000000
680.671	0.2114798	0.0000000	0.0000000
680.671	0.2114798	0.0000000	0.0000000
719.292	0.2114798	0.0000000	0.0000000
757.913	0.2114798	0.0000000	0.0000000
800.916	0.2114798	0.0000000	0.0000000
843.919	0.2114798	0.0000000	0.0000000
843.919	0.2114798	0.0000000	0.0000000
843.919	0.2114798	0.0000000	0.0000000

843.919	0.2114798	0.0000000	0.0000000
883.667	0.2114798	0.0000000	0.0000000
923.415	0.2114798	0.0000000	0.0000000
923.415	0.2114798	0.0000000	0.0000000
966.9075	0.2114798	0.0000000	0.0000000
1033.585	0.2114798	0.0000000	0.0000000
1056.77	0.2114798	0.0000000	0.0000000
1077.38	0.2114798	0.0000000	0.0000000
1097.99	0.2136439	0.0021641	0.0046656
1097.99	0.2136439	0.0000000	0.0000000
1097.99	0.2136439	0.0000000	0.0000000
1121.295	0.2136439	0.0000000	0.0000000
1144.6	0.2173145	0.0036706	0.0079135
1178.69	0.2173145	0.0000000	0.0000000
1212.78	0.2208940	0.0035795	0.0077171
1241.585	0.2208940	0.0000000	0.0000000
1270.39	0.2254309	0.0045369	0.0097811
1350.335	0.2254309	0.0000000	0.0000000
1448.34	0.2254309	0.0000000	0.0000000
1480.36	0.2254309	0.0000000	0.0000000
1494.32	0.2254309	0.0000000	0.0000000
1494.32	0.2254309	0.0000000	0.0000000
1516.495	0.2254309	0.0000000	0.0000000

1562.555	0.2254309	0.0000000	0.0000000
1586.44	0.2254309	0.0000000	0.0000000
1586.44	0.2254309	0.0000000	0.0000000
1615.02	0.2254309	0.0000000	0.0000000
1662.255	0.2263046	0.0008737	0.0018837
1705.54	0.2270175	0.0007129	0.0015370
1807.26	0.2282725	0.0012550	0.0027056
1884.35	0.2519607	0.0236882	0.0510699
1884.35	0.2519607	0.0000000	0.0000000
1963.825	0.2519607	0.0000000	0.0000000
2069.655	0.2843947	0.0324341	0.0699253
2117.61	0.2934327	0.0090380	0.0194852
2158.49	0.2993586	0.0059259	0.0127757
2208.65	0.3037664	0.0044078	0.0095029
2239.53	0.3112942	0.0075277	0.0162292
2267.99	0.3112942	0.0000000	0.0000000
2323.64	0.3170757	0.0057815	0.0124645
2350.83	0.3195222	0.0024465	0.0052745
2350.83	0.3195222	0.0000000	0.0000000
2412.815	0.3195222	0.0000000	0.0000000
2540.055	0.3213497	0.0018275	0.0039400
2674.005	0.3213497	0.0000000	0.0000000
2815.02	0.3213497	0.0000000	0.0000000

2909.115	0.3213497	0.0000000	0.0000000
2952.07	0.3213497	0.0000000	0.0000000
3026.085	0.3223800	0.0010302	0.0022211
3078.92	0.3299600	0.0075801	0.0163420
3078.92	0.3299600	0.0000000	0.0000000
3108.455	0.3299600	0.0000000	0.0000000
3159.6	0.3361264	0.0061664	0.0132942
3203.595	0.3412827	0.0051563	0.0111166
3295.935	0.3475142	0.0062315	0.0134345
3438.88	0.3693832	0.0218691	0.0471479
3588.02	0.3934191	0.0240359	0.0518195
3743.625	0.4184956	0.0250765	0.0540629
3877.25	0.4401515	0.0216559	0.0466885
3931.42	0.4506774	0.0105259	0.0226930
3981.175	0.4506774	0.0000000	0.0000000
4078.805	0.4587341	0.0080567	0.0173696
4126.68	0.4616600	0.0029259	0.0063080
4126.68	0.4616600	0.0000000	0.0000000
4235.49	0.4616600	0.0000000	0.0000000
4458.845	0.4638390	0.0021790	0.0046977
4693.98	0.4638390	0.0000000	0.0000000
4941.52	0.4638390	0.0000000	0.0000000
5106.76	0.4638390	0.0000000	0.0000000

5182.275	0.4638390	0.0000000	0.0000000
5312.54	0.4638390	0.0000000	0.0000000
5440.375	0.4638390	0.0000000	0.0000000
5510.415	0.4638390	0.0000000	0.0000000
5581.36	0.4638390	0.0000000	0.0000000
5689.84	0.4638390	0.0000000	0.0000000
5837.29	0.4638390	0.0000000	0.0000000
5988.56	0.4638390	0.0000000	0.0000000
6143.75	0.4638390	0.0000000	0.0000000
6302.96	0.4638390	0.0000000	0.0000000
6466.295	0.4638390	0.0000000	0.0000000
6633.865	0.4638390	0.0000000	0.0000000
6805.775	0.4638390	0.0000000	0.0000000
6982.145	0.4638390	0.0000000	0.0000000
7163.085	0.4638390	0.0000000	0.0000000
7348.71	0.4638390	0.0000000	0.0000000
7539.145	0.4638390	0.0000000	0.0000000
7734.52	0.4638390	0.0000000	0.0000000
7934.96	0.4638390	0.0000000	0.0000000
8140.59	0.4638390	0.0000000	0.0000000
8348.85	0.4638390	0.0000000	0.0000000

Figure. C-9. Normalized Fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 0-hours of EH

Figure. C-10. Normalized fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 4-hours of EH

Figure. C-11. Normalized fraction of pore volume distribution of poplar biomass sample with 8 Min of DAH and 24-hours of EH

Figure. C-12. Normalized fraction of pore volume distribution of poplar biomass sample with 13 Min of DAH and 0-hours of EH

Figure. C-13. Normalized fraction of pore volume distribution of poplar biomass sample with 13 Min of DAH and 24-hours of EH

Figure. C-14. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 0-hours of EH

Figure. C-15. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 4-hours of EH

Figure. C-16. Normalized fraction of pore volume distribution of poplar biomass sample with 15 Min of DAH and 24-hours of EH

Figure. C-17. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 0-hours of EH

Figure. C-18. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 4-hours of EH

Figure. C-19. Normalized fraction of pore volume distribution of poplar biomass sample with 21 Min of DAH and 24-hours of EH

Figure. C-20. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAH and 0-hours of EH

Figure. C-21. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAH and 4-hours of EH

Figure. C-22. Normalized fraction of pore volume distribution of poplar biomass sample with 40 Min of DAP and 24-hours of EH

Figure. C-23. Porosity distribution of enzymatic hydrolyzed 13-min pretreated poplar biomass sample over time

Figure. C-24. Porosity distribution of enzymatic hydrolyzed 15-min pretreated poplar biomass sample over time

Figure. C-25. Porosity distribution of enzymatic hydrolyzed 21-min pretreated poplar biomass sample over time

Figure. C-26. Porosity distribution of enzymatic hydrolyzed 40-min pretreated poplar biomass sample over time

Figure. C-27. Absolute pore volume of enzymatic hydrolysis poplar biomass over time (with 13-min of acid pretreatment)

Figure. C-28. Absolute pore volume of enzymatic hydrolysis poplar biomass over time (with 8 min of acid pretreatment)

Figure. C-29. Normalized pore volume fraction of enzymatic hydrolysis poplar biomass over time a) 13 min of dilute acid pretreatment (DAP), b) 15 min DAP, c) 21 min DAP, d) 40 min DAP.

C.6 Calculations used for determining the initial rate of hydrolysis

Initially, the Glucose concentration (gram/L) for 0-, 0.5-, 1- hour are plotted for each dilute acid pretreated samples (8-, 13-, 15-, 21- and 40-min) using the scatter plot. The data is then linearly fitted using Origin by setting intercept to 0 to determine the initial rate of hydrolysis. The obtained line equation is expressed in Figures C-30 to C-34 including the regression (R^2) value.

Figure. C-30. Initial rate of hydrolysis for 8-min dilute acid pretreated poplar biomass samples

Figure. C-31. Initial rate of hydrolysis for 13-min dilute acid pretreated poplar biomass samples

Figure. C-32. Initial rate of hydrolysis for 15-min dilute acid pretreated poplar biomass samples

Figure. C-33. Initial rate of hydrolysis for 21-min dilute acid pretreated poplar biomass samples

Figure. C-34. Initial rate of hydrolysis for 40-min dilute acid pretreated poplar biomass samples

The pore volume of the individual pretreated samples with a pore diameter greater than critical pore size ($>51 \text{ \AA}$) is calculated using the information from Section-1. The relation between rate of hydrolysis (Slope) and pore volume with pore size greater than $51 \text{ \AA}$ is plotted for different pretreatment time and show in Figure 10 of Main manuscript.

C.7 References

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D Supporting Information for Chapter 5

GIS-integrated optimization for locating food waste and manure anaerobic co-digestion facilities

D.1 Introduction to food waste and circular economy

This section provides the background information on food waste and manure anaerobic co-digestion in the US.

Figure. D-1 . Circular flow diagram of food and food waste using AD.

Total MSW Generation by Material 267.8 million tons

Figure. D-2 2017 US total MSW generation by material in percentage.

Figure. D-3 Availability of dairy manure at each farm in Wisconsin (in dry tons/day)

Figure. D-4 Availability of food waste at each courthouse in Wisconsin (in dry tons/day)

Figure. D-5 Transportation network for scenario-2 from potential biogas facilities (mapping feedstock location and plant locations) [X- potential plants, ▲ - courthouses, ● - dairy farms, ---- network, X – potential plants with no capacities)

D.2 Mathematical formulation of optimization model:

This section gives the detailed information on mathematical formulation and constraints used in the optimization model.

AF – allocation factor [0.83]

CO_{2gwp} – GWP of CO_2 (1 in (kg CO_2 eq)/ (kg CO_2))

$conv_{day}$ – conversion factor for converting hours to days (24 hrs.)

$conv_{month}$ – conversion factor for converting days to month (30 days)

$conv_{ton}$ – conversion factor for converting tons to kg (1000 kg)

$cost_{CO_2}$ – is in the units of \$/kg CO_2 , dependent on the policies in place

$cost_{digestate}$ – cost of digestate is constant and it is \$2.64 per wet ton ¹

$\text{cost}_{\text{elec}}$ – cost of electricity is constant, and it is 6.4 cents per kWh ¹
 dr – monthly discount rate (0.6%)
 $D1[i, k]$ – distance from farm location i to biopower facility location k (miles)
 $D2[j, k]$ – distance from farm location j to biopower facility location k (miles)
 DLF – distance to landfill from biopower facility (assumed to be 70 miles)
 $E1[k]$ – capacity of electricity produced (kW) at location k and is a discrete integer variable
 $E_{\text{cap}}[k, h]$ – electricity production at location k with capacity level h (kW)
 $\text{Fert}[k]$ – capacity of fertilizer (wet metric tons) produced at location k and is a variable
 $\text{fw}^{\text{aq.}}$ – FW acquisition cost \$/ (dry metric ton) (varied from 0 to 100)
 fw_{trans} – FW transportation cost includes hauling, \$0.43 per dry metric ton-mile ²
 i – index for location of farm ranges from 1 to 240 locations
 $\text{INV}[k, h]$ – investment cost at location k with capacity level h (\$/kW)
 j – index for location of county courthouse and ranges from 1 to 72 locations
 k – index for location of potential biopower facility and ranges from 1 to 24 locations
 LFEF_{ss} – steady state landfilling emission factor for food waste, 10.2 in (kg CO₂ eq)/ (kg dry FW)
 $\text{m}^{\text{aq.}}$ – manure acquisition cost in \$/ (dry ton) (varied from 0 to 100)
 m_{trans} – manure transportation cost includes hauling (\$0.43/ (dry metric ton)) ²
 MC – moisture content (assumed to be 50% moisture in FW and manure)
 MMEF_{L} – lagoon manure management emission factor [5.32 in (kg CO₂ eq)/ (kg dry manure)]
 MMEF_{S} – slurry manure management emission factor [1.38 in (kg CO₂ eq)/ (kg dry manure)]
 MMEF_{SP} – solid pile manure management emission factor [0.631 in (kg CO₂ eq)/ (kg dry manure)]
 N_1 – time period of discounting investment costs (240 months)

N_2 – time period of discounting annual operating costs (12 months)

NO_{2gwp} – GWP of NO_2 (4.94 in (kg CO_2 eq)/ (kg NO_2))

NO_{gwp} – GWP of NO (1.81 in (kg CO_2 eq)/ (kg NO))

$OM[k, h]$ – operating cost at location k with capacity levels h (\$/kW)

PBL – percentage of manure management by lagoon in the US (65%)

PBS – percentage of manure management by slurry in the US (25%)

PBSP – percentage of manure management by solid piles in the US (10%)

$rf1$ – recovery factor for investment costs [0.007873]

$rf2$ – recovery factor for operating costs [0.0866]

RCFE – ratio of CO_2 mass flows from combustion stream to electricity production [0.0147]

RNFE – ratio of NO_2 mass flows from combustion stream to electricity production [0.0000029]

RNOFE – ratio of NO mass flows from combustion stream to electricity production [0.000245]

RSFE – ratio of SO_2 mass flows from combustion stream to electricity production [0.00017]

SO_{2gwp} – GWP of SO_2 (0.378 in (kg CO_2 eq)/ (kg SO_2))

TEF_{onward} – transportation outward trip emission factor [0.254 in (kg CO_2 eq)/ (t*mile)]

TEF_{ret} – transportation return trip emission factor [0.194 in (kg CO_2 eq)/ (t*mile)]

$X2[j, k]$ – amount of FW in dry tons acquired from locations j to k and is a variable

$X4[k, h]$ – Number of biopower facilities built at location k with capacity h , is an integer

D.2.1 Revenues include:

1. Income from sale of electricity:

$$\sum_{k=1}^{24} \binom{24}{k} (E1[k] * conv_{day} * conv_{month} * cost_{elec})$$

2. Income from sale of digestate:

$$\sum_{k=1}^{24} \binom{24}{k} (Fert[k] * Cost_{digestate} * conv_{month})$$

3. Food waste landfill steady state uncontrolled emissions:

$$\sum_{j=1}^{72} \binom{72}{j} \sum_{k=1}^{24} \binom{24}{k} (LFEF_{ss}) * X2[j, k] * conv_{month} * cost_{CO_2} * AF$$

4. Avoided food waste transportation emissions:

$$\sum_{j=1}^{72} \binom{72}{j} \sum_{k=1}^{24} \binom{24}{k} (TEF_{ret} + TEF_{onward}) * MC * DLF * X2[j, k] * conv_{month} * cost_{CO_2} * conv_{ton} * AF$$

5. Avoided manure management emissions:

$$\begin{aligned} & \sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} (MMEF_L * PBL) * X1[i, k] * conv_{month} * cost_{CO_2} * AF + \\ & \sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} (MMEF_S * PBS) * X1[i, k] * conv_{month} * cost_{CO_2} * AF + \\ & \sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} (MMEF_{SP} * PBSB) * X1[i, k] * conv_{month} * cost_{CO_2} * AF \end{aligned}$$

D.2.2 Costs include:

1. Cost of acquisition of manure:

$$\sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} m^{aq} * X1[i, k] * conv_{month}$$

2. Cost of acquisition of food waste:

$$\sum_{j=1}^{72} \binom{72}{j} \sum_{k=1}^{24} \binom{24}{k} fw^{aq} * X2[j, k] * conv_{month}$$

3. Cost of transportation of food waste:

$$\sum_{j=1}^{72} \binom{72}{j} \sum_{k=1}^{24} \binom{24}{k} (fw_{trans} * D2[j, k] * MC * 2) * X2[j, k] * conv_{month}$$

4. Cost of transportation of manure:

$$\sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} (m_{trans} * D1[i, k] * MC * 2) * X1[i, k] * conv_{month}$$

5. Investment, operating and maintenance costs:

$$\sum_{h=1}^5 \binom{5}{h} \sum_{k=1}^{24} \binom{24}{k} (INV[k, h] * rf1 + OM[k, h] * rf2) * E_{cap}[k, h] * X4[k, h]$$

Operational costs are assumed to be 5% of the investment costs. Present values of investment costs, operating and maintenance costs are converted using the equations (a) and (b) below, in equal monthly installments over a period at a specific discount rate. The monthly discount rate of 0.6% is used ³ in this study. Where

$$rf1 = \frac{dr * (dr+1)^{N1}}{(dr+1)^{N1}-1} \rightarrow (a)$$

$$rf2 = \frac{dr*(dr+1)^{N2}}{(dr+1)^{N2}-1} \rightarrow (b)$$

6. Transportation emissions of AD: Food waste transportation emissions + Manure transportation emissions:

$$\sum_{j=1}^{72} \binom{72}{j} \sum_{k=1}^{24} \binom{24}{k} (TEF_{ret} + TEF_{onward}) * MC * D2[j, k] * X2[j, k] * conv_{month} * cost_{CO_2} * conv_{ton} * AF + \sum_{i=1}^{240} \binom{240}{i} \sum_{k=1}^{24} \binom{24}{k} (TEF_{ret} + TEF_{onward}) * MC * D1[i, k] * X1[i, k] * conv_{month} * cost_{CO_2} * conv_{ton} * AF$$

7. AD combustion emissions:

$$\sum_{k=1}^{24} \binom{24}{k} (E1[k] * (CO_{2gwp} * RCFE + SO_{2gwp} * RSFE + NO_{2gwp} * RNFE + NO_{gwp} * RNOFE)) * conv_{month} * cost_{CO_2} * AF$$

The objective function is optimized subjected to the following constraints, where the location-specific availabilities of food waste ($A2[j]$) and manure ($A1[i]$) are obtained from GIS data and analysis. The capacities of electricity production ($EC1[k, h]$), combined food waste and manure dry capacity ($C1[k, h]$), fertilizers ($Fertcap[k, h]$), conversion factors for biomass to electricity and biomass to fertilizer were obtained from process simulation software ASPEN +.

The constraints for the problem statement are as follows:

Constraint 1: Limit the amount of animal manure procured to the amount that is available monthly in each manure producing location $\rightarrow \sum\{k \text{ in } K\} X1[i, k] \leq A1[i] \quad \forall i$

Constraint 2: Limit the amount of food waste procured to the amount that is available monthly in each food waste producing location $\rightarrow \sum\{k \text{ in } K\} X2[j, k] \leq A2[j] \quad \forall j$

Constraint 3: Amount of converted animal manure and food waste equals the electricity produced by relating it to conversion rates at biopower plants $\rightarrow (\sum\{j \text{ in } J\} X2[j, k] + \sum\{i \text{ in } I\} X1[i, k]) * (DWFEC) = E1[k] \quad \forall k$

Constraint 4: Amount of converted animal manure and food waste is proportional to the fertilizer produced by relating it to conversion rates at biopower plants $\rightarrow (\sum\{j \text{ in } J\} X2[j, k] + \sum\{i \text{ in } I\} X1[i, k]) * (DWFEC) = Fert[k] \quad \forall k$

Constraint 5: Ensure that the amount of biomass that can be processed at a biopower plant is limited by the plant capacity $\rightarrow \sum\{j \text{ in } J\} X2[j, k] + \sum\{i \text{ in } I\} X1[i, k] \leq \sum\{h \text{ in } H\} X4[k, h] * C1[k, h] \quad \forall k$

Constraint 6: Limit the electricity production by the plant capacity and number of plants built $\rightarrow E1[k] \leq \sum\{h \text{ in } H\} X4[k, h] * EC1[k, h] \quad \forall k$

Constraint 7: Limit the fertilizer production by the plant capacity and number of plants built $\rightarrow Fert[k] \leq \sum\{h \in H\} X4[k, h] * Fertcap[k, h] \forall k$

Constraint 8: Ensure the food waste and manure ratio is maintained $\rightarrow \sum\{j \in J\} X2[j, k] - \sum\{i \in I\} X1[i, k] * (RFBM) = 0 \forall k$, where

$A1[i]$ - availability of manure at farm location i (dry metric tons per day)

$A2[j]$ - availability of FW at county courthouse location j (dry metric tons per day)

$C1[k, h]$ - amount of food waste and manure at facility location k in dry tons at capacity level h

DWFEC - feedstock to electricity conversion rate on dry basis for FW and Manure

$EC1[k, h]$ - electricity production at biopower facility location k in dry tons at capacity level h

$Fert[k]$ - amount of fertilizer produced at biopower facility location k

$Fertcap[k, h]$ - fertilizer production at biopower facility location k in dry tons at capacity level h

RFBM - ratio of food waste to manure

D.3 System boundary and process simulation for AD

This section provides the system boundary and process simulation for AcoD of food waste and manure. Different calculations used in emission savings and emissions factors used in LCA.

Figure. D-6 ASPEN + two stage co-digestion biopower facility

Figure. D-7 Cradle-gate system boundary for biopower system.

D.3.1 Emission savings calculation:

Table. D-1 The volume and energy flows were obtained from ASPEN+

Electricity produced	458,640	kWh/day
Digestate volume	556,756.8	Gallons/day
Cost of digestate	0.025	\$/gallon
Cost of electricity	0.082	\$/kWh
Total sales of electricity/day	37,632.46	\$
Total sales of digestate/day	13,918.92	\$
Allocation to electricity	$=(37632.46/(37632.46+13918.92))$	0.27
Allocation to digestate	$=(13918.92/(37632.46+13918.92))$	0.83

Table. D-2 LCA emission factors for biopower systems analysis 4

Avoided FW emission (Uncontrolled landfill)	Emission factor	Units
Transport from landfill to county courthouse	0.194	kg CO ₂ eq/ t*mile
Transport from county courthouse to landfill	0.243	kg CO ₂ eq/ t*mile
Emission from landfill process (steady state)	10.2	kg CO ₂ eq/kg dry FW
Avoided manure emissions (Manure management)	Emission factor	Units
Manure lagoon emissions	5.32	kg CO ₂ eq/ kg dry manure
Slurry storage emissions	1.38	kg CO ₂ eq/ kg dry manure
Solid pile storage emissions	0.631	kg CO ₂ eq/ kg dry manure

Transportation emissions	Emission factor	Units
Food waste transport- from biopower plant - county courthouse	0.194	kg CO ₂ eq/ t*mile
Food waste transport- from county courthouse - Biopower plant	0.243	kg CO ₂ eq/ t*mile
Manure transport - from farm - biopower plant	0.243	kg CO ₂ eq/ t*mile
Manure transport - from biopower plant – farm	0.194	kg CO ₂ eq/ t*mile
Combustion emission from AD biopower	GWP	Units
CO ₂ emissions	1	kg CO ₂ eq/kg CO ₂
SO ₂ emissions	0.378	kg CO ₂ eq/kg SO ₂
NO ₂ emissions	4.94	kg CO ₂ eq/kg NO ₂
NO emissions	1.81	kg CO ₂ eq/kg NO

D.4 Results from optimization model

This section presents results of GIS and the optimization model:

Table. D-3 The amount of manure and supply chain distances from farm to plant in scenario 2

Farm #	Plant #	Amount of manure(tons)	Distance(miles)
200	1	2.52976	9
202	3	5.05952	9
139	4	10.119	3
190	7	2.52976	9
192	8	10.119	4

181	9	2.52976	7
196	10	2.52976	12
156	11	20.2753	4
110	12	5.05952	9
41	13	12.6488	5
115	14	5.05952	14
46	15	7.5506	12
47	15	33	12
10	16	10	20
30	16	21	10
35	16	19	17
44	16	1.10119	20
50	16	30	7
3	17	15	8
9	17	16	6
33	17	9.5506	12
129	18	20.2753	9
90	19	10.119	3
160	21	0.550595	3
213	21	40	2
52	22	10.119	5
171	23	15.1786	7

Table. D-4 The amount of food waste and supply chain distances from courthouse to plant in scenario 2

Courthouse #	Plant #	Amount of food waste(tons)	Distance(miles)
58	1	2.6	37
65	1	2.3	24
66	1	1.4244	57
31	3	7.2	15
34	3	1.55595	40
61	3	2.5	16
62	3	1.39286	46
18	4	14.1	17
34	4	5.34405	41
35	4	5.85357	16
32	7	2.17798	19
35	7	0.846429	30
67	7	2.1	29
69	7	1.2	5
15	8	16.5	12
24	8	3.8756	15
32	8	4.92202	14
24	9	6.3244	13
41	10	5.5	24
52	10	0.824405	36
10	11	21.6	38

22	11	11.7	43
23	11	11.3	46
44	11	3.61265	51
52	11	2.4756	30
27	12	8.3	25
57	12	2.7	19
59	12	1.64881	60
9	13	25.722	21
39	13	5.9	18
42	14	1.15357	50
46	14	4.2	44
48	14	3.8	29
56	14	2.8	15
59	14	0.695238	64
2	15	84.8	7
25	15	10.2	42
26	15	6.37649	32
1	16	108.585	48
3	16	63.8	33
5	16	0.190327	74
9	16	0.177976	34
14	16	16.5	34
20	16	13.5	6

1	17	44.1153	52
11	17	21.5	23
13	17	5.26116	29
16	17	16.4	19
17	17	14.1	31
7	18	21.4647	25
19	18	14	32
26	18	2.72351	41
47	18	3.9	37
53	18	3.2	60
55	18	3	7
63	18	2.4	29
13	19	13.1388	29
21	19	12.1588	12
4	21	41.6	22
6	21	29.6	23
7	21	5.73527	39
21	21	0.54122	27
28	21	8.2	60
29	21	8	21
45	21	4.4	65
51	21	3.3	39
36	22	6.6	30

37	22	6.5	35
38	22	6	23
44	22	0.297619	87
54	22	3.1	59
68	22	1.4	68
71	22	0.7	29
72	22	0.7	86
12	23	18.9	37
30	23	7.3	26
42	23	3.74643	56
43	23	4.7	23
50	23	3.3	18

Table. D-5 Capacities of potential plant locations in WI with \$0 CO2 credits, \$0 tipping fee, and \$40 per ton of manure

Potential plant locations (WI)	Capacity 1 (0.5 MW)	Capacity2 (1.1 MW)	Capacity3 (2.3 MW)	Capacity4 (4.6 MW)	Capacity5 (9.2 MW)	Total (MW)
Weirgor						0
Doyle						0
Bear Lake						0
Rush River		1				1.153
Emerald						0
El Paso	1					0.576
Waubeek						0

Wheaton			1			2.307
Howard	1					0.576
Warner						0
Eau Pleine						0
Smelser						0
Spring Valley						0
Bear Creek						0
Dane County	1		1	1		7.506
Jefferson		1				1.153
Auburn						0
Metomen						0
Liberty		1				1.153
Charlestown	1					0.576
Holland						0
Spruce						0
Franklin						0
Pleasant Valley						0
Total	4	3	2	1	0	15

Table. D-6 Scenario 1 monthly income and costs of the entire supply chain

Incomes in the scenario 1		
	Value (\$/month)	% of total income
Electricity sale	\$ 691,407	83.15

Fertilizer sale	\$ 140,105	16.85
CO ₂ credits	-	-
Food waste tipping fee	-	-
Total income	\$ 831,512	
Costs in the scenario 1		
	Value (\$/month)	% of total cost
Manure transportation cost	\$ 72,505	9.7
Manure purchasing cost	\$ 78,973	10.6
Food waste transportation cost	\$ 128,913	17.3
Plant investment and operating cost (monthly)	\$ 465,385	62.4
CO ₂ costs	-	-
Total cost	\$ 745,776	
Profit (objective function value)	\$ 85,735	

Table. D-7 Capacity levels of potential plant location with \$15 CO₂ credits, \$20 tipping fee, and \$40 per ton of manure

Potential plant locations (WI)	Capacity1 0.57MW	Capacit2 1.1 MW	Capacit3 2.3 MW	Capacit4 4.6 MW	Capacit5 9.2 MW	Total (MW)
Weirgor	1					0.577
Doyle						0.000
Bear Lake		1				1.154
Rush River			1			2.307
Emerald						0.000
El Paso						0.000

Waubeek	1					0.577
Wheaton			1			2.307
Howard	1					0.577
Warner	1					0.577
Eau Pleine				1		4.623
Smelser		1				1.154
Spring Valley	1		1			2.884
Bear Creek		1				1.154
Dane County					1	9.245
Jefferson					2	18.491
Auburn					1	9.245
Metomen				1		4.623
Liberty			1			2.307
Charlestown						0.000
Holland					1	9.245
Spruce			1			2.307
Franklin		1	1			3.461
Pleasant Valley						0.000
Total	5	4	6	2	5	76.812

Table. D-8 Scenario-2 monthly costs and incomes of the entire supply chain.

Incomes in the scenario 2		
	Value (\$/month)	% of total income
Electricity sale	\$ 3,539,500	41.77
Fertilizer sale	\$ 717,235	8.46
CO ₂ credits	\$ 3,712,390	43.81
Food waste tipping fee	\$ 505,357	5.96
Total income	\$ 8,474,483	
Costs in the scenario 2		
	Value (\$/month)	% of total cost
Manure transportation cost	\$ 348,849	6.20
Manure purchasing cost	\$ 404,286	7.18
Food waste transportation cost	\$ 2,127,809	37.79
Plant investment cost and operating cost	\$ 2,297,177	40.80
CO ₂ costs	\$ 452,378	8.03
Total cost	\$ 5,630,498	
Profit (objective function value)	\$ 2,843,985	

Table. D-9 Calculation of overall emission savings in WI considering scenario 2

Cost of carbon credits	\$15	per kg CO ₂
Total carbon revenues per annum	=\$3,260,012*12 =>\$39120144	

Total emission savings from the model (scenario 2)	2608009000	kg CO ₂ savings
Total capacity in scenario 2	76.812	MW
Emission savings (considering 8000 hours of operation per annum)	4244.14	kg CO ₂ /MWh
Electric power emissions from coal (US EIA) ⁵ {EIA, 2018 #50}	1002	kg CO ₂ /MWh
	=4244.14+1002	
Total emissions saving annually	=> 5246.14	kg CO ₂ /MWh
	=5246.14*76.812*8000	
Total emissions saving annually	=> 3,223,734,592	kg CO ₂
		thousand metric tons of CO ₂
Total emissions saving annually	3,223	
WI total electricity emissions (US EIA) ⁶	41779	thousand metric tons
Electric power emissions saving in WI	7.71	%

Table. D-10 The locations specific cost and incomes on a monthly basis for scenario 1

Scenario-1	Location 4	Location 6	Location 8	Location 9	Location 15	Location 16	Location 19	Location 20	Total
Manure purchasing cost	\$(6,071)	\$(3,036)	\$(12,143)	\$(3,036)	\$(39,509)	\$(6,071)	\$(6,071)	\$(3,036)	\$(78,973)
Manure transportation cost	\$(1,958)	\$(2,284)	\$(5,221)	\$(2,284)	\$(50,967)	\$(4,569)	\$(1,958)	\$(3,263)	\$(72,505)
FW tipping fee	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Food waste transportation cost	\$(17,999)	\$(6,364)	\$(27,072)	\$(6,894)	\$(48,312)	\$(6,364)	\$(12,727)	\$(3,182)	\$(128,913)
INV and OM	\$(35,633)	\$(19,347)	\$(70,310)	\$(19,347)	\$(230,133)	\$(35,633)	\$(35,633)	\$(19,347)	\$(465,385)
Electricity sale	\$53,155	\$26,578	\$106,310	\$26,578	\$345,899	\$53,155	\$53,155	\$26,578	\$691,407

Fertilizer sale	\$10,771	\$5,386	\$21,542	\$5,386	\$70,092	\$ 10,771	\$10,771	\$5,386	\$140,105
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Table. D-11 The locations specific cost and incomes on a monthly basis for Scenario 2

Scenario 2	Location 1	Location 3	Location 4	Location 7	Location 8
Manure purchasing cost	\$(3,036)	\$(6,071)	\$(12,143)	\$(3,036)	\$(12,143)
Manure transportation cost	\$(2,937)	\$(5,874)	\$ (3,916)	\$ (2,937)	\$ (5,221)
FW tipping fee	\$3,795	\$7,589	\$15,179	\$3,795	\$15,179
Food waste transportation cost	\$(19,503)	\$(23,001)	\$(46,324)	\$(11,209)	\$(27,255)
INV and OM	\$(19,347)	\$(35,633)	\$(70,310)	\$(19,347)	\$(70,310)
Electricity sale	\$26,578	\$53,155	\$106,310	\$26,578	\$106,310
Fertilizer sale	\$5,386	\$10,771	\$21,542	\$5,386	\$21,542
Carbon credits	\$235	\$470	\$939	\$235	\$939
Carbon credits	\$24,094	\$48,188	\$96,376	\$24,094	\$96,376
Carbon credits	\$3,547	\$7,094	\$14,187	\$3,547	\$14,187

Carbon costs	\$(123)	\$(146)	\$(293)	\$(71)	\$(172)
Carbon costs	\$(19)	\$(37)	\$(25)	\$(19)	\$(33)
Carbon costs	\$(3,167)	\$(6,333)	\$(12,667)	\$(3,167)	\$(12,667)
Carbon costs	\$(14)	\$(28)	\$(55)	\$(14)	\$(55)
Carbon costs	\$(3)	\$(6)	\$(12)	\$(3)	\$(12)
Carbon costs	\$(96)	\$(191)	\$(382)	\$(96)	\$(382)

Scenario 2	Location 9	Location 10	Location 11	Location 12	Location 13	Location14	Location 15
Manure purchasing cost	\$(3,036)	\$(3,036)	\$(24,330)	\$(6,071)	\$(15,179)	\$(6,071)	\$(48,661)
Manure transportation cost	\$(2,284)	\$(3,916)	\$(10,462)	\$(5,874)	\$(8,158)	\$(9,138)	\$(62,772)
FW tipping fee	\$3,795	\$3,795	\$30,413	\$7,589	\$18,973	\$7,589	\$60,826
Food waste transportation cost	\$(6,894)	\$(13,557)	\$(176,271)	\$(29,996)	\$(54,198)	\$(36,825)	\$(102,804)
INV and OM	\$(19,347)	\$(19,347)	\$(140,476)	\$(35,633)	\$(89,657)	\$(35,633)	\$(271,019)

Electricity sale	\$26,578	\$26,578	\$213,011	\$53,155	\$132,888	\$53,155	\$426,022
Fertilizer sale	\$5,386	\$5,386	\$43,164	\$ 10,771	\$26,928	\$10,771	\$86,328
Carbon credits	\$235	\$235	\$1,882	\$470	\$1,174	\$470	\$3,764
Carbon credits	\$24,094	\$24,094	\$193,107	\$48,188	\$120,470	\$48,188	\$386,214
Carbon credits	\$3,547	\$3,547	\$28,427	\$7,094	\$17,734	\$7,094	\$56,853
Carbon costs	\$(44)	\$(86)	\$(1,115)	\$(190)	\$(343)	\$(233)	\$(650)
Carbon costs	\$(14)	\$(25)	\$(66)	\$(37)	\$(52)	\$(58)	\$(397)
Carbon costs	\$(3,167)	\$(3,167)	\$(25,380)	\$(6,333)	\$(15,834)	\$(6,333)	\$(50,761)
Carbon costs	\$(14)	\$(14)	\$(111)	\$(28)	\$(69)	\$(28)	\$(222)
Carbon costs	\$(3)	\$(3)	\$(25)	\$(6)	\$(15)	\$(6)	\$(49)
Carbon costs	\$(96)	\$(96)	\$(766)	\$(191)	\$(478)	\$(191)	\$(1,531)

Location 16	Location 17	Location 18	Location 19	Location 21	Location 22	Location 23	Total
\$(97,321)	\$(48,661)	\$(24,330)	\$(12,143)	\$(48,661)	\$(12,143)	\$(18,214)	\$(404,286)

\$(124,488)	\$(42,648)	\$(23,540)	\$(3,916)	\$(10,533)	\$(6,527)	\$(13,706)	\$(348,849)
\$121,652	\$60,826	\$30,413	\$15,179	\$60,826	\$15,179	\$22,768	\$505,357
\$(669,089)	\$(309,387)	\$(127,719)	\$(44,183)	\$(243,919)	\$(79,489)	\$(106,188)	\$(2,127,809)
\$(542,039)	\$(271,019)	\$(140,476)	\$(70,310)	\$(271,019)	\$(70,310)	\$(105,943)	\$(2,297,177)
\$852,044	\$426,022	\$213,011	\$106,310	\$426,022	\$106,310	\$159,465	\$3,539,500
\$172,656	\$86,328	\$43,164	\$21,542	\$86,328	\$21,542	\$32,314	\$717,235
\$7,529	\$3,764	\$1,882	\$939	\$3,764	\$939	\$1,409	\$31,275
\$772,428	\$386,214	\$193,107	\$96,376	\$386,214	\$96,376	\$144,565	\$3,208,765
\$113,706	\$56,853	\$28,427	\$14,187	\$56,853	\$14,187	\$21,281	\$472,349
\$(4,233)	\$(1,957)	\$(808)	\$(280)	\$(1,543)	\$(503)	\$(672)	\$(13,461)
\$(788)	\$(270)	\$(149)	\$(25)	\$(67)	\$(41)	\$(87)	\$(2,207)
\$(101,521)	\$(50,761)	\$(25,380)	\$(12,667)	\$(50,761)	\$(12,667)	\$(19,000)	\$(421,733)
\$(444)	\$(222)	\$(111)	\$(55)	\$(222)	\$(55)	\$(83)	\$(1,844)
\$(99)	\$(49)	\$(25)	\$(12)	\$(49)	\$(12)	\$(19)	\$(411)
\$(3,063)	\$(1,531)	\$(766)	\$(382)	\$(1,531)	\$(382)	\$(573)	\$(12,722)

D.5 AMPL script for optimization model

The following section describes the formulations and data sets used in the optimization model

D.5.1 MOD file:

```
param m;  
  
param n;  
  
param o;  
  
param s;  
  
set I: = {1..m}; # No of Farms  
  
set J: = {1..n}; # No of City centers  
  
set K: = {1..o}; # No of Plants  
  
set H: = {1..s}; # No of Capacities  
  
param D1 {I, K} >=0; # Distance matrix from farms to plants  
  
param D2 {J, K} >=0; # Distance matrix from City center to plants  
  
param A1 {I} >= 0; # amount of manure available  
  
param A2 {J} >= 0; # amount of food waste available  
  
param INV {K, H} >=0; # Capital cost Matrix at capacity H  
  
param C1 {K, H} >=0; # Capacity in tons Matrix at capacity H  
  
param OM {K, H} >=0; # OM cost Matrix at capacity H  
  
param EC1 {K, H} >=0; # Electricity (kW) Matrix at capacity H  
  
param Fert cap {K, H} >=0; # amount of digestate (gallons) Matrix at capacity H  
  
param a = 40; # Cost of manure acquisition  
  
param b = -20; #cost of food waste acquisition  
  
param c = 0.064; # electricity cost- fix
```

```

param d = 2.64; # Digestate cost: -fix

param e = 0.015; # Carbon credits

var X1 {I, K} >= 0; # Amount of manure from farm to plant

var X2 {J, K} >= 0; # Amount of food waste from city to plant

var X4 {K, H} integer >= 0;

var E1 {K} >= 0;

var Fert {K} >= 0;

maximize z: - sum {i in I, k in K} X1[i,k] * a * 30 # Acquisition cost of manure per month
               - sum {i in I, k in K} X1[i,k] * D1[i,k] * 0.43 * 5*2*30 # transportation
costs of manure per month
               - sum {j in J, k in K} X2[j,k] * b * 30 # Acquisition cost of food waste per month
               - sum {j in J, k in K} X2[j,k] * D2[j,k] * 0.43 * 3.25*2*30 # transportation costs of
food waste
per month
               - sum {k in K, h in H} (INV[k,h]*0.007873 + OM[k,h]*0.0866)*EC1[k,h]*X4[k,h] #
Capital and operating costs per month
               + sum {k in K} E1[k]*24*c*30 # revenue from electrcity per month E1 is in kW
               + sum {k in K} Fert[k]*d*30 # Revenue from digestate per month
               + sum {j in J, k in K} 70 *(0.194+0.243)* 3.25* X2[j,k]* e*30*0.83
               + sum {j in J, k in K} X2[j,k] * 10.2 *e*30*1000*0.83
               + sum {i in I, k in K} X1[i,k] *
(5.32*0.65+1.38*0.1+0.631*0.25)*e*30*1000*0.83
               - sum {j in J, k in K} X2[j,k] * D2[j,k] * 3.25
*(0.194+0.243)*e*30*0.83 # Food waste transportation emissions per annum
               - sum {i in I, k in K} X1[i,k] * D1[i,k] * 5*(0.194+0.243)*e*30*0.83
               - sum {k in K} E1[k]*e*30*0.0147*1000*0.83

```

$$\begin{aligned}
& - \sum_{k \in K} E1[k] * 0.378 * e * 1000 * 30 * 0.00017 * 0.83 \\
& - \sum_{k \in K} E1[k] * 4.94 * e * 1000 * 30 * 0.0000029 * 0.83 \\
& - \sum_{k \in K} E1[k] * 1.81 * e * 1000 * 30 * 0.000245 * 0.83;
\end{aligned}$$

s.t. constraint1 {i in I}:

$$\sum_{k \in K} X1[i,k] \leq A1[i]; \# i \text{ is farm}$$

s.t. constraint2 {j in J}:

$$\sum_{k \in K} X2[j,k] \leq A2[j]; \# j \text{ is County}$$

s.t. constraint3 {k in K}:

$$(\sum_{j \in J} X2[j,k] + \sum_{i \in I} X1[i,k]) * (65.141) = E1[k];$$

s.t. constraint4 {k in K}:

$$\sum_{j \in J} X2[j,k] + \sum_{i \in I} X1[i,k] \leq \sum_{h \in H} X4[k,h] * C1[k,h];$$

s.t. constraint5 {k in K}:

$$E1[k] \leq \sum_{h \in H} X4[k,h] * EC1[k,h];$$

s.t. constraint6 {k in K}:

$$(\sum_{j \in J} X2[j,k] + \sum_{i \in I} X1[i,k]) * (7.68) = Fert[k];$$

s.t. constraint7 {k in K}:

$$Fert[k] \leq \sum_{h \in H} X4[k,h] * Fertcap[k,h]; \# Fertcap$$

s.t. constraint8 {k in K}:

$$\sum_{j \in J} X2[j,k] - \sum_{i \in I} X1[i,k] * (2.5) = 0;$$

D.5.2 DATA file:

param m := 240; # No of farms

param o := 24; # No of plants

param n := 72; # No of city centers

param s := 5; # No of capacities

param	D1:	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20	21
	22	23	24	:=							
1	262 176 191	266 129 210	280 133	272 93	274 89	279 25	234 42	233 23	236 10	175 29	146 87
2	262 151 166	252 104 198	266 107	250 68	253 58	242 17	223 30	214 55	235 41	174 58	145 122
3	278 174 190	282 127 222	295 131	288 92	290 83	266 8	247 50	249 38	252 30	191 52	162 124
4	267 156 172	271 109 204	284 113	256 74	259 58	248 15	229 38	237 60	240 46	179 62	150 127
5	279 147 171	257 100 203	271 103	255 64	258 51	247 23	228 51	218 72	227 59	192 75	163 139
6	267 181 197	271 134 215	285 138	276 99	279 94	284 25	239 47	238 24	241 11	180 36	150 92
7	260 160 175	264 113 207	277 116	269 77	272 72	251 12	232 31	230 48	233 34	172 51	143 120
8	273 199 214	277 152 254	291 155	283 116	285 115	290 42	274 72	244 11	247 19	200 36	172 90
9	268 161 177	272 115 209	286 118	278 79	280 66	253 6	234 40	239 49	242 39	181 60	152 128
10	289 128 181	267 72 213	281 98	265 51	268 20	257 51	238 56	228 95	237 82	212 98	193 162

11	276 203 219	280 156 256	293 160	285 121	288 113	292 40	276 70	246 11	249 19	202 39	175 93
12	275 153 180	279 106 213	293 110	264 71	267 60	256 14	237 47	246 56	249 55	188 71	159 135
13	268 127 160	246 80 192	259 84	244 44	247 32	236 40	217 33	207 79	216 66	189 82	160 136
14	268 182 197	271 135 215	285 138	277 99	280 94	284 25	240 48	238 24	241 11	180 36	151 92
15	551 437 503	519 495 511	513 494	451 526	465 544	462 600	490 581	493 631	503 617	549 634	575 688
16	259 170 185	263 123 217	277 126	269 87	271 83	261 25	242 36	230 30	233 17	172 35	143 89
17	277 193 209	281 147 223	294 150	286 111	289 119	294 37	277 59	247 11	250 14	204 31	159 94
18	266 166 181	270 119 214	283 123	275 84	278 79	257 19	238 32	236 35	240 22	178 40	149 94
19	271 200 201	275 153 252	288 157	280 118	283 119	288 46	271 66	241 7	245 19	198 32	170 88
20	272 197 212	276 150 222	290 154	282 115	284 120	289 42	273 63	243 6	246 17	199 30	171 89
21	273 198 213	277 151 223	290 155	282 116	285 118	290 42	274 64	244 7	247 19	200 31	172 90

22	264 164 179	268 117 212	281 121	273 81	276 77	255 20	236 31	234 37	237 24	176 43	147 96
23	265 153 169	269 106 201	283 110	253 71	256 56	245 16	226 37	216 58	239 45	178 61	149 125
24	288 194 199	292 134 231	305 133	283 94	286 85	275 16	256 59	258 37	261 35	200 55	171 123
25	298 194 209	302 143 242	315 151	308 111	310 94	315 18	266 60	269 38	272 33	201 54	172 115
26	295 168 192	299 126 224	312 124	276 85	279 77	268 24	249 68	239 49	270 47	209 67	180 138
27	289 190 205	293 143 237	306 146	298 107	301 109	306 28	262 56	259 20	262 22	216 41	168 106
28	290 187 203	294 140 235	308 144	300 105	303 105	307 27	260 54	261 23	264 27	195 47	166 108
29	278 144 169	255 97 201	268 101	253 62	256 51	245 23	226 49	216 71	225 57	190 74	161 138
30	278 117 170	256 62 202	269 87	254 40	257 10	246 62	227 52	217 102	226 88	201 105	182 158
31	276 175 191	280 128 223	294 132	286 93	288 88	267 13	248 48	247 32	250 24	189 45	160 121
32	315 114 207	293 57 239	307 125	291 77	294 43	283 88	264 103	254 128	263 120	238 151	219 205

33	260 161 176	264 114 208	278 117	270 78	273 73	252 12	233 32	231 48	234 35	173 51	144 120
34	315 110 207	293 54 239	306 125	291 77	294 50	283 101	264 109	254 142	263 134	238 165	219 219
35	290 122 182	268 44 214	281 100	266 52	269 17	258 89	239 78	229 130	238 122	213 131	194 185
36	286 166 191	289 119 223	303 123	275 84	277 74	267 14	247 57	256 47	259 42	198 62	169 136
37	298 185 198	302 125 231	316 155	283 108	285 76	274 27	255 69	268 54	271 46	210 66	181 131
38	281 186 202	285 140 234	299 143	299 104	302 102	278 25	259 53	260 20	263 19	194 39	165 107
39	262 74 154	240 23 186	253 57	238 35	241 53	230 109	211 90	201 140	210 127	185 143	177 197
40	254 93 146	232 46 178	245 63	230 16	233 35	222 79	203 61	193 110	202 97	177 113	158 167
41	289 60 181	267 5 213	281 83	265 51	268 58	257 125	238 106	228 156	237 143	212 159	193 213
42	294 59 185	272 9 217	285 80	269 55	272 62	261 129	242 110	232 160	241 147	216 163	197 217
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9	283 82 175	261 21 207	274 92	259 45	261 34	251 99	231 89	222 155	231 126	206 142	187 194
10	133 205 125	137 178 114	151 159	143 136	145 175	150 145	134 118	104 140	107 133	60 115	38 80
11	292 157 191	277 119 224	291 115	275 75	278 60	267 23	248 63	239 69	265 52	204 73	175 144

12	158 112 37	136 177 73	150 81	116 135	122 173	100 184	85 136	96 216	106 202	92 188	117 224
13	289 194 209	293 147 242	306 151	298 112	301 104	306 29	290 60	260 29	263 34	216 52	172 104
14	307 112 199	285 55 231	299 117	283 69	286 34	275 85	256 121	246 126	255 118	230 138	211 201
15	77 189 58	55 213 14	68 151	49 171	52 210	46 220	33 172	12 238	17 212	56 213	81 188
16	253 154 169	257 107 200	270 111	262 72	265 67	270 19	225 23	223 45	226 31	165 47	136 111
17	301 180 232	318 120 264	332 150	316 103	319 71	308 31	289 72	280 55	289 49	213 78	184 130
18	114 252 122	82 277 76	76 214	17 235	26 273	35 298	53 236	58 297	69 286	115 272	140 247
19	268 127 160	246 80 192	259 84	244 45	247 32	236 40	217 32	207 80	216 66	189 82	160 134
20	275 107 167	253 49 199	267 85	251 37	254 6	243 71	224 61	214 130	223 98	198 114	179 166
21	265 216 198	269 170 246	282 173	274 134	277 127	282 53	265 83	235 12	239 26	192 27	164 80
22	151 160 76	150 143 96	163 97	148 102	151 140	140 122	121 77	111 119	120 110	70 100	43 119

23	163 171 93	167 144 109	181 125	172 103	175 141	180 111	134 79	134 108	137 99	74 89	46 99
24	64 198 68	45 223 26	59 160	54 181	57 219	61 229	45 182	15 228	13 218	46 203	71 178
25	210 89 102	188 74 134	201 36	186 42	189 80	178 90	159 58	149 122	158 108	133 125	110 177
26	218 100 110	196 74 142	210 54	194 32	197 70	186 74	167 41	158 106	166 91	146 108	117 160
27	238 25 114	216 90 162	229 54	214 99	217 116	192 173	178 154	177 204	186 190	161 207	169 259
28	193 177 118	197 150 140	210 131	202 109	205 118	210 82	165 49	163 79	166 70	105 60	76 80
29	254 182 180	258 136 202	271 139	263 100	266 95	271 30	226 49	224 18	228 6	166 21	137 77
30	150 112 26	128 151 74	141 76	126 109	128 147	117 158	98 110	89 190	98 176	72 162	86 193
31	48 239 109	16 264 67	15 201	58 222	46 260	68 277	57 223	57 276	41 266	94 251	119 226
32	83 209 78	70 233 32	58 171	31 191	34 230	32 254	19 193	14 253	25 242	70 228	96 203
33	108 335 204	101 359 163	92 297	147 317	135 356	158 372	161 318	153 371	136 361	189 346	214 321

34	76 273 142	50 297 101	40 235	41 255	36 294	62 310	75 256	81 309	74 299	127 284	152 259
35	125 216 99	93 258 58	83 196	16 217	30 255	12 266	30 218	58 296	68 286	114 271	139 246
36	189 229 172	193 182 170	206 188	198 147	201 142	206 105	189 87	159 84	163 80	116 59	88 30
37	225 269 239	263 222 240	276 225	268 186	271 181	276 145	259 127	229 101	233 98	186 77	158 35
38	237 247 217	241 200 218	255 204	247 165	250 160	254 123	238 105	208 79	211 77	164 56	137 23
39	278 47 169	256 18 202	269 69	254 61	256 71	245 134	226 116	217 166	226 152	201 168	203 220
40	111 262 182	121 235 171	141 216	199 193	202 231	207 201	190 175	160 181	163 190	117 156	94 96
41	111 165 45	105 190 51	118 127	103 148	105 186	94 169	75 143	66 167	75 158	24 147	36 157
42	180 81 56	158 124 104	172 50	156 100	159 138	130 157	116 140	120 189	129 175	103 192	121 227
43	115 159 23	93 193 27	106 131	91 151	93 190	70 201	51 153	54 211	63 203	65 192	87 212
44	119 219 139	122 192 128	139 173	156 150	159 188	164 158	147 132	117 157	121 147	74 132	51 87

45	267 262 233	271 216 248	285 219	277 180	280 175	284 126	268 121	238 84	241 86	194 65	167 80
46	179 102 71	157 108 103	170 44	155 66	158 105	147 116	128 68	118 147	127 133	102 124	75 180
47	203 149 111	193 122 139	206 103	191 80	194 93	183 79	164 37	154 97	176 88	115 78	86 108
48	246 34 125	224 54 171	238 29	222 62	225 80	214 136	195 117	186 168	195 154	169 170	143 222
49	117 287 207	147 260 196	149 241	224 218	227 257	232 199	216 200	186 195	189 191	142 170	120 109
50	123 138 18	101 163 47	115 101	99 121	102 160	91 170	72 122	63 178	72 169	46 159	65 187
51	256 244 214	260 197 237	273 200	265 161	268 159	273 86	256 102	226 43	229 55	182 39	155 69
52	86 205 102	91 221 91	105 147	119 179	122 217	127 187	110 161	80 186	83 176	36 161	30 136
53	190 130 86	168 113 114	181 67	166 71	168 110	157 111	138 60	129 128	138 120	102 109	73 148
54	145 224 159	155 197 154	191 178	182 155	185 176	190 139	174 121	144 136	147 132	100 111	78 59
55	239 149 129	215 102 162	229 101	213 67	216 67	205 49	186 7	177 72	186 58	152 64	123 113

56	208 60 90	186 90 132	200 15	184 65	187 104	165 146	157 105	148 178	157 164	131 181	117 233
57	284 19 147	262 49 208	275 51	260 82	263 100	252 156	233 137	223 188	232 174	207 190	165 242
58	37 292 162	45 317 120	49 254	105 275	92 313	116 298	119 276	110 297	94 286	120 272	146 218
59	216 60 97	194 119 130	207 64	175 108	181 136	158 192	144 154	154 224	164 210	148 226	166 279
60	87 363 219	102 336 177	106 262	162 295	149 333	173 303	176 277	167 302	151 291	153 277	146 217
61	43 265 134	31 289 92	16 226	71 247	59 285	82 302	91 248	82 301	66 291	119 276	144 251
62	69 291 160	57 315 118	46 252	69 273	61 311	87 328	100 274	108 327	92 317	145 302	170 277
63	215 125 107	193 98 139	206 79	191 56	194 94	183 72	163 29	154 95	163 81	136 86	107 135
64	91 354 223	106 348 182	111 316	166 306	154 344	177 314	180 288	172 313	155 303	164 288	157 228
65	24 233 103	33 257 74	52 195	106 215	84 254	104 249	97 223	67 248	52 238	66 223	91 181
66	57 286 136	79 259 122	89 188	151 217	130 255	158 225	142 199	112 224	98 214	78 199	72 153

67	122 166 57	100 225 37	114 135	60 183	66 222	44 232	29 184	55 246	61 237	94 227	116 234
68	137 274 194	147 247 183	166 228	211 205	214 208	219 172	203 154	173 158	176 146	129 125	107 68
69	106 193 71	76 230 29	76 167	44 188	45 226	24 237	5 189	33 238	45 229	86 219	111 218
70	98 325 207	120 298 179	128 279	183 256	171 294	194 264	197 238	171 263	157 253	154 238	157 174
71	192 237 176	196 190 173	210 192	202 154	205 150	209 113	193 95	163 92	166 88	119 67	92 29
72	170 325 248	198 278 237	202 282 ;	266 243	268 238	273 201	257 183	227 157	230 154	183 133	161 86

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1	15
2	12
3	15
4	37
5	23
6	12
7	26
8	123
9	16
10	10
11	13

12	22
13	52
14	23
15	0
16	53
17	62
18	27
19	61
20	20
21	21
22	25
23	30
24	24
25	15
26	21
27	14
28	12
29	34
30	21
31	22
32	30
33	17
34	20
35	19

36	16
37	15
38	18
39	12
40	23
41	19
42	32
43	18
44	19
45	24
46	21
47	33
48	18
49	58
50	30
51	64
52	38
53	15
54	31
55	24
56	19
57	36
58	26
59	42

60	43
61	16
62	33
63	24
64	9
65	20
66	34
67	30
68	10
69	103
70	19
71	58
72	20
73	25
74	16
75	84
76	75
77	20
78	64
79	27
80	57
81	69
82	17
83	11

84	66
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100	18
101	26
102	42
103	22
104	24
105	36
106	31
107	12

108	36
109	75
110	27
111	48
112	12
113	29
114	20
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116	12
117	20
118	29
119	40
120	13
121	36
122	15
123	25
124	16
125	22
126	12
127	36
128	19
129	22
130	21
131	18

132	14
133	161
134	22
135	21
136	12
137	13
138	64
139	16
140	68
141	17
142	16
143	25
144	16
145	18
146	22
147	17
148	12
149	42
150	55
151	16
152	37
153	31
154	37
155	29

156	37
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158	22
159	12
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161	23
162	18
163	16
164	21
165	16
166	10
167	36
168	24
169	12
170	22
171	18
172	37
173	13
174	42
175	16
176	33
177	26
178	25
179	21

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181	16
182	34
183	12
184	12
185	15
186	24
187	16
188	8
189	12
190	12
191	16
192	21
193	57
194	11
195	12
196	14
197	16
198	24
199	15
200	25
201	14
202	22
203	18

204	20
205	10
206	38
207	26
208	12
209	66
210	129
211	17
212	52
213	40
214	157
215	33
216	23
217	22
218	14
219	15
220	0
221	16
222	18
223	133
224	48
225	13
226	18
227	26

228	10
229	29
230	42
231	162
232	22
233	25
234	30
235	43
236	35
237	26
238	13
239	18
240	45

 ;

param A2: =

1	152.7
2	84.8
3	63.8
4	41.6
5	31.3
6	29.6
7	27.2
8	26.9
9	25.9
10	21.6

11	21.5
12	18.9
13	18.4
14	16.5
15	16.5
16	16.4
17	14.1
18	14.1
19	14.0
20	13.5
21	12.7
22	11.7
23	11.3
24	10.2
25	10.2
26	9.1
27	8.3
28	8.2
29	8.0
30	7.3
31	7.2
32	7.1
33	6.9
34	6.9

35	6.7
36	6.6
37	6.5
38	6.0
39	5.9
40	5.7
41	5.5
42	4.9
43	4.7
44	4.5
45	4.4
46	4.2
47	3.9
48	3.8
49	3.5
50	3.3
51	3.3
52	3.3
53	3.2
54	3.1
55	3.0
56	2.8
57	2.7
58	2.6

59	2.6
60	2.5
61	2.5
62	2.4
63	2.4
64	2.4
65	2.3
66	2.2
67	2.1
68	1.4
69	1.2
70	0.9
71	0.7
72	0.7 ;

param Fert cap: 1 2 3 4 5: =

1	68	136	272	545	1090
2	68	136	272	545	1090
3	68	136	272	545	1090
4	68	136	272	545	1090
5	68	136	272	545	1090
6	68	136	272	545	1090
7	68	136	272	545	1090
8	68	136	272	545	1090
9	68	136	272	545	1090

10	68	136	272	545	1090
11	68	136	272	545	1090
12	68	136	272	545	1090
13	68	136	272	545	1090
14	68	136	272	545	1090
15	68	136	272	545	1090
16	68	136	272	545	1090
17	68	136	272	545	1090
18	68	136	272	545	1090
19	68	136	272	545	1090
20	68	136	272	545	1090
21	68	136	272	545	1090
22	68	136	272	545	1090
23	68	136	272	545	1090
24	68	136	272	545	1090 ;

param OM: 1 2 3 4 5:=

1	137.15	126.3	124.55	124.45	120.05
2	137.15	126.3	124.55	124.45	120.05
3	137.15	126.3	124.55	124.45	120.05
4	137.15	126.3	124.55	124.45	120.05
5	137.15	126.3	124.55	124.45	120.05
6	137.15	126.3	124.55	124.45	120.05
7	137.15	126.3	124.55	124.45	120.05
8	137.15	126.3	124.55	124.45	120.05

9	137.15	126.3	124.55	124.45	120.05
10	137.15	126.3	124.55	124.45	120.05
11	137.15	126.3	124.55	124.45	120.05
12	137.15	126.3	124.55	124.45	120.05
13	137.15	126.3	124.55	124.45	120.05
14	137.15	126.3	124.55	124.45	120.05
15	137.15	126.3	124.55	124.45	120.05
16	137.15	126.3	124.55	124.45	120.05
17	137.15	126.3	124.55	124.45	120.05
18	137.15	126.3	124.55	124.45	120.05
19	137.15	126.3	124.55	124.45	120.05
20	137.15	126.3	124.55	124.45	120.05
21	137.15	126.3	124.55	124.45	120.05
22	137.15	126.3	124.55	124.45	120.05
23	137.15	126.3	124.55	124.45	120.05
24	137.15	126.3	124.55	124.45	120.05 ;

param EC1: 1 2 3 4 5:=

1	578	1156	2313	4625	9250
2	578	1156	2313	4625	9250
3	578	1156	2313	4625	9250
4	578	1156	2313	4625	9250
5	578	1156	2313	4625	9250
6	578	1156	2313	4625	9250
7	578	1156	2313	4625	9250

8	578	1156	2313	4625	9250
9	578	1156	2313	4625	9250
10	578	1156	2313	4625	9250
11	578	1156	2313	4625	9250
12	578	1156	2313	4625	9250
13	578	1156	2313	4625	9250
14	578	1156	2313	4625	9250
15	578	1156	2313	4625	9250
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18	578	1156	2313	4625	9250
19	578	1156	2313	4625	9250
20	578	1156	2313	4625	9250
21	578	1156	2313	4625	9250
22	578	1156	2313	4625	9250
23	578	1156	2313	4625	9250
24	578	1156	2313	4625	9250 ;

param C1: 1 2 3 4 5: =

1	9	18	36	72	142
2	9	18	36	72	142
3	9	18	36	72	142
4	9	18	36	72	142
5	9	18	36	72	142
6	9	18	36	72	142

7	9	18	36	72	142
8	9	18	36	72	142
9	9	18	36	72	142
10	9	18	36	72	142
11	9	18	36	72	142
12	9	18	36	72	142
13	9	18	36	72	142
14	9	18	36	72	142
15	9	18	36	72	142
16	9	18	36	72	142
17	9	18	36	72	142
18	9	18	36	72	142
19	9	18	36	72	142
20	9	18	36	72	142
21	9	18	36	72	142
22	9	18	36	72	142
23	9	18	36	72	142
24	9	18	36	72	142 ;

param INV: 1 2 3 4 5 :=

1	2743	2526	2491	2489	2401
2	2743	2526	2491	2489	2401
3	2743	2526	2491	2489	2401
4	2743	2526	2491	2489	2401
5	2743	2526	2491	2489	2401

6	2743	2526	2491	2489	2401
7	2743	2526	2491	2489	2401
8	2743	2526	2491	2489	2401
9	2743	2526	2491	2489	2401
10	2743	2526	2491	2489	2401
11	2743	2526	2491	2489	2401
12	2743	2526	2491	2489	2401
13	2743	2526	2491	2489	2401
14	2743	2526	2491	2489	2401
15	2743	2526	2491	2489	2401
16	2743	2526	2491	2489	2401
17	2743	2526	2491	2489	2401
18	2743	2526	2491	2489	2401
19	2743	2526	2491	2489	2401
20	2743	2526	2491	2489	2401
21	2743	2526	2491	2489	2401
22	2743	2526	2491	2489	2401
23	2743	2526	2491	2489	2401
24	2743	2526	2491	2489	2401 ;

D.5.3 RUN file: solving using cplex

reset;

model Biogas_1.mod;

data Biogas_1.dat;

expand z, constraint1, constraint2, constraint3, constraint4, constraint5, constraint6, constraint7, constraint8;

option solver **cpex**;

solve;

display z, X1,X2,X4;

RUN COMMAND: After loading these files into AMPL software, use include Biogas_1.run in the console to run the model

D.5.4 Google script for calculating distances:

```
function GOOGLEMAPS (start_address,end_address,return_type) {  
  
var mapObj = Maps.newDirectionFinder();  
  
mapObj.setOrigin(start_address);  
  
mapObj.setDestination(end_address);  
  
var directions = mapObj.getDirections();  
  
var getTheLeg = directions["routes"][0]["legs"][0];  
  
var meters = getTheLeg["distance"]["value"];  
  
switch(return_type){  
  
    case "miles":  
  
        return meters * 0.000621371;  
  
        break;  
  
    case "minutes":  
  
var duration = getTheLeg["duration"] ["value"];  
  
return duration / 60;  
  
break;  
  
    case "hours":  
  
var duration = getTheLeg["duration"]["value"];  
  
return duration / 60 / 60;  
  
break;
```

```
case "kilometers":  
    return meters / 1000;  
break;  
default:  
    return "Error: Wrong Unit Type";  
} }
```


D.6 References:

- (1) Aui, A.; Wright, M. M., Life Cycle Cost Analysis of the Operations of Anaerobic Digesters in Iowa. Grant: 2018.
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- (3) Balaman, Ş. Y.; Selim, H., A network design model for biomass to energy supply chains with anaerobic digestion systems. *Applied Energy* **2014**, *130*, 289-304.
- (4) Ankathi, S. K.; Potter, J. S.; Shonnard, D. R., Carbon footprint and energy analysis of bio-CH₄ from a mixture of food waste and dairy manure in Denver, Colorado. *Environmental Progress & Sustainable Energy* **2018**, *37* (3), 1101-1111.
- (5) USEIA. U.S. electric utility and independent power electricity generation and resulting CO₂ emissions by fuel in 2018. <https://www.eia.gov/tools/faqs/faq.php?id=74&t=11> (accessed July 26).
- (6) USEIA. Wisconsin Electricity Profile 2018. <https://www.eia.gov/electricity/state/wisconsin/> (accessed July 26).

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Figure E-1. Copyright clearance for Chapter 2.

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Carbon footprint and energy analysis of bio-CH4 from a mixture of food waste and dairy manure in Denver, Colorado

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Publication: Environmental Progress & Sustainable Energy

Publisher: John Wiley and Sons

Date: Sep 26, 2017

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Figure E-2. Copyright clearance for Chapter 3.

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Life cycle assessment of oilseed crops produced in rotation with dryland cereals in the inland Pacific Northwest

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Date: Jun 4, 2018

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Author: Sharath Kumar Ankathi, Wen Zhou, J. Beau W. Webber, et al

Publication: ACS Sustainable Chemistry & Engineering

Publisher: American Chemical Society

Date: Aug 1, 2019

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