Appendices

Appendix A

Appendix to Chapter 2 - Biomass Consumed in the Current Bioeconomy

Table A-1 | Fuel-Related Conversion Factors and Other Values

Parameter or conversion factor		Reference
Fuels	Conversion efficiency (gallons/ton)	
Corn grain to ethanol	118	RFS2, USDA, Mueller and Kwik (2013), GREET
Cellulosic biomass to ethanol	85	*BETO Multi-Year Program Plan*
Biogenic MSW to ethanol	85	Assumed based on cellulosic
Cellulosic biomassto hydrocarbon drop-in blendstocks	56	*BETO Multi-Year Program Plan*
Vegetable oils and other fats, oils, and greases to biodiesel	267	2011 *Billion-Ton Update*

Table A-2 | Power-Related Energy Contents

Source	Energy Content	Reference
Biogenic municipal solid waste	9.80 MM Btu/ton	Calculated from EPA Advanced Sustainable Materials Management 2015
Other waste biomass	9.8 MMBtu/ton	Calculated from EPA Advanced Sustainable Materials Management 2015
Landfill gas	488.20 Btu/million cubic feet	Calculated from EIA 2015 *Electric Power* Annual, tables 5.5, 5.6, 5.7, and 5.8
Animal manure	885 Btu/lb (dairy heifer) to 2,949 Btu/lb (poultry	GREET biogas output and default assumptions applied by animal to estimate the total biomass digested
Woody biomass	13.00 MMBtu/ton	Conservative average (various sources)

Table A-3 | Distribution of Biopower Energy to Electric and Thermal Use by Sector

	Electric sector (%)		Industrial sector (%)		Commercial sector (%)	
Electrical vs. thermal output[a]	Electricity	Thermal	Electricity	Thermal	Electricity	Thermal
Biogenic portion of MSW	96.5	3.5	4.1	95.9	67.5	32.5
Other waste biomass	70.4	29.6	13.2	86.8	79.8	20.2
Landfill gas	99.9	0.1	96.8	3.2	98.2	1.8

[a] Tables 5.5, 5.6, 5.7, and 5.8 of the EIA 2015 *Electric Power Annual* report the consumption of wood/wood waste biomass, landfill gas, biogenic municipal solid waste, and other waste biomass for electricity generation, useful thermal output, and total output in billion Btu. An analysis of this data allows for the distribution of energy generated for electrical or thermal output to be determined for 2013 data. This energy distribution relationship is assumed to remain constant and is applied to future biopower projections.

Table A-4 | Power-Related Conversion Efficiencies

Parameter or conversion factor			Reference
Power	Electric[b] (%)	Thermal[c] (%)	
Conversion efficiency[a]			
Biogenic municipal solid waste	25	45	2015 *Annual Energy Outlook*
Other waste biomass	25	45	2015 *Annual Energy Outlook*
Landfill gas and anaerobic digester gas	30[d]	78[e]	EIA 2015 *Electric Power Annual*
Woody biomass	25	60	2015 *Annual Energy Outlook*

[a] Depending on the technology and combustion method, electrical and thermal conversion efficiency may vary. For thermal conversion efficiency, a conservative estimate of 45%, based on the annual fuel utilization of woody biomass, was used as a simplifying assumption for biogenic municipal waste.

[b] Electrical conversion efficiency calculation: Table A16 of the EIA *Annual Energy Outlook* reports the renewable electrical generation for biogenic municipal solid waste and for wood and other biomass, whereas table A17 reports renewable energy consumption for electric power. These values were used to estimate an electrical conversion efficiency of 26% of biogenic municipal solid waste.

[c] Thermal efficiencies are conservative estimates based on the annual fuel utilization efficiency of woody biomass, which range from 45% to 90% for conventional and state-of-the-art technology, respectively (see energy.gov/energysaver/furnaces-and-boilers).

[d] Electrical conversion efficiency calculation: Table 8.2 of the EIA *Electric Power Annual* reports the average tested heat rates by technology and energy source from 2007 to 2013. Natural gas combustion via gas turbine was used to estimate an electrical conversion efficiency of 30% for landfill gas and anaerobic digester gas.

[e] A conservative estimate of 78%, based on the annual fuel utilization efficiency of a mid-efficiency natural gas boiler, was used as a simplifying assumption for landfill gas and anaerobic digester gas.

Appendix B

Appendix to Chapter 3 - At the Roadside: Forest Resources

ForSEAM Model Constraints (Eq. A1–A18)

Timber land and harvest intensity constraints

(A1).
$$(X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} \leq \omega_{i,j,k} A_{i,j,k,o,m,t} \alpha_{i,j,k,c,t}$$
$$\forall \text{ all } i,j,o,m,t,k=1,c=1,p=1$$

(A2).
$$\sum_{c=1}^{2} \left[X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t} + Z_{i,j,k,o,m,c,t}\right] \alpha_{i,j,k,c,t} \leq \sum_{c=1}^{1} \omega_{i,j,k} A_{i,j,k,o,m,t} \alpha_{i,j,k,c,t}$$
$$\forall \text{ all } i,j,o,m,t,k=2,p=2$$

(A3).
$$Z_{i,j,k,o,m,c,t} \alpha_{i,j,k,c,t} \leq \omega_{i,j,k} A_{i,j,k,o,m,t} \alpha_{i,j,k,c,t} \ \forall \text{ all } i,j,m,t,k=3,c=1$$

(A4).
$$X_{i,j,k,o,m,c,p,t} = XCTL_{i,j,k,o,m,c,p,t} \ \forall \text{ all } i \in (NC, IW), j,m,c,t,o=1,k=1{,}2$$

(A5).
$$U_{i,j,k,o,m,n,c,t} \leq \sum_{p=1}^{2} X_{i,j,k,o,m,c,p,t} \ \forall \text{ all } i,j,m,c,t,k=1{,}3$$

Proportion of thinning and clear-cut

(A6).
$$\sum_{c=1}^{1} \sum_{m=1}^{2} \sum_{p=1}^{2} (X_{i,j,k,m,c,p,t} + XCTL_{i,j,k,o,m,c,p,t} + Z_{i,j,k,c,t})$$
$$= r_{i,j} \sum_{c=1}^{2} \sum_{m=1}^{2} \sum_{p=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t} + Z_{i,j,k,c,t}) \ \forall \text{ all } i,j,t,o,k=2$$

Growth constraint

(A7).
$$\sum_{si} \sum_{c=1}^{2} \sum_{p=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\alpha_{i,j,k,c,t} + \sum_{c=1}^{2} Z_{i,j,k,o,m,c,t} \beta_{i,j,k,c,t} +$$
$$\sum_{c=1}^{2} U_{i,j,k,o,m,c,t} \theta_{i,j,k,c,t} \leq \sum_{si} \bar{G}_{i,j,k,o,m} + g_{i,j,k,m} A_{i,j,k,o,m,t} \ \forall \text{ all } si,j,o,m,t,k$$

Inter-period stand diameter class determination

(A8).
$$A_{i,j,k,o,m,t} = A^{0}_{i,j,k,o,m} \ \forall \text{ all } i,j,k,o,m,n,t=1$$

(A9).
$$A_{i,j,k,o,m,t} =$$
$$A_{i,j,k,o,m,t-1} - \sum_{c=1}^{2} (X_{i,j,k,o,m,c,p=1,t-1} + XCTL_{i,j,k,o=1,m,c,p=1,t-1})$$
$$+ \left\{ A_{i,j,kk,o,m,t-1} - \sum_{c=1}^{2} \left[\sum_{p=1}^{2} (X_{i,j,kk,o,m,c,p,t-1} + XCTL_{i,j,kk,o,m,c,p,t-1}) \right] \right.$$
$$\left. + Z_{i,j,kk,o,m,c,t-1} \right\} v_{i,j,kk,k,t-1} \ \forall all \ i,j,o,m,k=1,kk=2$$

(A10). $A_{i,j,k,o,m,t}$

$$= A_{i,j,k,o,m,t-1} - \sum_{c=1}^{2} (X_{i,j,k,o,m,c,p=2,t-1} + XCTL_{i,j,k,o=1,m,c,p=2,t-1} + Z_{i,j,k,o,m,c,t-1})$$
$$+ \{A_{i,j,kk,o,m,t-1} - Z_{i,j,kk,o,m,c,t-1}\} v_{i,j,kk,k,t-1} \ \forall all\ i, j, o, m, k = 2, kk = 3$$

(A11). $A_{i,j,k,o,m,t} = A_{i,j,k,o,m,t-1} + AR_{i,j,o,m,t-1}\ \forall\ \text{all}\ i, j, o, m, k = 3$

(A12). $AR_{i,j,k,o,m,t+n-1} = \sum_{n=1}^{26} R_{i,j,o,m,n,t} u_{i,j,n}\ \ \forall\ \text{all}\ i, j, o, m, n, t, k = 2$

(A13). $R_{i,j,o,m,n-t+1,t} = \sum_{c=1}^{2} \sum_{k=1}^{3} \left[\sum_{p=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t})\right] + Z_{i,j,k,o,m,c,t}\ \forall\ \text{all}\ i, j, o, m, n, t$

Conventional demand

Hardwood Sawlogs

(A14). $$\sum_{i=si} \sum_{j=1}^{2} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t}$$
$$+ 0.375 \sum_{i=si} \sum_{j=5}^{5} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t}$$

$\forall\ \text{all}\ s, t, o, f = 1, k = 1, p = 1$

Softwood Sawlogs

(A15). $\sum_{si \in i} \sum_{j=3}^{4} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} +$

0.625 $\sum_{si \in i} \sum_{j=5}^{5} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall\ \text{all}\ s, t, f = 2, k = 1, p = 1$

Hardwood Pulpwood

(A16). $\sum_{si \in i} \sum_{j=1}^{2} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{k=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} +$

0.375 $\sum_{si \in i} \sum_{j=5}^{5} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{k=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall\ \text{all}\ s, t, f = 1, p = 2$

Softwood Pulpwood

(A17). $\sum_{si \in i} \sum_{j=3}^{4} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{k=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} +$

0.625 $\sum_{si \in i} \sum_{j=5}^{5} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{k=1}^{2} \sum_{o=1}^{2} (X_{i,j,k,o,m,c,p,t} + XCTL_{i,j,k,o=1,m,c,p,t}) \alpha_{i,j,k,c,t} \geq D_{s,f,k,t}$

$\forall\ \text{all}\ s, t, f = 2, p = 2$

Woody biomass supply target

(A18). $\sum_{i=1}^{305} \sum_{j=1}^{5} \sum_{k=1}^{2} \sum_{m=1}^{2} \sum_{o=1}^{2} (0.7 U_{i,j,k,o,m,c,t}\ \theta_{i,j,k,o,m,t}) + \sum_{i=1}^{305} \sum_{j=1}^{5} \sum_{k=2}^{3} \sum_{m=1}^{2} \sum_{c=1}^{2} \sum_{o=1}^{2} Z_{i,j,o,m,c,t} \beta_i$

$B_t\ [\lambda_t]\ \forall\ \text{all}\ t$

Conventional Wood Volumes Generated by Scenario and Year

Table B-1 | USFPM Projection of Conventional Demand Under Scenario Baseline ML (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.62	6.18	6.70	7.17	7.37	7.60
Softwood pulpwood	4.02	4.43	4.80	5.02	5.18	5.03	4.51
Softwood sawlogs	10.55	12.56	13.12	13.41	13.86	13.88	13.31
Hardwood pulpwood	13.62	17.08	18.07	18.50	19.01	18.80	18.13
Other industrial roundwood	0.66	0.78	0.84	0.88	0.93	0.94	0.94
Total roundwood harvested	*33.43*	*40.49*	*43.01*	*44.52*	*46.16*	*46.03*	*44.49*
South							
Softwood sawlogs	27.18	37.84	45.46	51.78	57.87	60.63	61.36
Softwood pulpwood	39.90	43.85	46.57	48.22	50.91	53.88	54.20
Softwood sawlogs	14.92	15.31	16.36	17.45	18.61	19.37	19.03
Hardwood pulpwood	11.57	17.71	20.59	21.99	23.45	24.44	24.09
Other industrial roundwood	1.79	2.15	2.50	2.77	3.03	3.19	3.22
Total roundwood harvested	*95.36*	*116.85*	*131.48*	*142.21*	*153.87*	*161.50*	*161.89*
West							
Softwood sawlogs	25.76	36.51	39.80	42.56	45.27	46.25	47.32
Softwood pulpwood	1.25	0.68	0.35	0.18	0.14	0.18	0.26
Softwood sawlogs	1.22	1.31	1.39	1.49	1.60	1.77	1.88
Hardwood pulpwood	0.32	0.27	0.28	0.39	0.74	1.02	1.08
Other industrial roundwood	0.60	0.82	0.90	0.96	1.02	1.05	1.08
Total roundwood Harvested	*29.14*	*39.59*	*42.72*	*45.57*	*48.77*	*50.26*	*51.62*
United States							
Softwood sawlogs	57.52	79.97	91.44	101.04	110.32	114.26	116.28
Softwood pulpwood	45.17	48.96	51.73	53.42	56.24	59.09	58.97
Softwood sawlogs	26.70	29.18	30.87	32.35	34.07	35.02	34.22
Hardwood pulpwood	25.50	35.06	38.94	40.88	43.20	44.26	43.30
Other industrial roundwood	3.04	3.76	4.23	4.61	4.98	5.17	5.23
Total roundwood harvested	*157.93*	*196.93*	*217.20*	*232.30*	*248.80*	*257.79*	*258.00*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-2 | USFPM Projection on Conventional Demand Under Scenario MM (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.72	6.30	6.86	7.39	7.52	7.71
Softwood pulpwood	4.02	4.43	4.79	4.94	4.99	4.84	4.30
Softwood sawlogs	10.55	12.65	13.48	13.85	14.32	14.18	13.58
Hardwood pulpwood	13.62	17.48	18.86	19.47	20.06	19.46	18.69
Other industrial roundwood	0.66	0.80	0.87	0.92	0.97	0.97	0.96
Total roundwood harvested	*33.43*	*41.09*	*44.30*	*46.04*	*47.74*	*46.97*	*45.23*
South							
Softwood sawlogs	27.18	38.69	46.32	52.92	59.47	61.69	62.22
Softwood pulpwood	39.91	43.20	44.85	45.13	46.32	48.92	49.00
Softwood sawlogs	14.92	15.63	16.55	17.53	18.69	19.35	19.24
Hardwood pulpwood	11.57	17.35	19.79	21.29	22.75	24.06	23.07
Other industrial roundwood	1.79	2.21	2.55	2.82	3.11	3.22	3.25
Total roundwood harvested	*95.37*	*117.08*	*130.06*	*139.69*	*150.33*	*157.25*	*156.78*
West							
Softwood sawlogs	25.76	36.47	39.84	42.59	45.16	46.46	47.60
Softwood pulpwood	1.25	0.63	0.30	0.08	-	0.01	0.07
Softwood sawlogs	1.22	1.34	1.42	1.52	1.64	1.76	1.89
Hardwood pulpwood	0.32	0.26	0.26	0.34	0.61	1.01	1.09
Other industrial roundwood	0.60	0.82	0.90	0.96	1.02	1.05	1.08
Total roundwood Harvested	*29.14*	*39.53*	*42.72*	*45.50*	*48.43*	*50.29*	*51.73*
United States							
Softwood sawlogs	57.52	80.89	92.46	102.38	112.02	115.67	117.52
Softwood pulpwood	45.18	48.26	49.94	50.16	51.31	53.78	53.37
Softwood sawlogs	26.70	29.62	31.46	32.90	34.66	35.28	34.71
Hardwood pulpwood	25.50	35.10	38.91	41.09	43.42	44.53	42.85
Other industrial roundwood	3.04	3.83	4.31	4.71	5.10	5.24	5.29
Total roundwood harvested	*157.94*	*197.70*	*217.09*	*231.24*	*246.50*	*254.51*	*253.75*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-3 | USFPM Projection on Conventional Demand Under Scenario MH (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwoodsawlogs	4.58	5.76	6.40	7.04	7.59	7.53	7.52
Softwoodpulpwood	4.02	4.46	4.84	4.95	4.86	4.57	4.01
Softwoodsawlogs	10.55	12.77	13.94	14.86	15.76	14.92	13.84
Hardwoodpulpwood	13.62	17.78	19.91	21.56	23.00	20.81	19.14
Otherindustrialroundwood	0.66	0.81	0.90	0.98	1.05	1.00	0.95
Totalroundwoodharvested	*33.43*	*41.59*	*46.00*	*49.38*	*52.25*	*48.82*	*45.46*
South							
Softwoodsawlogs	27.18	38.97	47.12	54.02	61.02	62.29	63.50
Softwoodpulpwood	39.91	42.90	42.69	39.84	38.01	42.36	43.14
Softwoodsawlogs	14.92	15.84	17.06	18.48	19.84	19.57	18.72
Hardwoodpulpwood	11.57	16.69	17.78	16.67	15.95	19.80	21.38
Otherindustrialroundwood	1.79	2.23	2.60	2.91	3.22	3.26	3.33
Totalroundwoodharvested	*95.37*	*116.63*	*127.26*	*131.92*	*138.05*	*147.28*	*150.07*
West							
Softwoodsawlogs	25.76	36.46	39.79	42.53	44.89	46.19	47.13
Softwoodpulpwood	1.25	0.61	0.26	0.04	-	-	-
Softwoodsawlogs	1.22	1.35	1.45	1.58	1.72	1.77	1.90
Hardwoodpulpwood	0.32	0.26	0.25	0.31	0.52	1.02	1.09
Otherindustrialroundwood	0.60	0.83	0.91	0.97	1.03	1.05	1.07
TotalroundwoodHarvested	*29.14*	*39.51*	*42.66*	*45.43*	*48.16*	*50.02*	*51.16*
United States							
Softwood sawlogs	57.52	81.19	93.32	103.58	113.50	116.01	118.14
Softwood pulpwood	45.18	47.97	47.79	44.83	42.87	46.93	47.12
Softwood sawlogs	26.70	29.96	32.45	34.92	37.32	36.26	34.45
Hardwood pulpwood	25.50	34.73	37.94	38.53	39.47	41.62	41.62
Other industrial roundwood	3.04	3.87	4.41	4.87	5.31	5.30	5.36
Total roundwood harvested	*157.94*	*197.72*	*215.91*	*226.73*	*238.46*	*246.12*	*246.69*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-4 | USFPM Projection on Conventional Demand Under Scenario HL (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.62	6.23	6.81	7.33	7.52	7.74
Softwood pulpwood	4.02	4.43	4.77	4.96	5.09	4.96	4.48
Softwood sawlogs	10.55	12.56	13.09	13.32	13.68	13.72	13.36
Hardwood pulpwood	13.62	17.08	18.10	18.47	18.88	18.61	18.08
Other industrial roundwood	0.66	0.78	0.84	0.89	0.93	0.94	0.95
Total roundwood harvested	*33.43*	*40.49*	*43.03*	*44.45*	*45.91*	*45.75*	*44.60*
South							
Softwood sawlogs	27.18	37.84	46.12	53.31	60.35	63.14	64.21
Softwood pulpwood	39.90	43.85	46.50	48.13	50.95	54.14	54.30
Softwood sawlogs	14.92	15.31	16.36	17.44	18.57	19.31	19.11
Hardwood pulpwood	11.57	17.71	20.63	21.98	23.40	24.37	24.18
Other industrial roundwood	1.79	2.15	2.52	2.82	3.11	3.26	3.31
Total roundwood harvested	*95.36*	*116.85*	*132.13*	*143.68*	*156.38*	*164.22*	*165.11*
West							
Softwood sawlogs	25.76	36.51	40.18	43.22	46.27	47.25	48.37
Softwood pulpwood	1.25	0.68	0.35	0.16	0.13	0.18	0.27
Softwood sawlogs	1.22	1.31	1.39	1.48	1.59	1.77	1.89
Hardwood pulpwood	0.32	0.27	0.28	0.40	0.78	1.02	1.09
Other industrial roundwood	0.60	0.82	0.91	0.97	1.04	1.07	1.10
Total roundwood Harvested	*29.14*	*39.59*	*43.11*	*46.24*	*49.81*	*51.28*	*52.72*
United States							
Softwood sawlogs	57.52	79.97	92.53	103.34	113.95	117.91	120.32
Softwood pulpwood	45.17	48.96	51.62	53.25	56.17	59.28	59.05
Softwood sawlogs	26.70	29.18	30.84	32.24	33.84	34.79	34.36
Hardwood pulpwood	25.50	35.06	39.01	40.85	43.06	44.00	43.35
Other industrial roundwood	3.04	3.76	4.27	4.68	5.08	5.27	5.35
Total roundwood harvested	*157.93*	*196.93*	*218.27*	*234.36*	*252.10*	*261.25*	*262.43*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-5 | USFPM Projection on Conventional Demand Under Scenario HM (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwoodsawlogs	4.58	5.72	6.35	6.97	7.56	7.69	7.86
Softwoodpulpwood	4.02	4.43	4.76	4.88	4.90	4.77	4.24
Softwoodsawlogs	10.55	12.65	13.43	13.73	14.11	14.02	13.43
Hardwoodpulpwood	13.62	17.48	18.82	19.34	19.83	19.28	18.54
Otherindustrialroundwood	0.66	0.80	0.87	0.92	0.98	0.97	0.97
Totalroundwoodharvested	*33.43*	*41.09*	*44.23*	*45.85*	*47.37*	*46.74*	*45.03*
South							
Softwoodsawlogs	27.18	38.69	47.01	54.40	62.01	64.32	64.98
Softwoodpulpwood	39.91	43.20	45.09	45.53	46.81	49.42	49.48
Softwoodsawlogs	14.92	15.63	16.49	17.47	18.61	19.32	19.23
Hardwoodpulpwood	11.57	17.35	20.01	21.67	23.09	24.07	22.90
Otherindustrialroundwood	1.79	2.21	2.57	2.87	3.18	3.31	3.35
Totalroundwoodharvested	*95.37*	*117.08*	*131.17*	*141.94*	*153.70*	*160.44*	*159.95*
West							
Softwoodsawlogs	25.76	36.47	40.21	43.32	46.13	47.41	48.51
Softwoodpulpwood	1.25	0.63	0.30	0.08	-	-	-
Softwoodsawlogs	1.22	1.34	1.41	1.51	1.63	1.76	1.89
Hardwoodpulpwood	0.32	0.26	0.26	0.35	0.65	1.01	1.08
Otherindustrialroundwood	0.60	0.82	0.91	0.98	1.04	1.07	1.10
TotalroundwoodHarvested	*29.14*	*39.53*	*43.09*	*46.24*	*49.44*	*51.25*	*52.65*
United States							
Softwood sawlogs	57.52	80.89	93.56	104.70	115.69	119.42	121.35
Softwood pulpwood	45.18	48.26	50.15	50.50	51.71	54.19	53.78
Softwood sawlogs	26.70	29.62	31.34	32.70	34.34	35.10	34.55
Hardwood pulpwood	25.50	35.10	39.09	41.37	43.56	44.37	42.53
Other industrial roundwood	3.04	3.83	4.34	4.77	5.20	5.35	5.41
Total roundwood harvested	*157.94*	*197.70*	*218.48*	*234.03*	*250.51*	*258.43*	*257.63*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2,000 pounds per short ton.

Table B-6 | USFPM Projection on Conventional Demand Under Scenario HH (million dry tons)

	2010	2015	2020	2025	2030	2035	2040
North							
Softwood sawlogs	4.58	5.76	6.46	7.14	7.76	7.70	7.67
Softwood pulpwood	4.02	4.46	4.81	4.89	4.76	4.49	3.94
Softwood sawlogs	10.55	12.77	13.93	14.75	15.56	14.78	13.69
Hardwood pulpwood	13.62	17.78	19.91	21.46	22.81	20.64	18.99
Other industrial roundwood	0.66	0.81	0.90	0.99	1.06	1.00	0.96
Total roundwood harvested	*33.43*	*41.59*	*46.02*	*49.22*	*51.95*	*48.61*	*45.25*
South							
Softwood sawlogs	27.18	38.97	47.86	55.62	63.54	65.07	66.44
Softwood pulpwood	39.91	42.90	43.02	40.57	38.46	42.74	43.50
Softwood sawlogs	14.92	15.84	17.02	18.42	19.78	19.55	18.72
Hardwood pulpwood	11.57	16.69	18.07	17.09	16.31	19.88	21.25
Other industrial roundwood	1.79	2.23	2.62	2.96	3.30	3.35	3.43
Total roundwood harvested	*95.37*	*116.63*	*128.59*	*134.66*	*141.39*	*150.59*	*153.35*
West							
Softwood sawlogs	25.76	36.46	40.17	43.23	45.94	47.09	47.99
Softwood pulpwood	1.25	0.61	0.26	0.04	-	-	-
Softwood sawlogs	1.22	1.35	1.45	1.57	1.71	1.77	1.89
Hardwood pulpwood	0.32	0.26	0.25	0.32	0.55	1.02	1.09
Other industrial roundwood	0.60	0.83	0.91	0.99	1.05	1.07	1.09
Total roundwood Harvested	*29.14*	*39.51*	*43.04*	*46.15*	*49.26*	*50.95*	*52.02*
United States							
Softwood sawlogs	57.52	81.19	94.49	105.99	117.24	119.87	122.10
Softwood pulpwood	45.18	47.97	48.09	45.50	43.22	47.23	47.41
Softwood sawlogs	26.70	29.96	32.40	34.74	37.04	36.09	34.30
Hardwood pulpwood	25.50	34.73	38.23	38.86	39.68	41.54	41.33
Other industrial roundwood	3.04	3.87	4.44	4.93	5.41	5.42	5.48
Total roundwood harvested	*157.94*	*197.72*	*217.65*	*230.03*	*242.59*	*250.15*	*250.62*

Note: Actual projections are in cubic meters; conversion to dry tons used 35.31 cubic feet per cubic meter, 30 dry pounds per cubic foot, and 2000 pounds per short ton.

Sampling Error[1]

FIA provides continuous forest estimates of forest area, numbers of trees, tree volume, biomass, growth, removals and mortality. The estimates are based on sampling. The process of sampling (selecting a random subset of a population and calculating estimates from this subset) causes estimates to contain error they would not have if every member of the population (e.g., every tree in the country) had been observed and included in the sample. Under the federal base grid sample, there is only one plot for approximately every six thousand acres. For most of the country, the plot footprint is only 1/6 of an acre. Therefore only about 1 in 24 thousand trees is actually measured on the ground under the federal base grid.

The procedures for statistical estimation outlined in the previous section and described in detail in Bechtold and Patterson (2005) provide the estimates of the population totals and means presented by FIA. Along with every estimate is an associated sampling error that is typically expressed as a percentage of the estimated value (the estimated value plus or minus the sampling error). This sampling error is the primary measure of the reliability of an estimate. FIA reports utilize a sampling error based on one standard error, which means the chances are two in three that, had a 100% inventory been taken using these methods, the results would have been within the limits indicated.

The sampling errors for state-level estimates of forest area and above ground tree biomass on timberland are presented in table B.7. Estimates for classifications smaller than the state totals will have larger sampling errors. To compute an approximate sampling error for an estimate that is smaller than a State total, use the following formula:

$$E = \frac{(SE)\sqrt{(\text{State total estimate})}}{\sqrt{(\text{Smaller estimate})}}$$

where:

E = approximate sampling error for smaller estimate

SE = sampling error for state total estimate (percent)

For example, to compute the error on the area of forest land in Autauga County, Alabama, proceed as follows:

The total forest land area of Autauga County is 305,711 acres.

The total area of all forest land in the State from table B.7 is 23,126,893 acres.

The State total error for forest land area from table B.7 is 0.48 percent.

Using formula (1):

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[1] Special appreciation Patrick Miles, Research Forester, Forest Inventory & Analysis, Northern Research Station, U.S. Forest Service for providing this appendix.

Sampling error = $E = \frac{(0.48)\sqrt{(23{,}126{,}893)}}{\sqrt{(305{,}711)}}$ = 4.17 percent.

This is just a rough approximation of sampling errors for smaller areas. Individuals seeking more accurate sampling errors should use the FIA estimation tools (fia.fs.fed.us/tools-data/index.php).

The estimators used by FIA are unbiased under the assumptions that the sample plots are a random sample of the total population and the observed value for any plot is the true value for that plot. Deviations from these basic assumptions are not reflected in the computation of sampling errors.

Table B-7 | USFPM Projection on Conventional Demand Under Scenario HH (million dry tons)

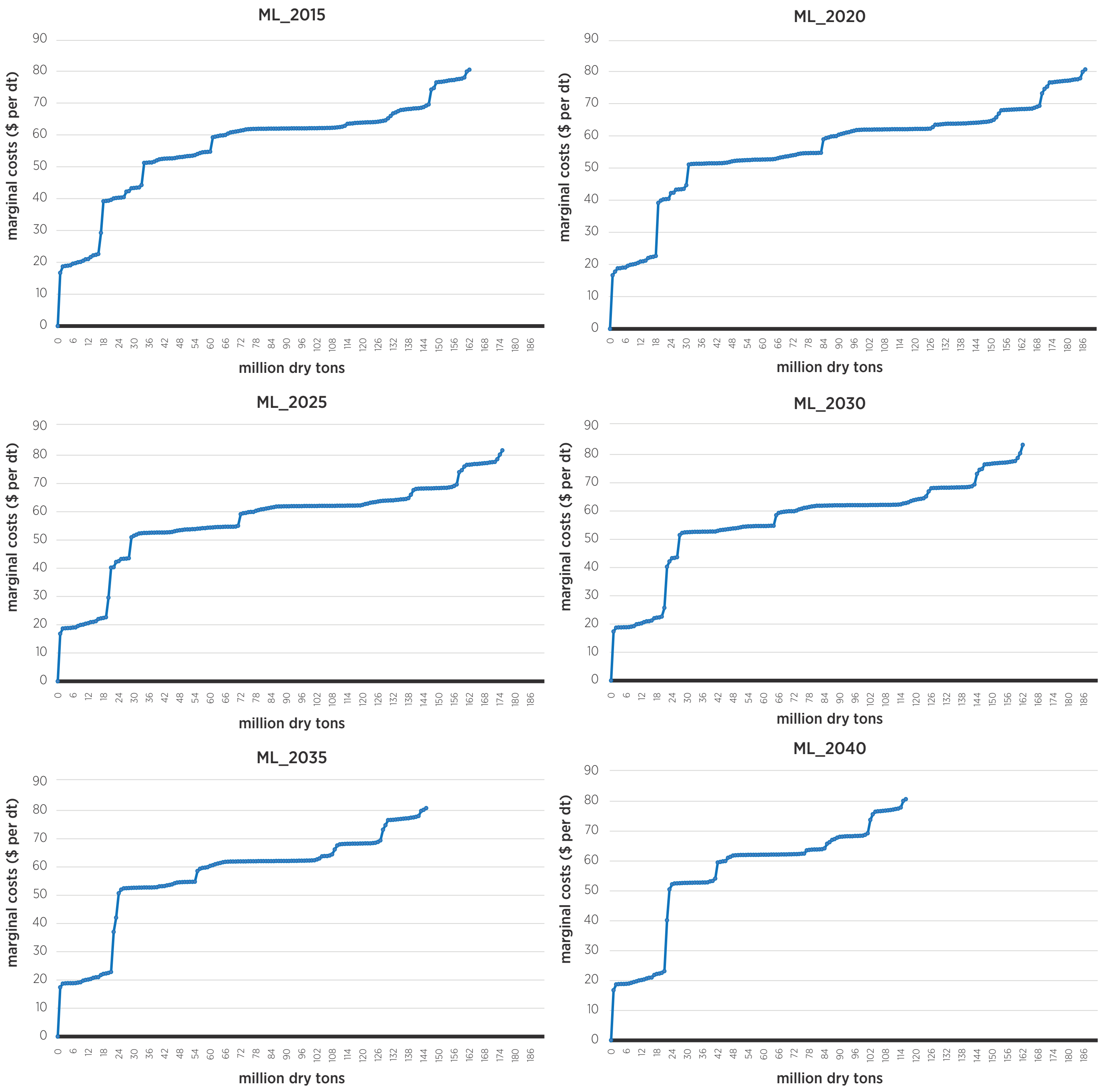
State	Forest land (acres)	Sampling error (%)	Forested plots	Biomass (short tons)	2030 Sampling error (%)	2035 Inventory year
Alabama	23,126,893	0.48	4,275	959,090,501	1.03	2014
Arizona	18,587,490	1.07	3,152	267,728,682	2.17	2013
Arkansas	19,024,429	0.53	3,568	807,091,786	1.06	2014
California	32,101,515	0.63	5,446	2,051,723,218	1.26	2013
Colorado	22,891,282	0.76	3,945	632,036,011	1.53	2013
Connecticut	1,799,342	2.27	320	132,303,437	2.93	2013
Delaware	362,115	3.69	136	25,709,535	5.11	2013
Florida	17,271,795	0.84	3,167	579,123,603	1.75	2013
Georgia	24,744,743	0.55	4,656	1,076,461,100	1.12	2013
Idaho	21,446,207	0.7	3,740	847,983,974	1.64	2013
Illinois	4,974,062	1.61	1,031	251,542,699	2.17	2014
Indiana	4,875,391	1.06	1,809	270,439,967	1.48	2013
Iowa	2,957,321	2.1	634	123,303,581	3.14	2014
Kansas	2,534,899	2.86	604	89,502,870	3.86	2014
Kentucky	12,510,090	0.8	2,469	669,017,945	1.28	2012
Louisiana	14,965,091	0.74	2,736	612,991,064	1.58	2013
Maine	17,636,080	0.4	3,171	693,847,907	0.97	2013
Maryland	2,462,478	2.08	451	185,024,536	3.01	2013
Massachusetts	3,035,792	1.49	545	215,848,770	2.05	2013
Michigan	20,297,434	0.56	4,289	867,096,120	0.98	2014
Minnesota	17,477,313	0.53	6,226	494,337,399	0.91	2014

Table B-7 | *(continued)*

State	Forest land (acres)	Sampling error (%)	Forested plots	Biomass (short tons)	2030 Sampling error (%)	2035 Inventory year
Mississippi	19,430,825	0.56	3,944	830,291,912	1.13	2014
Missouri	15,475,361	0.68	3,182	647,253,400	0.96	2014
Montana	25,702,117	0.68	4,459	787,098,301	1.41	2013
Nebraska	1,559,816	3.96	324	47,750,203	5.77	2014
Nevada	10,577,287	1.37	1,918	109,572,275	2.43	2013
New Hampshire	4,783,480	0.92	951	285,324,910	1.64	2013
New Jersey	2,001,604	2.24	364	117,139,711	3.49	2013
New Mexico	24,839,375	0.97	3,444	318,138,063	1.98	2012
New York	18,950,318	0.57	3,281	1,131,784,873	0.91	2013
North Carolina	18,814,431	0.6	3,672	1,017,871,527	1.12	2014
North Dakota	796,878	5.83	198	19,151,293	8.29	2014
Ohio	8,162,101	0.98	1,664	484,281,536	1.56	2013
Oklahoma	12,362,745	1.54	1,756	279,682,572	2	2013
Oregon	29,684,736	0.47	9,434	2,066,085,416	0.98	2014
Pennsylvania	16,999,249	0.59	3,015	1,085,126,496	0.95	2013
Rhode Island	367,372	3.58	123	24,818,359	4.71	2013
South Carolina	13,043,998	0.75	2,498	620,124,751	1.46	2013
South Dakota	1,943,716	2.73	389	45,260,669	4.2	2014
Tennessee	13,920,504	0.75	2,709	776,151,917	1.23	2012
Texas	62,614,955	0.75	9,004	850,772,597	1.14	2012
Utah	18,303,138	0.96	3,191	296,604,513	1.91	2013
Vermont	4,514,169	0.98	857	279,021,918	1.61	2013
Virginia	15,915,282	0.63	3,048	915,936,069	1.14	2013
Washington	22,195,806	0.54	5,897	1,779,980,873	1.2	2013
West Virginia	12,185,706	0.58	2,033	823,828,883	1.06	2013
Wisconsin	17,092,089	0.43	6,424	649,059,704	0.77	2014
Wyoming	10,455,769	2.37	556	266,018,228	4.34	2013
48 conterminous states	*687,774,585*	*0.14*	*134,705*	*28,406,335,673*	*0.23*	*N/A*

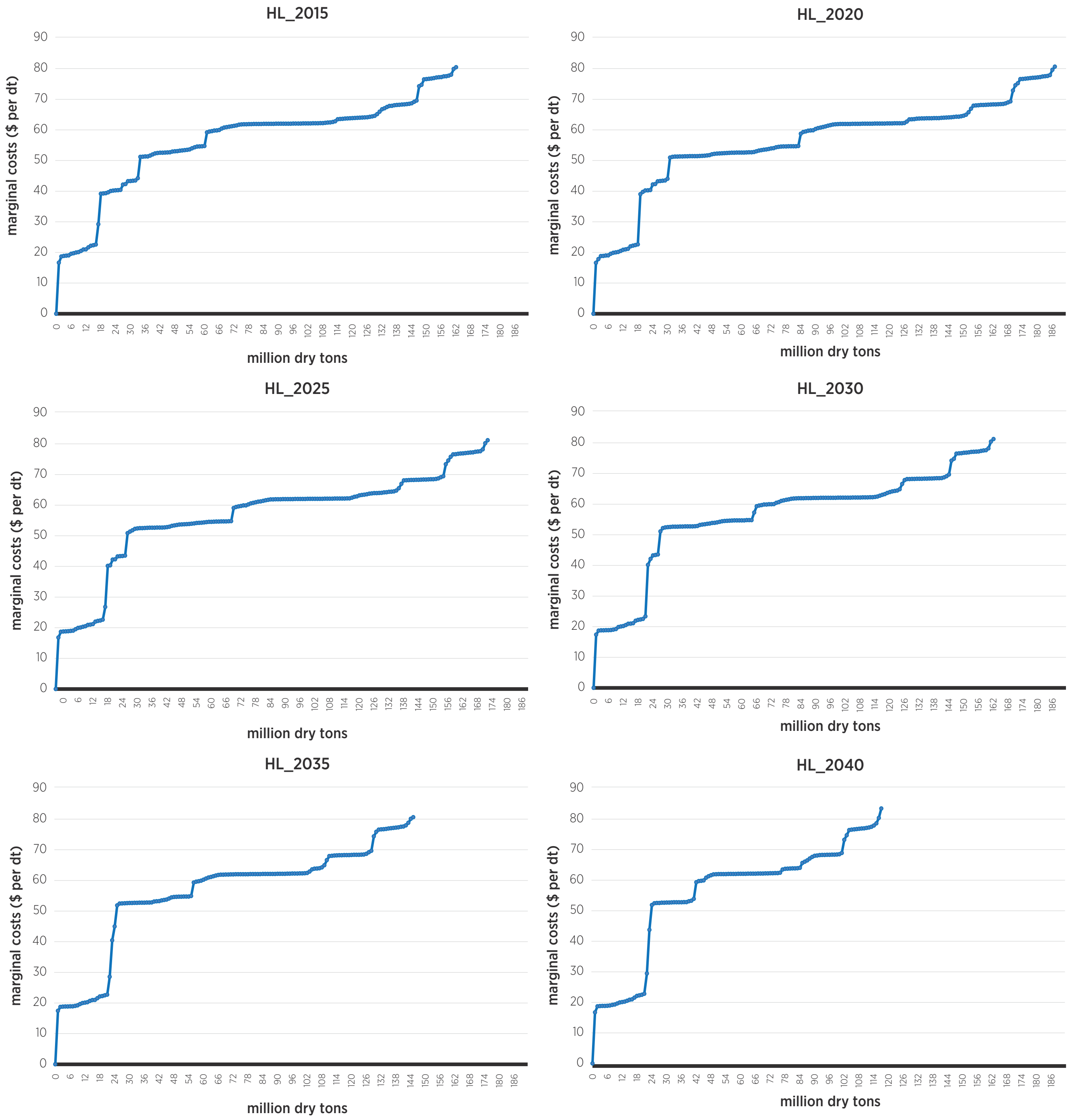
Supply Curves Generated for Each Scenario

Figure B-1 | Baseline_ML supply curves



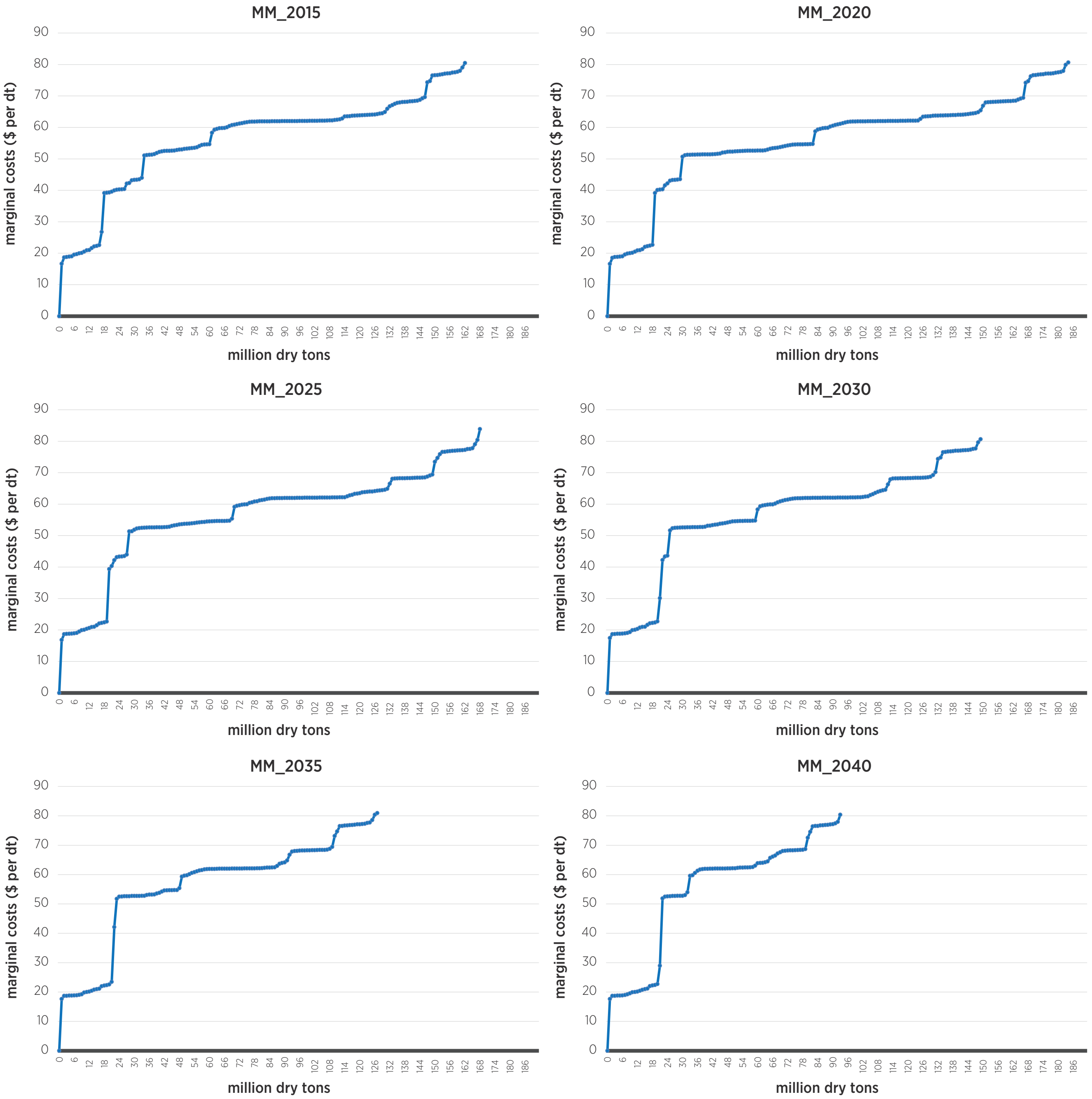
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-2 | HL supply curves



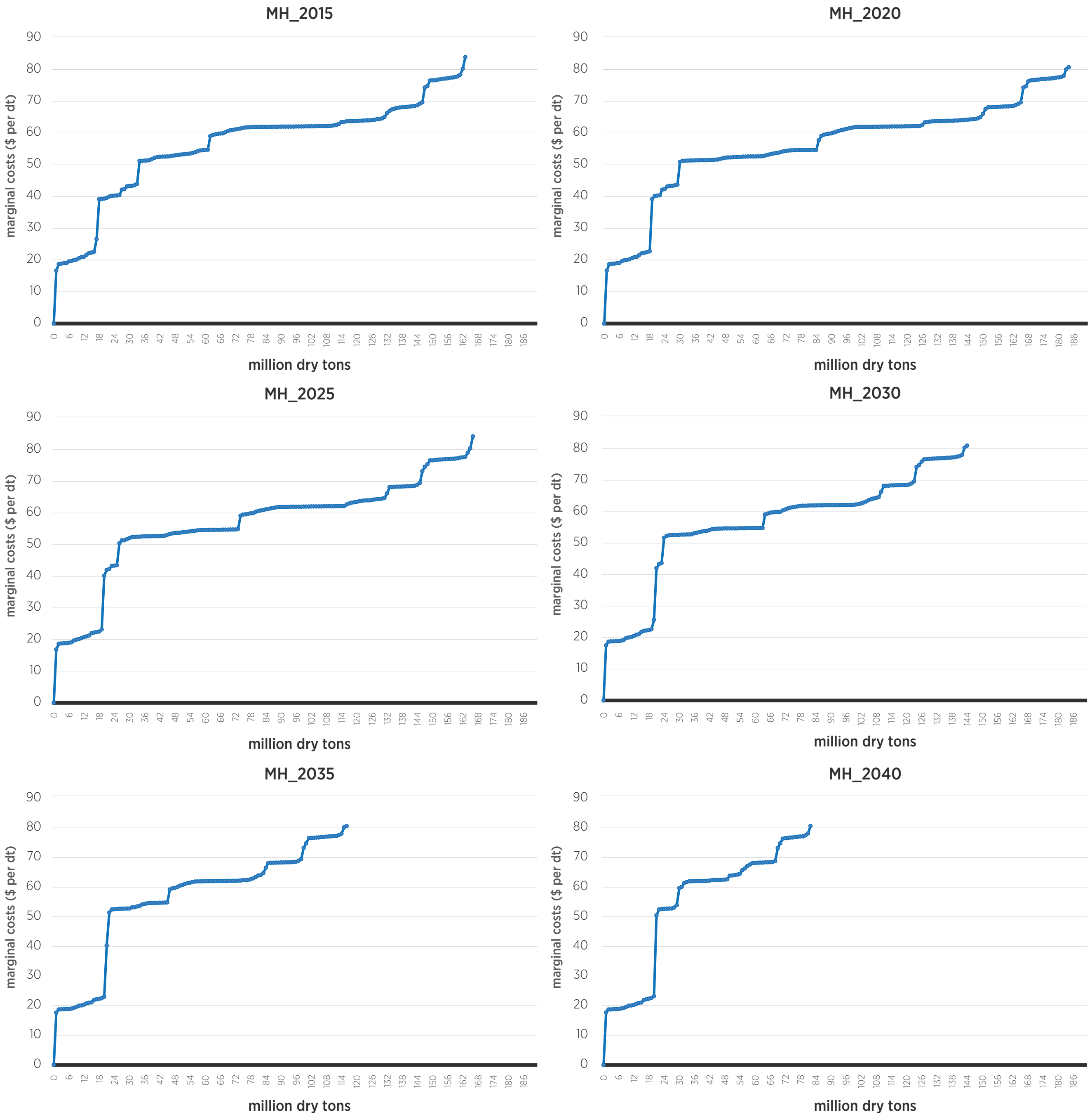
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-3 | MM supply curves



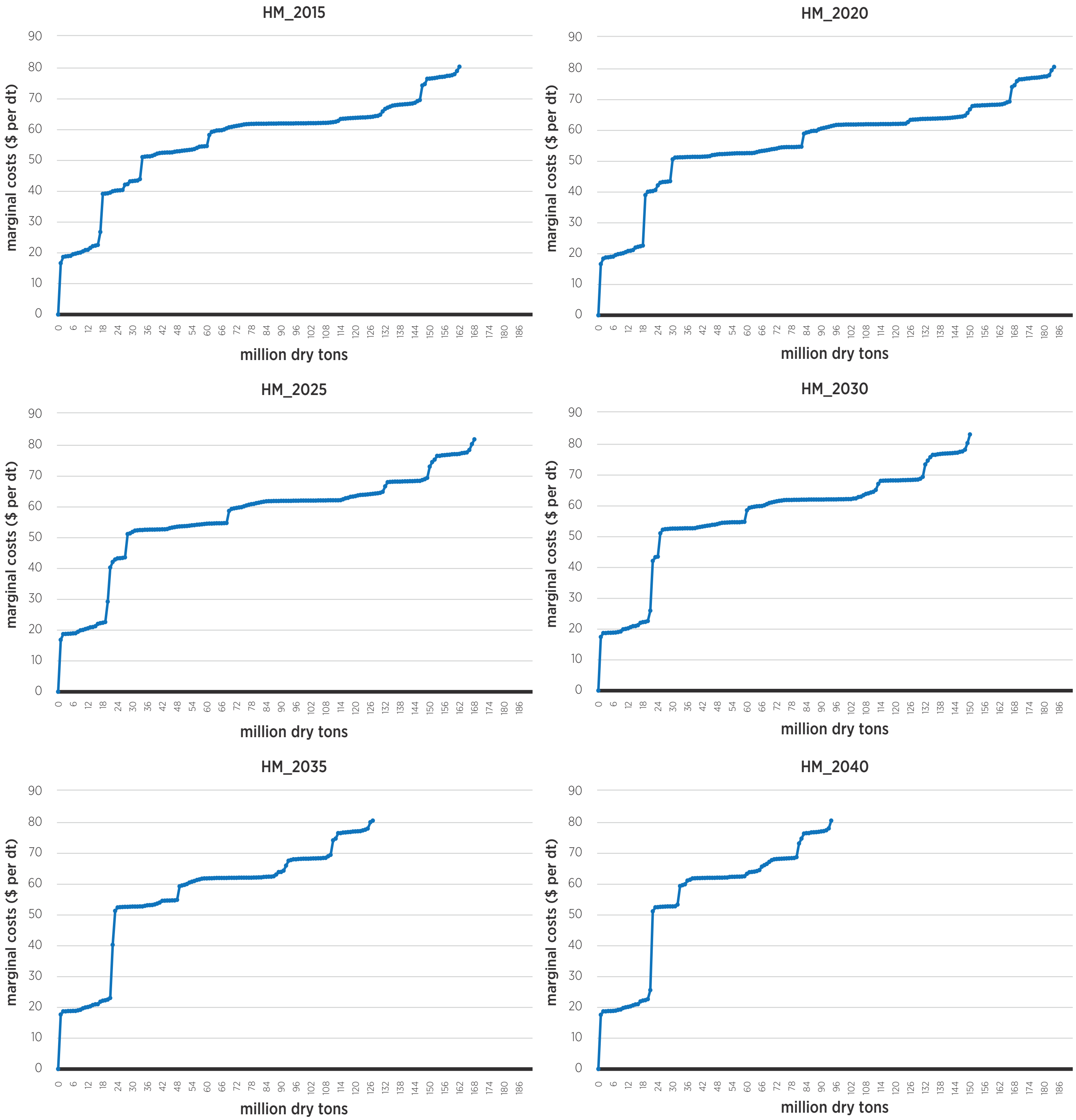
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-4 | MH supply curves



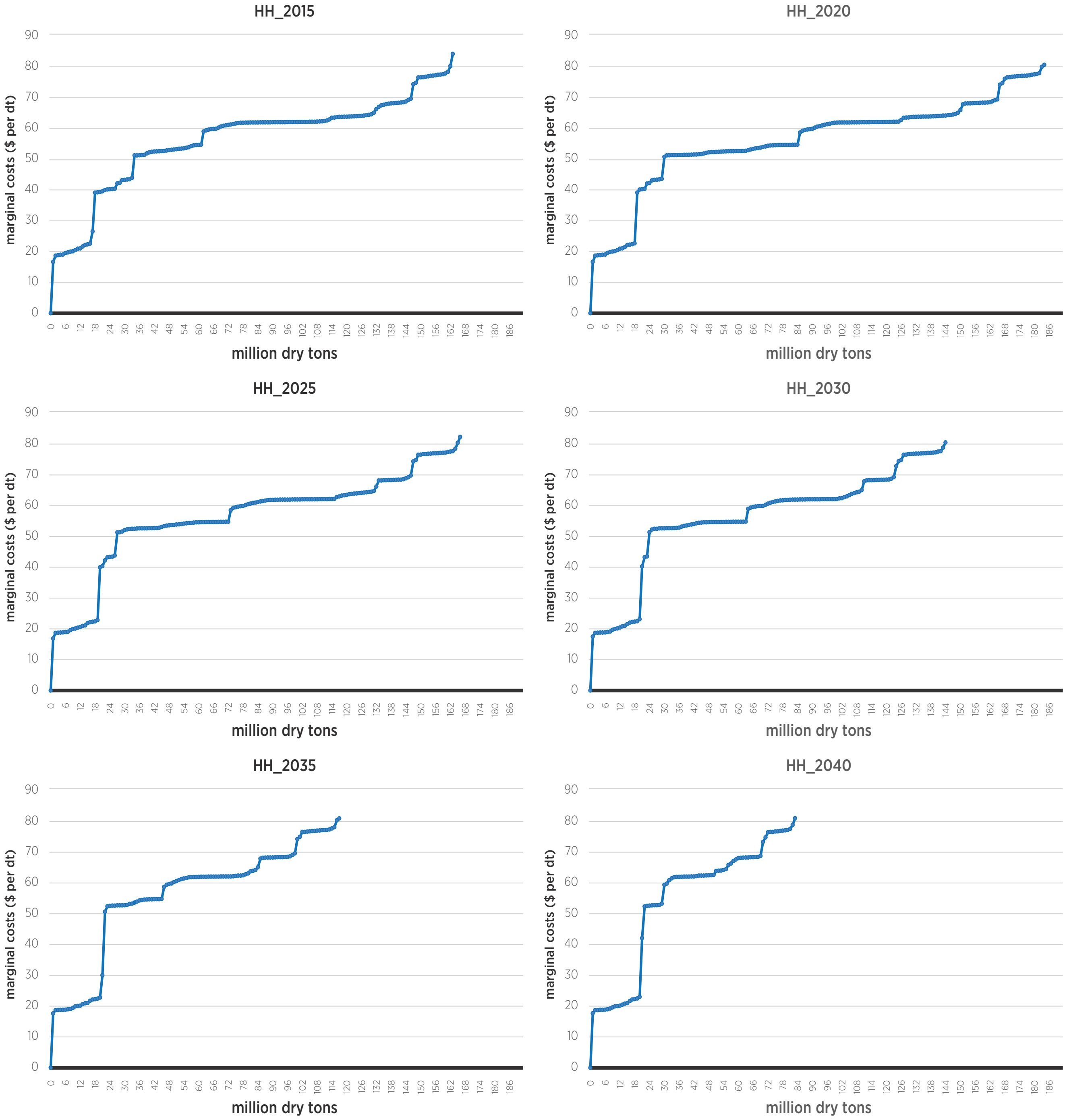
Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-5 | HM supply curves



Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Figure B-6 | HH supply curves



Note: The first letter of the code for the scenarios indicates level of housing starts (high and medium), and the second letter indicates the level of biomass harvested for fuel (high, medium, and low).

Sensitivity Analysis

Table B-8 | Tons Associated with Sensitivity Cases

Biomass price ($/dry ton)	Baseline (million tons)			HH scenario (million tons)		
	As modeled	Increased Volume case	Increased Volume Plus case	As modeled	Increased Volume case	Increased Volume Plus case
40	22	23	25	22	22	22
60	46	86	88	32	51	53
80	116	200	197	83	135	132

References

Bechtold, W. A. Patterson, P. L., eds. 2005. The Enhanced Forest Inventory and Analysis Program–National Sampling Design and Estimation Procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Appendix C

Appendix to Chapter 4 - At the Farmgate: Agricultural Residues and Biomass Energy Crops

C.1 POLYSYS

At its core, POLYSYS is structured as a system of interdependent modules simulating (a) county-level crop supply for the continental United States; (b) national crop demands and prices; (c) national livestock supply and demand; and (d) agricultural income. Variables that drive the modules include planted and harvested area, production inputs, yields, exports, costs of production, demand by use, commodity price, government program outlays, and net realized income. Crop transitions among agricultural lands based on cropland allocation decisions made by individual farmers are primarily driven by the expected productivity of land, the cost of crop production, the expected economic return on the crop, and market conditions. POLYSYS is used to model the introduction of a biomass market under specified agronomic assumptions and market scenarios. These assumptions are summarized in the following sections and described in more detail in the 2011 *BT2* section 5.2.

1. General Agricultural Land Modeling Assumptions

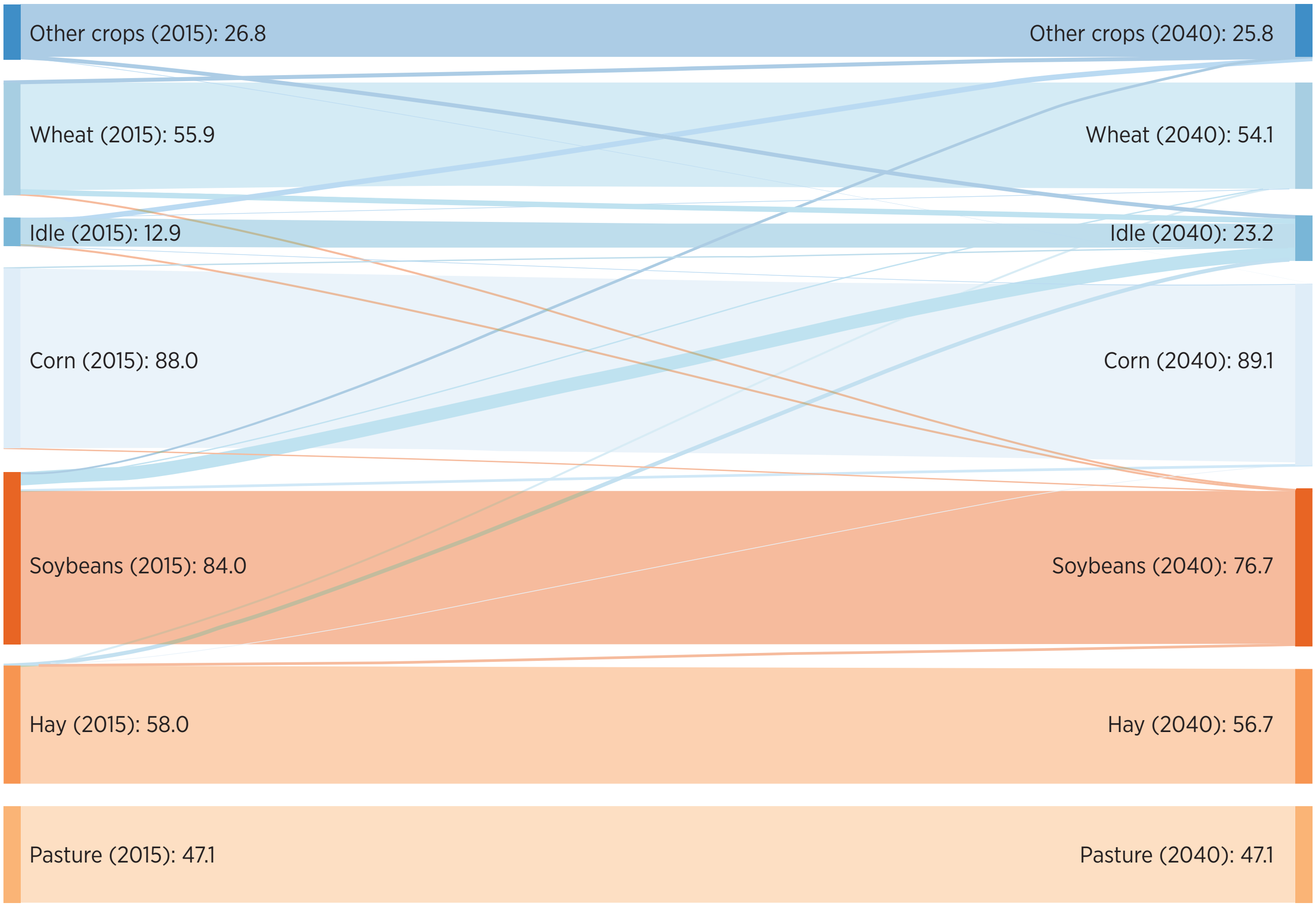
The following are assumptions applicable to all resources simulated in POLYSYS:

Land base: NASS data from USDA are used to generate initial county-level estimates of planted area, harvested area, harvested/planted ratio and yield for the conventional crops modelled in POLYSYS. Data sources include the annual tabular survey data and the geospatial Cropland Data Layers. The survey data are the primary source of county-level estimates of area and yield. However, in some states and for some crops, survey data is only reported at the Agricultural Statistic District (ASD). In those cases where only ASD-level estimates exist, county-level estimates are made by multiplying the ASD planted and harvested areas by the county crop fractions in the ASD which are derived from the Cropland Data Layers. The ASD harvested/planted ratio and yield are assigned to a county in the ASD if the Cropland Data Layers report planted area in the county. Four years of data (2010–2013) are averaged to reduce inter-annual variability, and the averages are provided as input to the county-level version of POLYSYS employed for this study.

- The starting year of simulation in POLYSYS is crop year 2014 (the most current complete year in the 2015 USDA Baseline). For the sake of simplicity, the crop year 2014 denotes the marketing year 2013/2014. For reporting of results, the year 2015 is assumed to be the initial year of simulation.

- It is assumed that all land within the POLYSYS model is fixed throughout the projection period. However, land is allowed to rotate between management regimes, including tillage practices and annual and perennial production, as well as to transition to fallow or idle[2] to satisfy baseline demands.[3] For example, under extension of a baseline scenario (BL0), transition among cropland, pasture and hay occurs, with some reduction in cropland as depicted in figure C.1 and table C. 1.

Figure C-1 | Land base transitions simulated under a baseline scenario (BL0)



Note: Other crops include barley, oats, rice, cotton, grain sorghum.

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[2] Idle land or "cropland idle" was reported in the 2012 USDA Agricultural census to include "1. Land used for cover crops or soil improvement but not harvested or grazed. 2. Land in Federal or State conservation programs that was not hayed or grazed in 2012. 3. Land occupied with growing crops for harvest in 2013 or later years but not harvested or summer fallowed in 2012 (except fruit or nuts in an orchard, grove, or vineyard or berries being maintained for production). Examples are acreage planted in winter wheat, strawberries, etc., for harvest in 2013 and no crop was harvested from these acres in 2012" (USDA 2012). Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (e.g., if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program (CRP) is included in idle cropland land base, although these lands are excluded from the land base available for transition to energy crops within POLYSYS.

[3] Total idle land is fixed across all scenarios beginning at 12.3 million acres in 2015 and ending at 23.2 million acres in 2040, following the USDA baseline projection (USDA 2015).

Cropland: Similar to the 2012 USDA Census of Agriculture definition of "total cropland," this land category includes planted and harvested acres of corn, wheat, grain sorghum, barley, soybeans, rice, cotton, barley, and hay. The cumulative land base is assumed equal to the amount needed to satisfy the crop supply and demand estimates of the USDA Baseline projections. County-level distribution is determined by a multi-year average of production from 2010–2013 USDA-NASS surveys of agricultural production.

The land class category excludes cropland used as pasture, permanent pasture, idle land, and land under retirement programs.

- It is assumed to be a total 312.6 million acres in the initial simulation year of agricultural production in 2015.
- Table C.1 provides estimates of land allocated to major crops and hay to satisfy assumed domestic and international demands of traditional crops and crop products.

Table C-1 | Selected Land Allocation of Major Crops and Hay for Selected Years in the Baseline (2014–2025) and Extended Baseline (2026–2040) Periods

Planted acres (millions)	2015	2017	2022	2030	2040
Corn	88	90	89	89.09	89.1
Grain Sorghum	7.5	7.4	7.1	7.01	7.02
Oats	3	2.5	2.5	2.47	2.44
Barley	3.5	3.2	3	2.96	2.9
Wheat	56	52.5	52	52.58	54.07
Soybeans	84	78	79	78.37	76.87
Cotton	9.8	9.8	10.2	10.38	10.53
Rice	2.94	2.94	3.03	3.06	3.06
Hay	57.9	57.24	56.65	56.65	56.65
Total All Crops	**312.6**	**303.58**	**302.48**	**302.57**	**302.64**

Pastureland, all: A category not explicitly defined in the 2012 USDA Census of Agriculture, but estimated as the reported composite category of cropland used as pasture, permanent pasture, woodland pasture, irrigated pastureland, rangeland and wasteland in the 2012 UDSA Census of Agriculture.

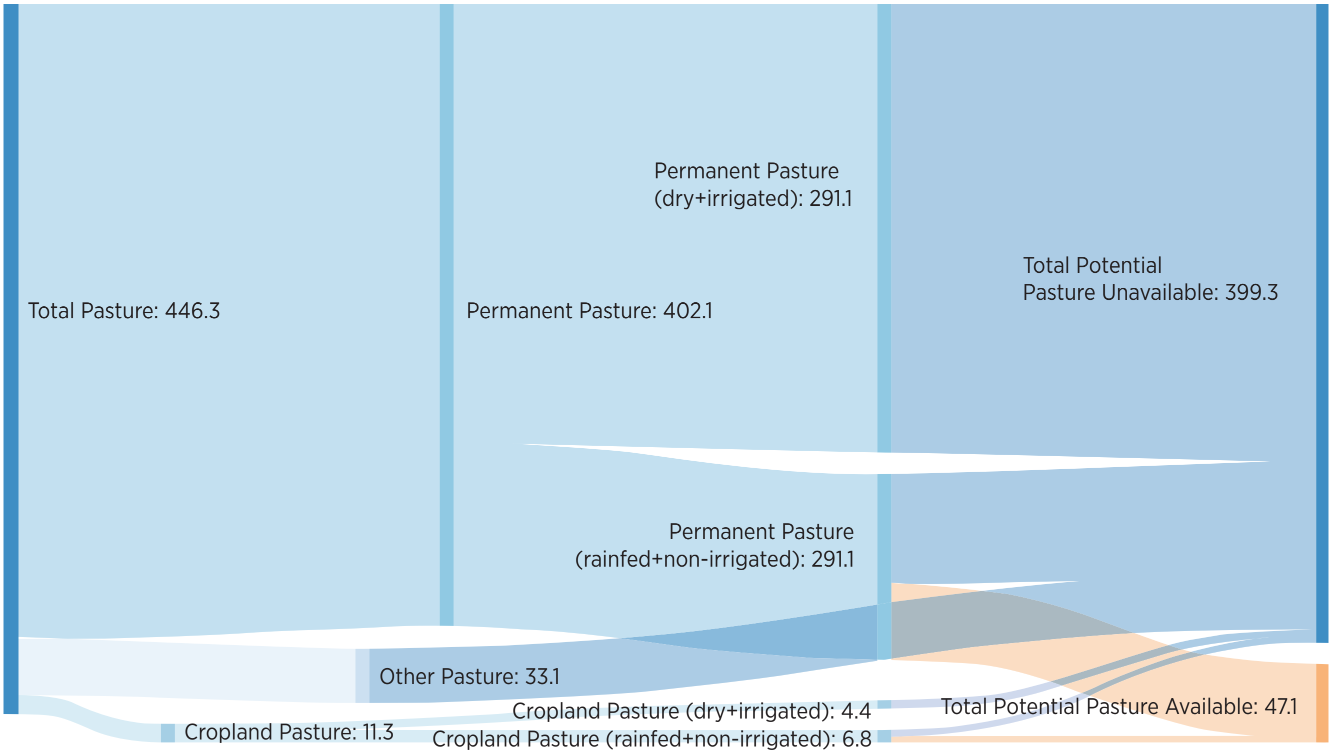
- It is assumed to be a total 446.3 million acres across the projection period.
- The following classes of pastureland are utilized in estimating the pastureland base for bioenergy crop production:
  - "Cropland pasture" or cropland used for pasture or grazing: Assumed to be a total 11.2 million acres across the projection period.
    - Permanent pasture:[6] Assumed to be a total 402.1 million acres across the projection period, of which irrigated pasture[7] is assumed to be 97.3 million acres across the projection period.

- Woodland and other pasture (including rangeland and wasteland): 33.1 million acres (estimated by subtraction, reported county-level acreage for woodland pasture equaled 24.3 million acres [USDA 2012]).

Land base transition constraints: Annual transition is limited to 5% of permanent pasture, 20% of cropland pasture, and 10% of cropland. Cumulative transition is limited to 40% of permanent pasture, 40% of cropland pasture, and 10% of cropland for most energy crops (except for biomass sorghum, which is constrained to USDA land capability classes I & II).

Additionally, in order to ensure successful establishment of energy crops and minimize impacts to existing grazing markets, it is assumed that pastureland must meet the following criteria to be available land for energy crop production: (1) be non-irrigated and (2) be in a county with a 30-year normal precipitation of 25 inches per year or more a (for transition from pastureland to energy crops or MiG). The resulting land availability after applied constraints totals 47.1 million acres of pastureland, as depicted in figure C.1 and figure C.2.

Figure C-2 | Sankey diagram of pastureland by type and criteria available and unavailable for bioenergy crop production



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[6] "Permanent pasture," or rangeland, other than cropland and woodland pastured: Defined in the 2012 USDA Census of Agriculture, appendix B, as a land category that "encompasses grazable land that does not qualify as woodland pasture or cropland pasture. It may be irrigated or dry land. In some areas, it can be a high quality pasture that could not be cropped without improvements. In other areas, it is barely able to be grazed and is only marginally better than wasteland" (USDA 2012).

[7] Irrigated pasture is defined to be any pasture land that falls under the "irrigated land" land class defined by USDA to include "all land watered by any artificial or controlled means, such as sprinklers, flooding, furrows or ditches, subirrigation, and spreader dikes. Included are supplemental, partial, and preplant irrigation" (USDA 2012).

Land uses: POLYSYS is calibrated to county-level major crops (corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay) based on a four-year average of the 2010 to 2013 USDA NASS annual survey data (USDA 2012).

Food, feed, fiber, and corn ethanol demands: POLYSYS prioritizes future demands for food, feed, fiber, and corn ethanol demands as specified in the 2015 USDA Baseline Projection (USDA 2015) before responding to simulated cellulosic biomass markets. As stated earlier, the potential supply estimates from agriculture are anchored to the USDA Long-Term Forecast (extended to 2040) such that all projected demands for food, feed, fiber, fuel, and exports are satisfied before biomass crops are planted. POLYSYS simultaneously balances available supply and sector demands via adjustments to commodity prices using known economic relationships. Food, feed, and industrial demands are adjusted by using crop "own-" and "cross-" price elasticities. Through these relationships, quantities of commodity demands can change from baseline via changes in available supply and price levels. Corn grain demand for ethanol remains fixed in all scenarios, and therefore does not change in quantity as corn price may change (see Ray et al. 1998).

Crop budgets: Both traditional crops and energy crop budgets are estimated at the county level through a spatial interpolation method of regional-level enterprise budgets. More information on budgets is described below.

Cellulosic biomass markets: Markets for biomass feedstocks are introduced as specified farmgate prices offered (≤$30–≤$100/dry ton in $5 increments) in specified-price simulations.[8] These prices (2014$) are adjusted for inflation using the Producer Price Index for Crude and Raw Materials (PPICRM)[9] and are applied to all counties for all years in the simulation period. Figure C.2 shows the index applied in each year. For example, when applying a ≤$60 real feedstock price ($/dry ton, base-2014) in a specified-price simulation, the offered price in 2040 has an index of 1.495. Therefore, the offered nominal feedstock price ($/dry ton) is ≤$89.7, rounded to ≤$90 in that year.

Table C-2 | Inflation Index Applied to Real Feedstock Price to Calculate Nominal Prices in Specified-Price Simulations

Year	2014	2015	2016	2017	2018	2019	2020			
Index	1.000	0.977	0.977	0.982	0.992	1.007	1.026			
Year	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Index	1.045	1.065	1.0852	1.106	1.127	1.148	1.170	1.192	1.215	1.238
Year	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Index	1.262	1.286	1.310	1.335	1.3603	1.386	1.412	1.439	1.467	1.495

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[9] The PPICRM is a price index specifically for crude goods that "have not been manufactured or fabricated but will undergo some processing before becoming intermediate or finished goods." (Bureau of Labor Statistics, 2012).

Fixed and Variable Costs of Production: Following prior analysis using POLYSYS (BT2 and De La Torre Ugarte et al. 2003), it is assumed that crop costs of production in the supply curve estimation scenarios are restricted to variable costs, such as land preparation, planting, maintenance, and crop harvest. Land rent is assumed to be a sunk cost and is excluded from crop costs budgets and planting decisions. This may differ from enterprise or business model approaches to costing, which include a broader characterization of costs. An exception to this is the estimation of the biomass cost curve generated from the ≤$60/dry ton base-case (1%) scenario represented in the delivered supply analysis. In this approach, it was assumed that profit was equal to 10% of variable costs of production. This approach also resolves the issue of backward-bending supply curves that occur when energy crops compete for land differently at each simulated price (see text box 4.2). The accounting of production and opportunity cost using a single estimate along the supply curve creates a monotonic supply curve (increasing in quantity supplied as price increases).

2. Agricultural Residue Modeling Assumptions

There are many harvest options for residues,[10] but for each crop, this study models and costs a crop-specific machinery complement.

For corn stover, the stover collection operations assumed are the following:

- Turn off spreader behind combine
- Shred
- Bale with large rectangular baler
- Move bales to roadside with automated bale wagon.

For wheat straw, the collection operations are the following:

- Turn off the spreader behind the combine,
- Bale with large rectangular baler
- Move bales to the roadside with automated bale wagon.

It is assumed that the removed nutrients (e.g., nitrogen, phosphorus, and potassium) need to be replaced, except for potassium in regions where potassium fertilizer is not added (western half of the United States). Table C.3 details assumptions about the crop characteristics used to estimate residues. These challenges and opportunities are described in more detail in chapter 8. In addition, sustainability and operational efficient restraints are imposed on agricultural residues and are discussed in chapter 4. They are represented in figure C.3.

Table C-3 | Assumptions about Crop Characteristics Used in Estimating Residues

Crop	Weight	Moisture	Dry weight	Residue-to-grain weight ratio	Residue
	lb/bu	%	lb/bua		dry tons/bu
Corn	56	15.5	47.32	1.0	0.0237
Sorghum	56	14.0	48.16	1.0	0.0241
Barley	48	14.5	41.04	1.5	0.0308
Oats	32	14.0	27.52	2.0	0.0275
Winter wheat	60	13.5	51.09	1.7	0.0441
Spring wheat	60	13.5	51.09	1.3	0.0337

abu = bushels

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[10] Crop residues modeled in POLYSYS include corn stover and wheat, barely, oats, and sorghum straw. Example of other residues not included are rice field residue (straw), cotton field residue, and sugarcane residues (trash-leaves, tops, and remaining stalk after primary harvest of the stalk).

Tillage flexibility: Tillage production distribution (CTIC 2007) is grouped into three categories of management: no-till production, reduced tillage, conventional tillage. A flexibility constraint is included in POLYSYS to control switching between these tillage classes among each individual crop. The methodology to control this constraint employs a +/- 10% annual change constraint,[11] which is multiplied by the following variable: additional change = 1.0 + absolute value (% change in net present value [NPV] between simulation NPV and baseline NPV) * index (tillflex). Where tillflex is equal to 3, a 0.75 index is used; where tillflex is equal to 2, a 0.50 index is used; and where tillflex is equal to 1, a 0.30 if index is used. This means that at all index levels, as the percent change in NPV between simulation and baseline becomes greater, more land is allowed to transition up to a maximum of 100% of tillage acreage. The difference between the index levels is simply one of intensity, with a value of 3 increasing the percentage allowed to transition more rapidly than a value of 1. See also chapter 4 sensitivity analysis section on tillage flexibility.

3. Energy Crop Modeling Assumptions

Energy crop yields: New in this analysis, energy crop yields are empirically modeled. Energy crop yields were derived from modeling of crop yields based on data from the Sun Grant Regional Feedstock Partnership in coordination with the Oregon State University PRISM modeling group. Following six crop-specific workshops, data from more than 110 field trails was used to estimate county-specific per-acre yields based on 30-year historic weather data (see chapter 4, text box 4.1).

Table C-4 | Regional Absolute Average and Range Yield Assumptions, in Dry Tons at Maturity (or mean annual increment at harvest) of Energy Crops in POLYSYS, Averaged Across All Counties with Simulated Production in 2040 (at ≤$60 per ton)

Farm production region	Switchgrass	Poplar	Willow	Biomass sorghum	Miscanthus	Energy cane
Appalachia	7.5 (5.7–9.3)	5.3 (4.4–6.8)	6.2 (3.7–7.9)	10.7 (9.7–11.4)	8.5 (6.8–10.9)	N/A
Corn Belt	7.6 (5.5–8.7)	5.6 (4.6–6.7)	6.7 (3.9–8.2)	11 (10.4–11.6)	10.2 (7.9–11.2)	N/A
Delta States	8.3 (6.1 - 9.5)	5.3 (4.7 - 6.5)	5.2 (4.8 - 5.6)	11.5 (10.3 - 12.3)	8.2 (7.2–10.3)	10.9 (8.8–12.1)
Lake States	3 (2.7–3.3)	4.7 (3.7–5.8)	5.3 (3.7–7.1)	N/A	7.7 (5.3–10.5)	N/A
Mountain	2.3 (1.5–3.2)	n/a	3.1 (2.9–3.2)	N/A	4 (3.9–4)	N/A
Northeast	6.4 (4.6–7.3)	5.1 (4.4–5.9)	6 (3.8–7.3)	N/A	8.1 (6.4–9.1)	N/A
Northern Plains	4.3 (2–8)	5.4 (5.3–5.6)	4.8 (2.8–6.2)	10.9 (10.3–11.5)	8.1 (4.4–11.2)	N/A
Pacific	2.3 (1.6–2.8)	3.9 (3.3–4.4)	3.8 (3.8–3.8)	N/A	N/A	N/A
Southeast	7 (4.7–9.3)	4.8 (4–6.6)	5.6 (3.8–7.5)	10.5 (9.2–11.8)	7.5 (5.8–8.6)	10.7 (8.1–13.3)
Southern Plains	5.3 (1.7 - 8.9)	4 (2.6 - 4.8)	2.8 (1.4 - 3.2)	10.2 (8.6 - 11.7)	5.9 (3.8–9.2)	N/A

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[11] "Additional change" is constrained to a maximum value of 10.0.

Table C-5 | Regional Average and Range Crop Suitability, as an Index (0 = unsuitable, 1 = highly suitable) of Energy Crops as Inputs to POLYSYS, Averaged Across All Counties with Simulated Production in 2040 (at ≤$60 per ton)

Farm production region	Switchgrass (0.75 lowland, 0.43 upland)	Poplar (0.70)	Willow (0.56)	Biomass sorghum (0.79)	Miscanthus (0.47)	Energy cane (0.96)
Appalachia	0.8 (0.6–1)	0.7 (0.6–0.9)	0.8 (0.4–1)	0.9 (0.8–0.9)	0.8 (0.6–1)	N/A
Corn Belt	0.8 (0.6–0.9)	0.7 (0.6–0.9)	0.8 (0.5–1)	0.9 (0.8–0.9)	0.9 (0.7–1)	N/A
Delta States	0.9 (0.6–1)	0.7 (0.6–0.9)	0.6 (0.6–0.7)	0.9 (0.8–1)	0.7 (0.6–0.9)	0.8 (0.7–0.9)
Lake States	0.3 (0.3–0.4)	0.6 (0.5–0.8)	0.6 (0.5–0.9)	N/A	0.7 (0.5–0.9)	N/A
Mountain	0.2 (0.2–0.3)	N/A	0.4 (0.3–0.4)	N/A	0.4 (0.3–0.4)	N/A
Northeast	0.7 (0.5–0.8)	0.7 (0.6–0.8)	0.7 (0.5–0.9)	N/A	0.7 (0.6–0.8)	N/A
Northern Plains	0.4 (0.2–0.8)	0.7 (0.7–0.7)	0.6 (0.3–0.8)	0.9 (0.8–0.9)	0.7 (0.4–1)	N/A
Pacific	0.2 (0.2–0.3)	0.5 (0.4–0.6)	0.5 (0.5–0.5)	N/A	N/A	N/A
Southeast	0.7 (0.5–1)	0.6 (0.5–0.9)	0.7 (0.5–0.9)	0.9 (0.7–1)	0.7 (0.5–0.8)	0.8 (0.6–1)
Southern Plains	0.6 (0.2–0.9)	0.5 (0.3–0.6)	0.3 (0.2–0.4)	0.8 (0.7–0.9)	0.5 (0.3–0.8)	N/A

Note: Under each crop name is included the R2 for the modeled yield and sampled field trial yield to develop the absolute yield transformation function.

4. Energy Crop Feedstock-Specific Assumptions

Switchgrass production: Switchgrass grows in every region, although it has been shown to be more productive and sustainable on rain-fed marginal land east of the 100th Meridian (see BT2 and Mitchell et al. 2010). The stand life is 10 years. POLYSYS allows for a 50% harvest in year 1, a 75% harvest in year 2, and a 100% harvest in years 3–10. It is assumed to be established with no-till. Seeding rate is 6 lb/acre and 10% is reseeded in year 2. Varieties planted include Alamo, Kanlow, Trailblazer, Cave-in-Rock, and Liberty. In year 1, limestone is applied in regions where it is needed at 1 ton/acre; phosphate (P_2O_5) at 40 lb/acre; and, in regions where it is needed, potassium (K_2O) at 80 lb/acre. In years 2 through 10 fertilizers are applied are: nitrogen 13 lb/dry ton harvested, phosphorus (as P_2O_5) 4 lb/dry ton harvested, and K_2O 14 lb per dry ton harvested. Herbicide treatments in year 1 are quinclorac, Atrazine, and 2,4-D; and in years 2, 5, and 8, herbicide treatment is 2,4-D. Switchgrass is harvested after a killing frost with equipment consisting of a mower-conditioner, large rectangular baler, and automatic bale wagon. For all baling operations, twine costs are assumed to be 2.56/dry ton (Klein et al. 2015).[12]

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[12] Klein et al. (2015, 7) show a twine cost for a large rectangular bale of $1.23/bale. To calculate a per ton twine cost we assume a bale of biomass would be 1000 dry lb, and thus use a twine cost of $2.56/dry ton.

Miscanthus production: Miscanthus is planted with conventional tillage. Rhizomes are used and planted at 8,750 per acre at a cost of 0.10/rhizome. Stand life is assumed to be 15 years. POLYSYS allows for 0% harvest in year 1, 50% in year 2, and 100% in years 3–15. Tillage is a chisel plow followed by two diskings at establishment. Herbicide treatments occur in the first year using 2,4-D and Harness Xtra and in the second year using 2,4-D. First-year fertilizer applications are 62 lb/acre of P_2O_5 and, in regions where potassium is needed, 50 lb/acre of K_2O. Fertilization takes place in years 2 through 15 with nitrogen at 9 lb/dry ton harvested, P_2O_5 at 1.5 lb/dry ton harvested, and K_2O (in regions where needed) at 8 lb/dry ton harvested. Harvesting is done after senescence and before regrowth starts (late winter/early spring), at which point miscanthus has dried and translocated much of its nutrients back into the roots. Harvesting equipment consists of a mower-conditioner, large rectangular baler, and automatic bale wagon.

Energy cane production: Energy cane is limited to the southern rim of the United States, but it is grown in a larger area than where sugar cane grows. Stand life is assumed to be 7 years with harvest once a year. POLYSYS allows for a harvest of 75% in year 1, and 100% in years 2–7. For establishment, conventional tillage is assumed with a chisel plow and an offset disk twice over. Cultured seed cane is hand planted in the same fashion as cultured sugar cane. Herbicide treatments are extensive. In year 1, Roundup, Sencor, and pendimethalin are applied. In years 2 to 7 pendimethalin, atrazine, and 2,4-D are applied. Establishment year fertilization is 62 lb/acre and 50 lb/acre of P_2O_5 and K_2O, respectively. In subsequent years, nitrogen, P_2O_5, and K_2O are applied at rates of 9, 1.5, and 8 lb per dry ton of energy cane harvested, respectively. Harvesting is done with a sugar cane billet harvester and three high-dump sugar cane wagons.

Biomass sorghum production: Biomass sorghum is an annual crop, similar to forage sorghum. Establishment is assumed to use conventional tillage with a chisel plow and an offset disk. Planting uses a row crop planter. Fertilization is limestone (in regions where needed), nitrogen, P_2O_5, and K_2O (in regions where needed). Herbicide treatments are Bicep II/ Magnum and 2,4-D. Harvest is with a self-propelled forage harvester and two high-dump forage wagons. Sorghum is restricted to a "1 in 4 year rotation" (i.e. it can only come into production on 1/4 of available land) based on the land capability classes I&II (source: USDA NRCS Map ID m6175; data source: 1997 National Resources Inventory, revisited December 2000). The annual yield increase for biomass sorghum is consistent with other energy crops in the BC1 scenario, but is as follows in the high yield scenarios: 1.5% in the 2% yield increase scenario (HH2), 1.75% in the 3% yield increase scenario (HH3), and 2% in the 4% yield increase scenario (HH4).

Hybrid poplar: Hybrid poplar is modeled as growing on an 8-year rotation schedule in most of the eastern United States and Pacific Northwest. Establishment uses conventional tillage: moldboard plow followed by an offset disk. Fertilization is limestone (2 tons/acre except in the Pacific Northwest) and K_2O (18 to 60 lb/acre, depending on the region) in the establishment year; nitrogen (90 lb/acre as a combination of urea and diammonium phosphate) and phosphorus (15 to 30 lb/acre, depending on the region as diammonium phosphate in year 3; and nitrogen (90 lb/acre as urea) in year 6. Herbicide treatments in the establishment year are glyphosate (Roundup) and pendimethalin, and in years 2 and 3, glyphosate. An insecticide is applied in year 4. Harvest is done in year 8. It is modeled in this study as a single-stem 8-year rotation for simplicity, but it is potentially coppiced at variable rotations. Harvest is costed as a custom operation with a fixed cost per dry ton, consisting of a feller buncher, skidder, chipper and chip van.

Southern pine: Pine is established using conventional tillage with a moldboard plow and offset disk. Seedlings are planted at 762 per acre. In the establishment year, limestone (2,000 tons/acre) and K_2O (48.2 lb/acre) are applied; in years 2, 4, and 6, nitrogen (at 90 lb/acre as urea) is applied; and in year 3, P_2O_5 (91.7 lb/acre as diammonium phosphate) is applied. Herbicide treatments in the establishment year are glyphosate and pendimethalin and in years 2 and 3, glyphosate. Harvest is done in year 8. Harvest is costed as a custom operation with a fixed cost per dry ton, consisting of: feller buncher, skidder, chipper and chip van.

Eucalyptus: Eucalyptus can be grown in the southeastern United States. Stands are harvested every 4 years with one coppice, for a stand life of 8 years. After the first harvest of all acres (year 4), an additional 15% boost in yield occurs for all additional harvests through the end of the rotation period. Eucalyptus is established using conventional tillage with a moldboard plow and offset disk. Containerized seedlings are planted at 1,575 per acre. Herbicide treatments in the establishment year are glyphosate and sulfmetruon methyl. In years 2 and 6, glyphosate is applied. Fertilizer is ground applied in year 1 as limestone (2,000 lb/acre); in years 1, 6, 11, 16, and 21 as P_2O_5 (114.6 lb/acre as triple superphosphate); in years 1, 6, 11, 16, and 21 as K_2O (40 lb/acre); and in year 6, 11, 16, and 21 as nitrogen and diammonium phosphate. Fertilizer is aerially applied as urea and diammonium phosphate at rates of 150 lb/acre of nitrogen and 115 lb/acre of P_2O_5. Harvest, at year 5, is costed as a custom operation with a fixed cost per dry ton, consisting of: feller buncher, skidder, chipper and chip van.

Willow: Willow budgets are based on the EcoWillow model from State University of New York College of Environmental Science and Forestry. Willow is modeled as a coppiced crop over a 32 year period, with harvest every 4 years. After the first harvest (year 4), an additional 15% boost in yield occurs for all additional harvests through the end of the rotation period. In the fall before planting, establishment uses brush hogging, plowing, and disking; and a cover crop is planted. In year 1, the cover crop is killed, willow cuttings are planted at 5,500 per acre, a preemergent herbicide is applied after planting, and additional weed control occurs. The herbicide treatments used in this establishment year are two applications of glyphosate (1.5 pt/acre each), oxyfluorfen (Goal) (2.5 pt/ac; see Abrahamson et al. [2010]), and pendimethalin (Prowl) (2.4 pt/acre). In year 2, the willows are cut down but not harvested, and additional weed control occurs. Fertilization occurs after the initial cutting in year 2 and after each harvest (except the final one) at a cost of approximately $65 per acre (nitrogen, P_2O_5, and K_2O at rates of 45, 20, and 45 lb/acre, respectively) mechanical weed control using a rototiller also occurs in year 2. Harvest is costed as a custom operation with a fixed cost per dry ton: self-propelled forage harvester equipped with a willow cutting head that cuts and chips the stems. The chips are blown into forage wagons transported to the road side. At the roadside, the chips are transferred to a chip van.

C.2 Enhancements and Modifications from BT2

Although this analysis follows the same general methodology for estimating farmgate supplies as was reported in the 2011 BT2, several changes have been made in this analysis. The changes include updating input data (see section C.3), adjusting for inflation, harmonizing with current and projected operational technology, and minor corrections in the modeling framework. Prominent updates and modifications of the modeling assumptions are as follows. See also table C.5.

- The simulation period is advanced from 2010–2030 in the 2011 BT2 to 2015–2040 in this report.
- POLYSYS is anchored in the USDA Baseline Projection from 2015 to 2025, extended linearly to 2040.

- Currently available resources are reported as 2015 unless otherwise specified.
- *BT2* reported flat nominal prices. Farmgate prices are reported as 2015 dollars, adjusted for inflation based on the PPICRM. In this report, inflation of operational costs over time was also harmonized across all crops consistent with the USDA Baseline Projection.
- Residue removal is allowed on conventionally tilled acres as long as residues remaining after harvest meet constraints described in chapter 4. This change reflects examples from extant cellulosic biofuels products.
- Operationally available residues are limited to 50% of total residues starting in 2015, increasing linearly to 90% of available residues in 2040 (see section 1.2, Agricultural Residue Modeling Assumptions). The operational constraint is a function of total stover yield. The total amount of "harvestable yield" is constrained by both "operational yield" and "sustainable removable yield" (whichever is more constraining). The harvestable residue is subsequently selected as economically harvestable at the county level in POLYSYS if and where the price offered for biomass exceeds the cost of production. The generalized work flow is illustrated in figure C.3.

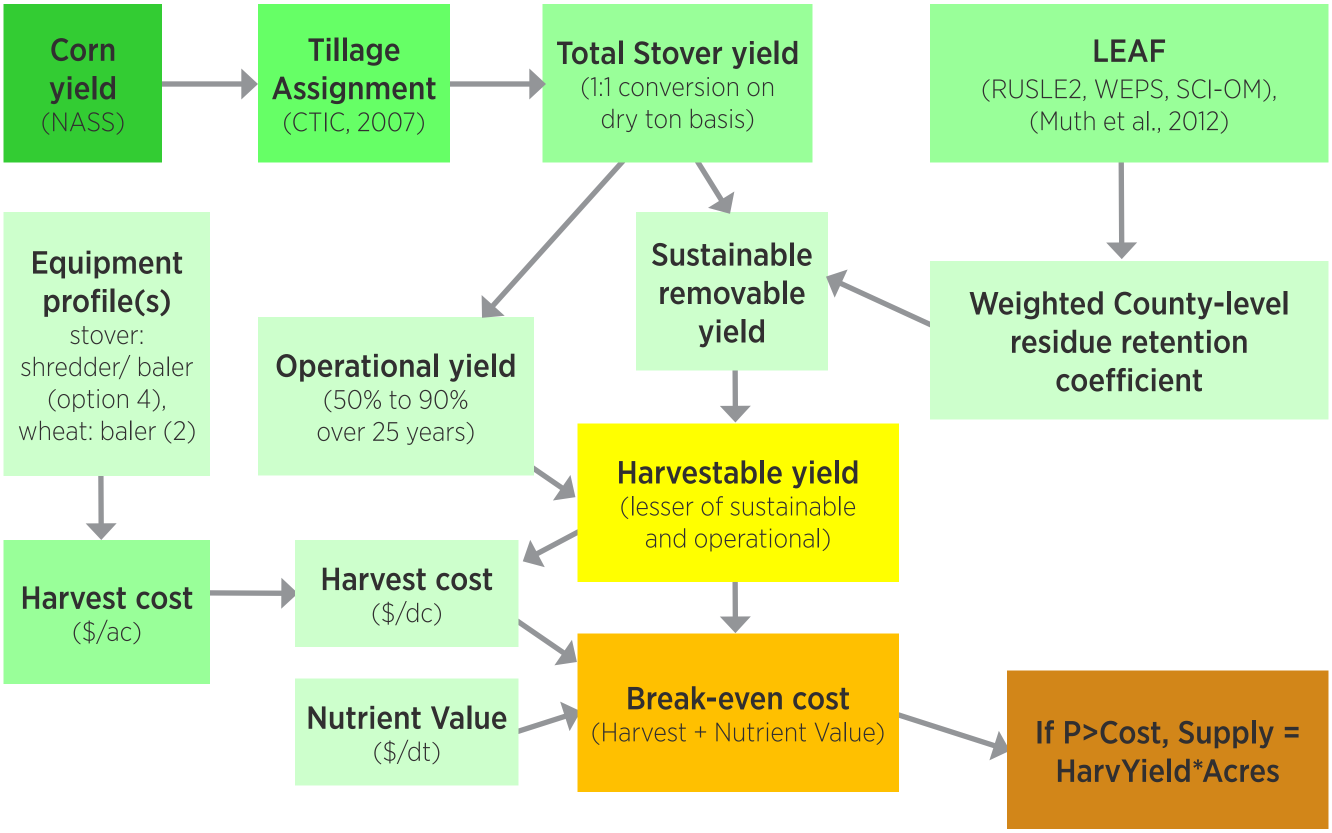
Table C-6 | Summary of Enhancements and Modifications in Agricultural Land Resource Modeling

Scope	2011 *BT2*	*BT16*
USDA Baseline	2010 USDA Baseline assumed, extrapolated from 2020 to 2030	2015 USDA Baseline assumed, extrapolated from 2025 to 2040
Energy crop types	Perennial herbaceous, annual herbaceous, coppice SRWC, non-coppice SRWC	Switchgrass, miscanthus, energy cane, biomass sorghum, non-coppice (poplar, loblolly pine), and coppice (willow and eucalyptus)
Energy crop yields	Regionally assigned yields based on literature	Modeled yields based on Regional Feedstock Partnership PRISM results (see chapter 4)
Pasture intensification	One acre of management-intensive grazing assumed capable of replacing forage production displaced by one acre of pasture converted to energy crops	1.5 acres of management-intensive grazing assumed capable of replacing forage production displaced by one acre of pasture converted to energy crops
Energy crop yield improvements	Base-case (1%) and high-yield (2%, 3%, and 4%)	Scenario-specific yield improvements (see chapter 4, table 4.1). Specified-price simulation scenario descriptions) at 1%, 2%, 3%, and 4% for most energy crops (see chapter 4, section 4.3.1)
Farmgate prices	Flat nominal prices	Flat real (inflation-adjusted) prices based on the Producer Price Index for Crude Materials for Further Processing

Table C-6 *(continued)*

Scope	2011 *BT2*	*BT16*
Operational constraints	All crop residues available after sustainability retention coefficients are met are assumed operationally available	Operational availability is assumed 50% in 2014 increasing linearly to 90% in 2040, not exceeding sustainability retention coefficients
Geographic range of energy crops on pasture land	East of the 100th Meridian	To account for precipitation, pastureland values from the 2012 USDA census were considered to constrain the transition of pastureland to energy crops in counties where the 30 year average annual precipitation is 25 in. or less
Nutrient replacement costs	Costs of nutrients for 1 dry ton/acre of energy crops included	Costs of nutrients for energy crops applied on a per dry ton basis
Adjustments to USDA baseline	Calculations made on harvest rather than production	Annuity with a 30-year planning horizon now used to calculate total net returns for all biomass crops
Grower payment	$10/dry ton additional grower payment reported to be included	No additional grower payment has been added
SRWC plantings	Averaged plantings over rotation cycle	Implemented a staggered planting, where 1/4 (coppice) or 1/8 (non-coppice) of the acres converted to SRWCs are planted every year.
SRWC price premium	No premium added	A $5/dry ton and $10/dry ton price premium is now offered for coppice (willow and eucalyptus) and non-coppice (pine and poplar) woody crops, respectively.
Tillage flexibility constraint	Exogenously determined tillage adoption rates for baseline and high-yield scenario	Tillage responsiveness allowed to vary based upon residue price at 4 levels (0, 1, 2, & 3; see section 1.2, Agricultural Residue Modeling Assumptions).

Table C-3 | Work-flow diagram illustrating calculation of sustainably available biomass



C.3 Production Budgets: Energy and Conventional Crops

Conventional crop yields and budgets were updated based on the 2015 USDA Baseline. Harvest costs of primary agricultural residues were revised to reflect the latest available information for specified residue harvest operations. We also summarize energy crop input costs:

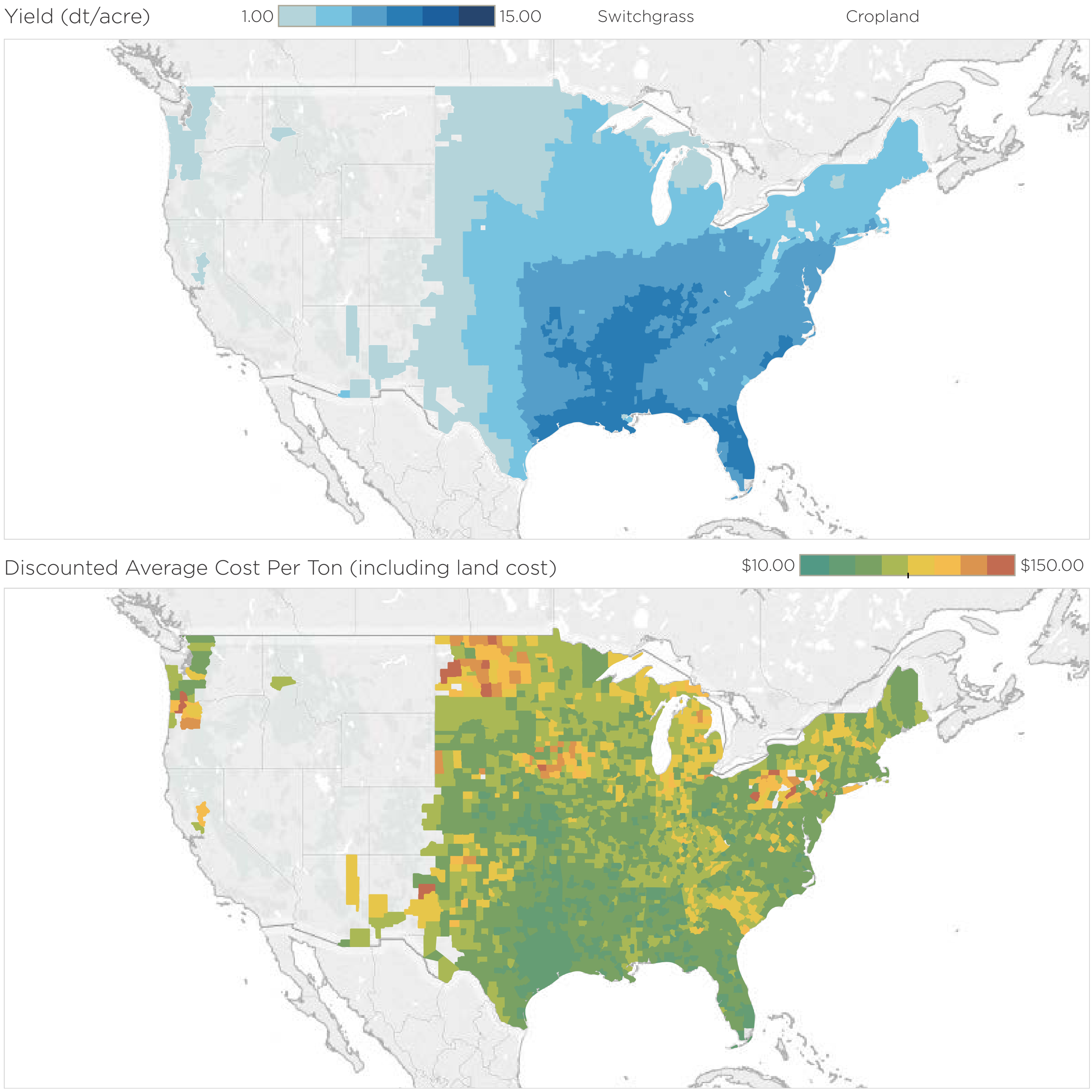
1. Spatial Interpolation of Crop Budgets

We create spatially explicit budgets by starting with detailed crop budgets for large regions and then using a spatial interpolation method to average across boundaries to create per acre production costs at the ASD Agricultural Statistic District (ASD) level. Larger regional budgets for all crops are developed using the Agricultural Policy Aanalysis Center Budgeting System (Slinsky and Tiller 1999). This system generates detailed field operation schedules and associates per-hectare crop production costs for all production systems considered. The method used is consistent with those used by USDA and recommended by the American Agricultural Economics Association (American Agricultural Economics Association 2000). The budgets were calculated using 2014 input costs and energy prices and are used in the model as “enterprise” budgets, in which each crop’s costs used individually and not in rotation. We then use spatial interpolation to refine the budgets to smaller geographic regions. Spatial interpolation is the process of using points with known values to estimate values at other points in spatial data environments in which a few points are known, but values in between the known points are not known. Spatial interpolation is a process of filling in values between the sample regions and resolves previous challenges with large cost transitions between political and agricultural regions. More detail on the interpolation methods used by POLYSYS to estimate geographically specific budgets can be found in the document (Hellwinckel et al. 2015).

2. Costs ($/dry ton) and Yield (dry tons/acre) Associated with Individual Energy Crops

The following figures depict yields by feedstock. We summarize the input cost for herbaceous and woody energy crops in tables C.6 and C.7.

Figure C-4 | Yield (dry tons per acre) for switchgrass[13]



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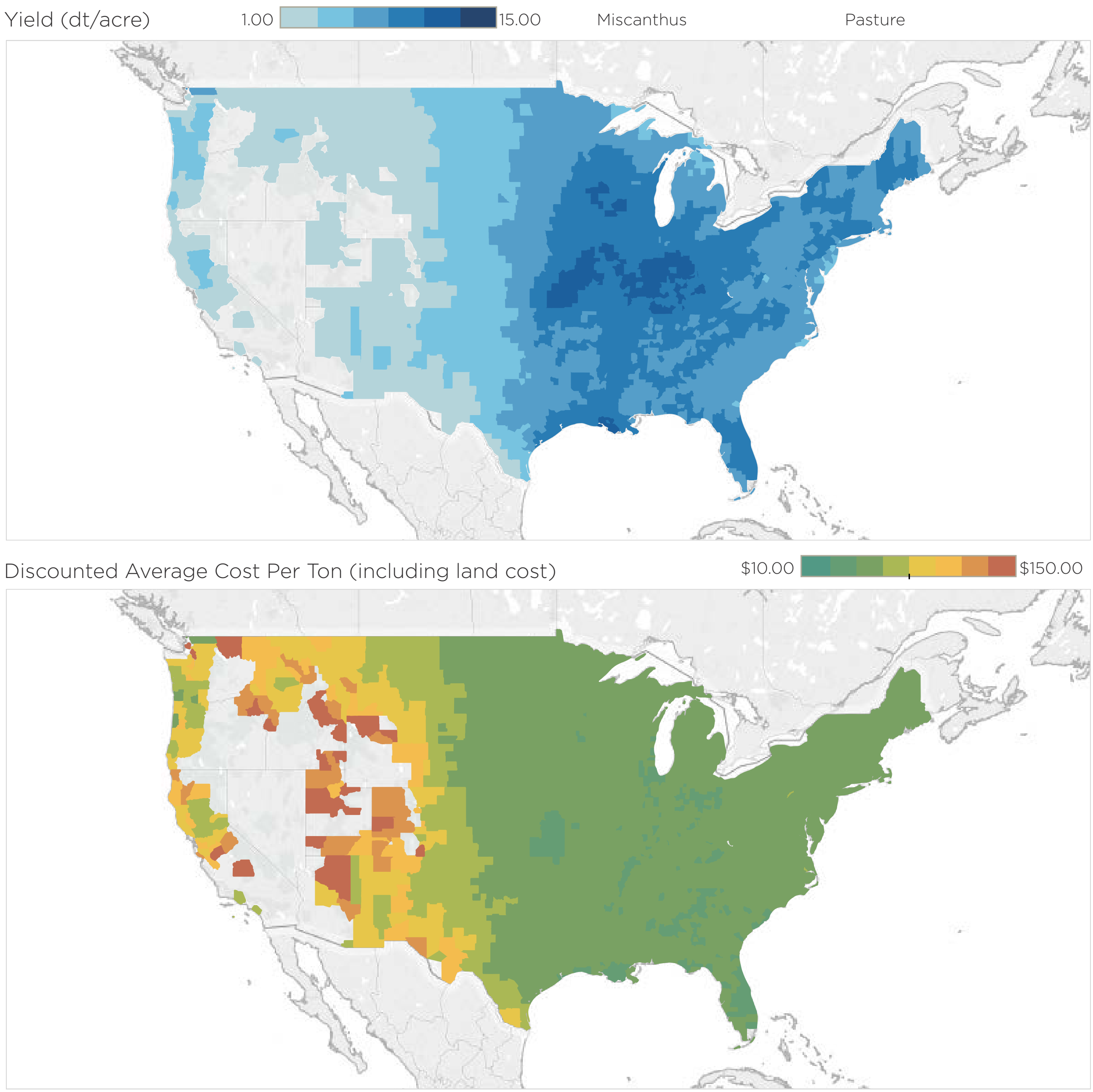
[13] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-5 | Yield (dry tons per acre) for miscanthus[14]



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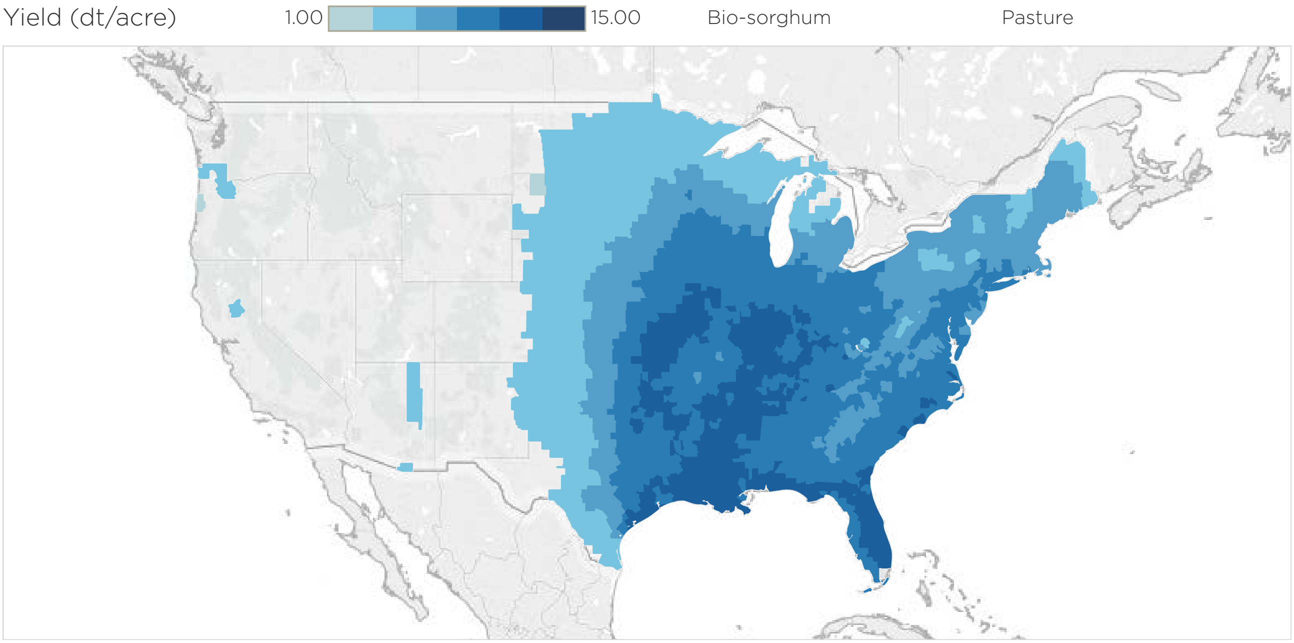
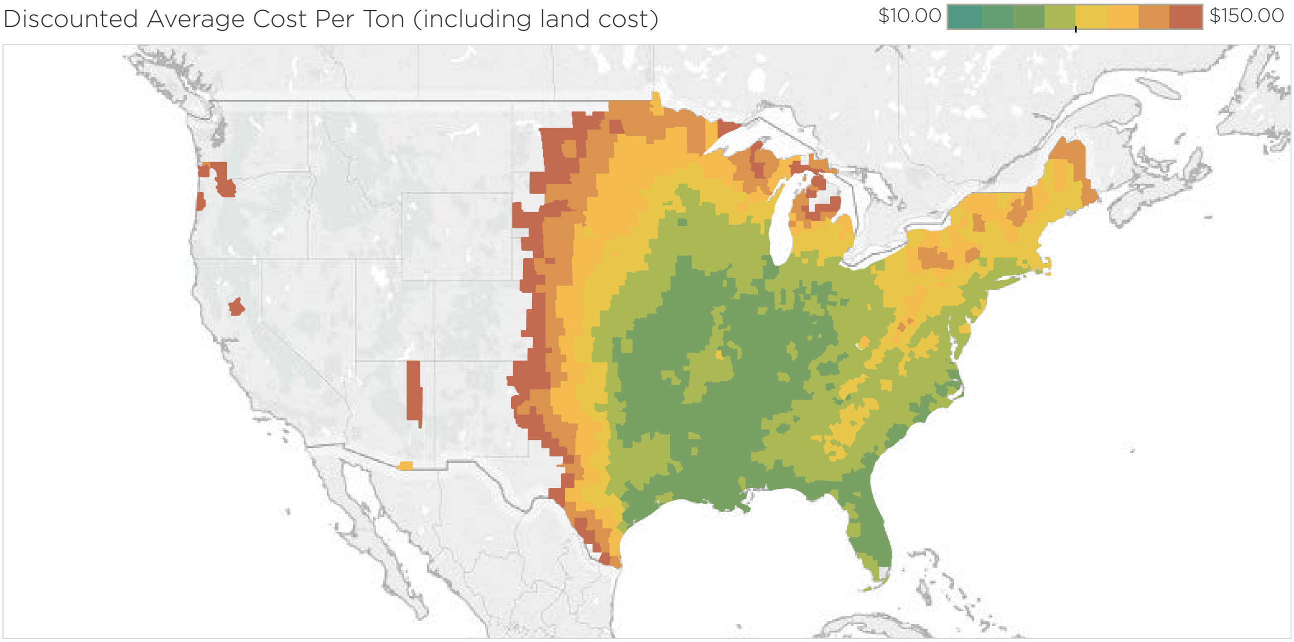
[14] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-6 | Yield (dry tons per acre) for biomass sorghum[15]



Discounted Average Cost Per Ton (including land cost)



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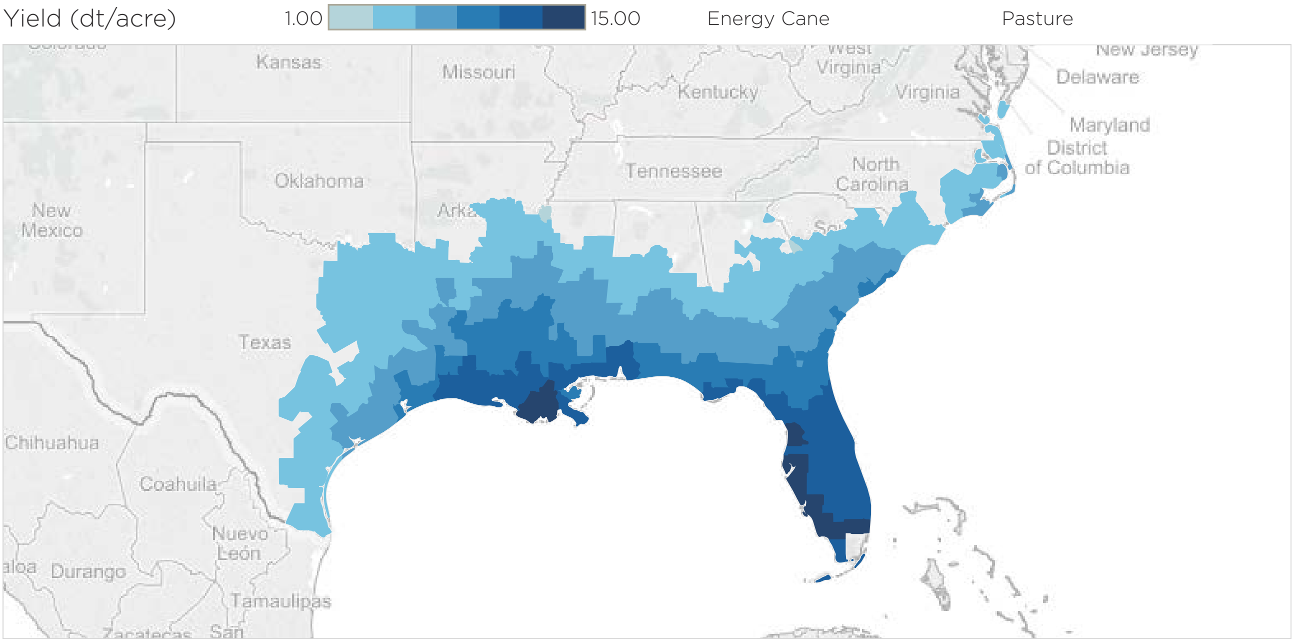
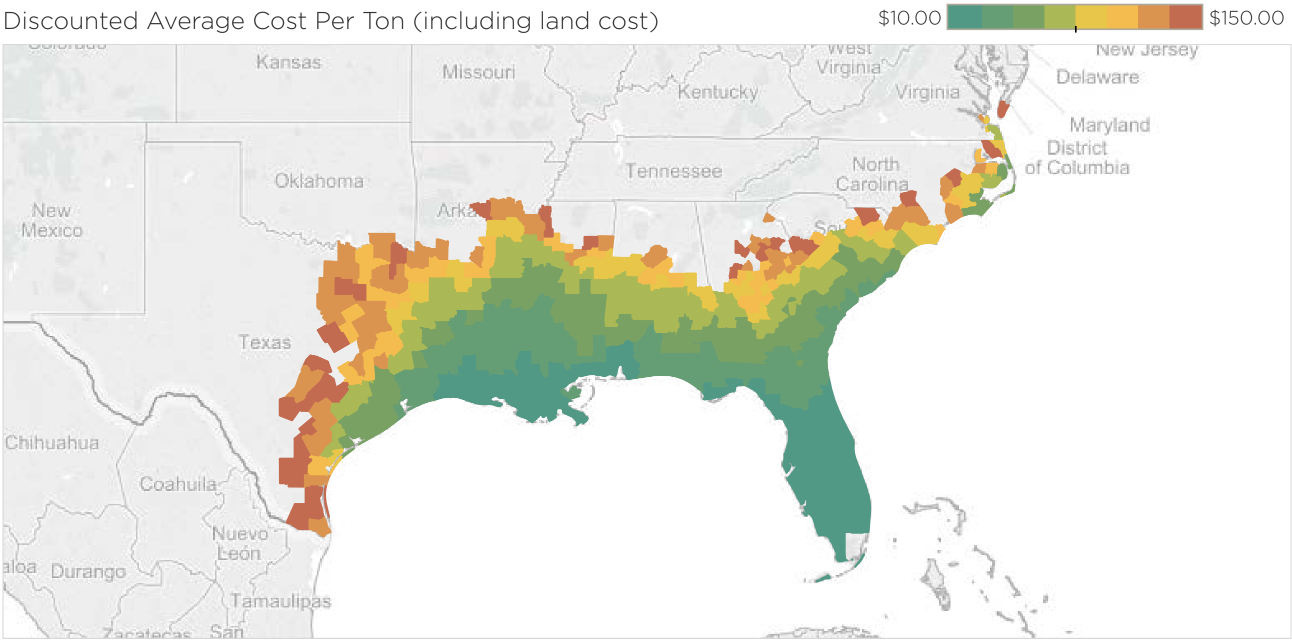
[15] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-7 | Yield (dry tons per acre) for energy cane[16]

Yield (dt/acre)



Discounted Average Cost Per Ton (including land cost)



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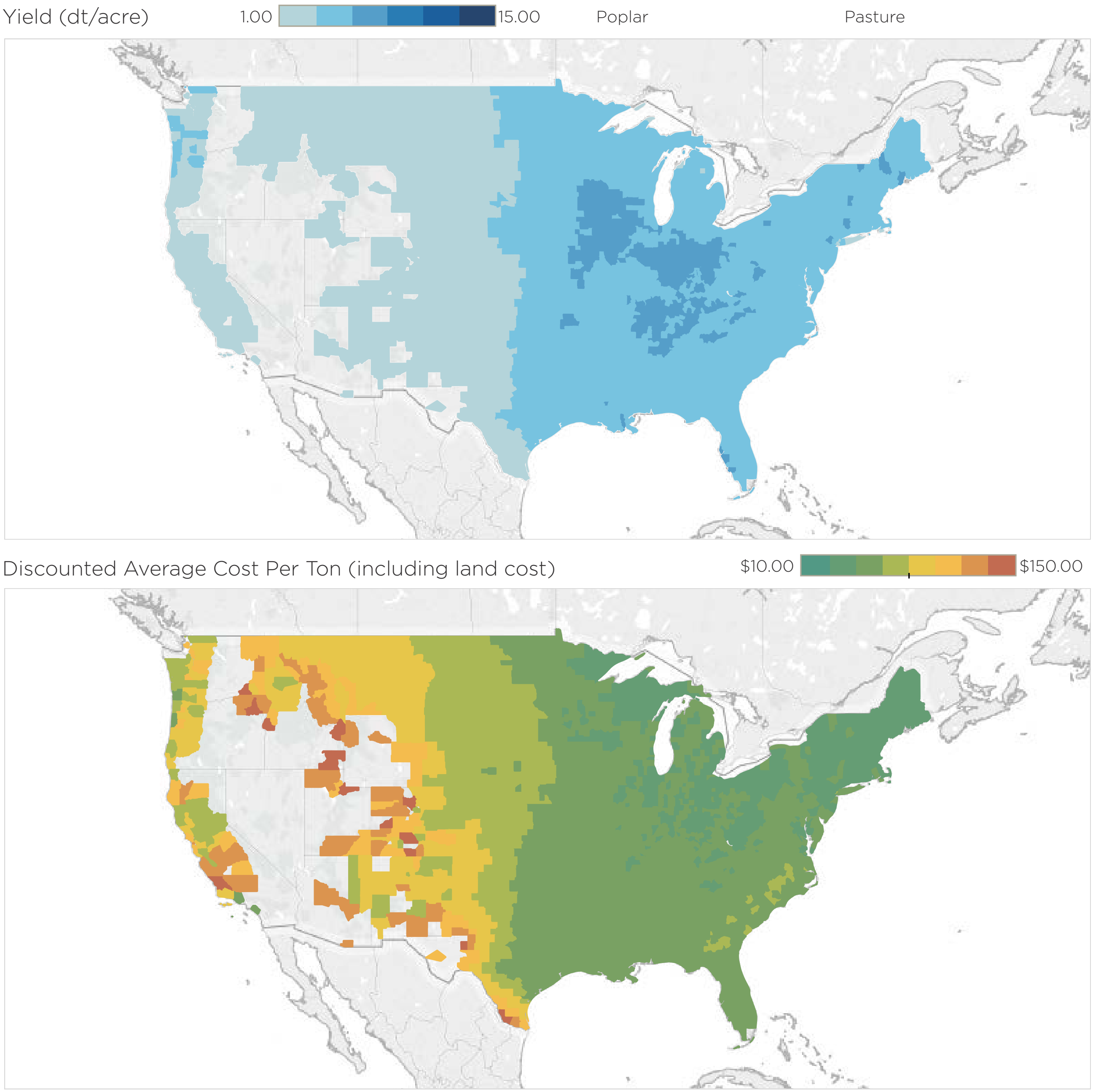
[16] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-8 | Yield (dry tons per acre) for non-coppice woody crops: poplar and pine[17]



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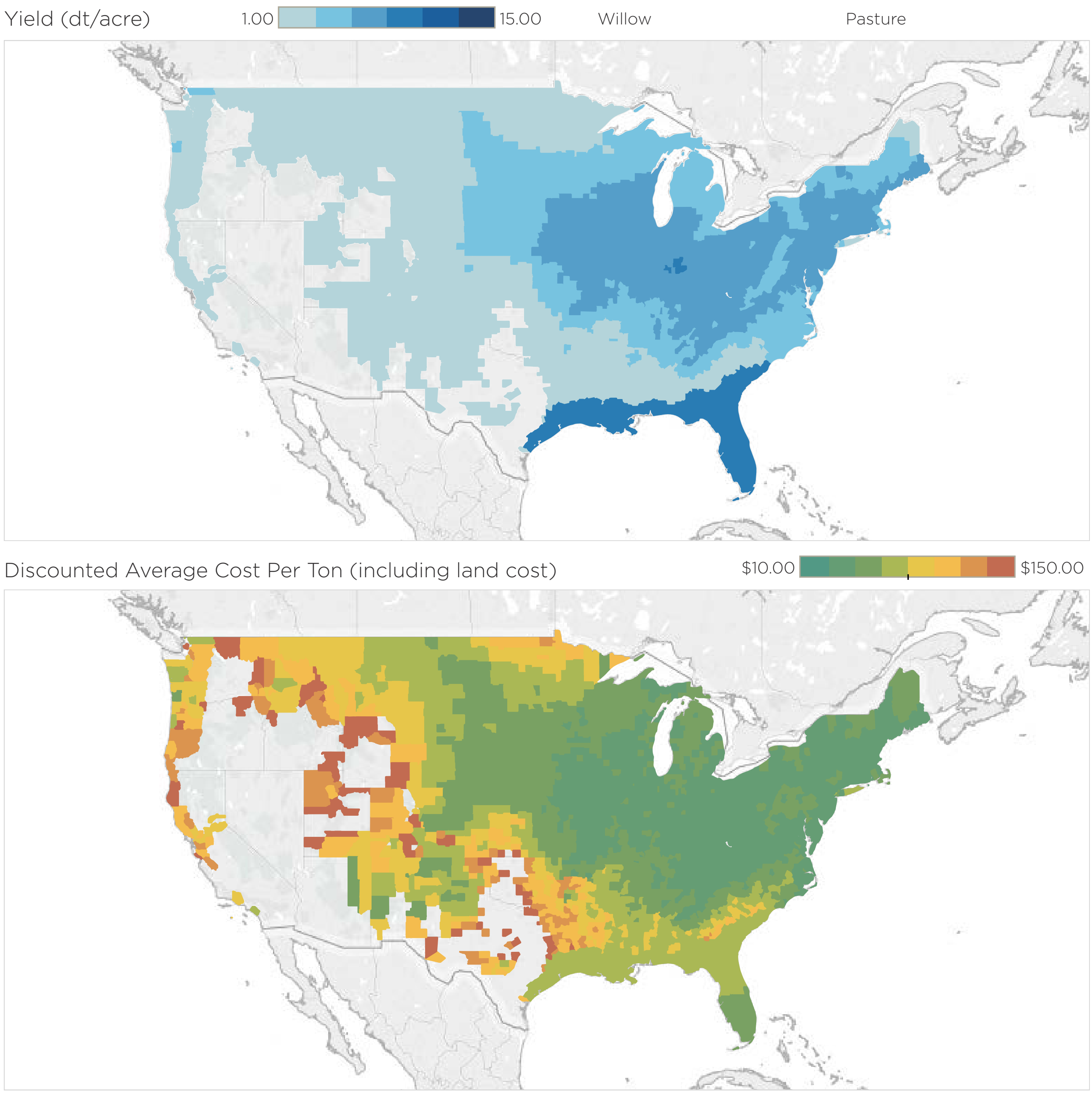
[17] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Figure C-9 | Yield (dry tons per acre) for coppice woody crops: willow and eucalyptus[18]



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[18] Interactive visualization: https://bioenergykdf.net/billionton2016/4/4/tableau

Table C-7 | Summary of Production Inputs and Costs for Herbaceous Energy Crops

Item	Units	Perennial			Annual		
		Switch-grass	Miscanthus	Energy cane	Biomass sorghum	Corn stover	Wheat straw
Stand life	years	10	15	7	1	N/A	N/A
Seed	\$/lb	4.75–14.49	N/A	N/A	2.46	N/A	N/A
Seed	\$/rhizome	N/A	0.10	N/A	N/A	N/A	N/A
Seed	\$/acre	N/A	N/A	467	N/A	N/A	N/A
Planting rate	lb/acre	6	N/A	N/A	5	N/A	N/A
Planting rate	rhizome / acre	N/A	8750	N/A	N/A	N/A	N/A
Replanting rate	%	10	0	0	0	N/A	N/A
Planting equipment	N/A	No-till drill	Miscanthus planter	Hand planting, opener, cover, flat roller	Row crop planter 8 row	N/A	N/A
Herbicide treatments	number, passes	3,3	2,2	3,3	2,2	N/A	N/A
Mechanical weeding	passes	0	0	0	1	N/A	N/A
Nitrogen (establishment)	lb N/acre	0	0	0	150	N/A	N/A
Phosphorus	lb P_2O_5/ acre	40	62	62	60	N/A	N/A
Potassium[19]	lb K_2O/ acre	80	50	50	120	N/A	N/A
Limestone[24]	tons/acre	1.0	1.0	1.0	1.0	N/A	N/A
Total establishment costs	\$/acre	215–410	985–1,140	910–970	175–360	N/A	N/A
Reseeding	year	2	None	None	N/A		
Herbicide treatments[25]	Number passes by year	1 in years 2,5,8	1 in year 2	4,2	N/A		
Nitrogen (maintenance)	lb N/dt	10	9	9	N/A	14.8	11.0
Phosphorus	lb P_2O_5/ dt	4	1.5	1.5	N/A	5.1	2.8
Potassium	lb K_2O/ dt	14	8	8	N/A	27.2	24.7
Year 1	\$/acre	N/A	N/A	120–225	30.90–32.90	10.10–28.45	7.30–23.00

[19] None in Great Plains and West

Table C-7 ***(continued)***

Item	Units	Perennial			Annual		
		Switch-grass	Miscanthus	Energy cane	Biomass sorghum	Corn stover	Wheat straw
Year 2	$/acre	N/A	17.50–18.40	N/A	N/A		
Years 2,5,8	$/acre	11.70–12.75	N/A	N/A	N/A		
Year 2–7	$/acre	N/A	N/A	85–210	N/A		
Years 3,4,6,7,9,10	$/acre	2.90–3.45	N/A	N/A	N/A		
Years 2–15	$/dt	N/A	6.70–11.80	N/A	N/A		
Years 3–15	$/acre	N/A	2.90–3.30	N/A	N/A		
All years	$/dt	8.50–17.15	N/A	N/A	N/A		
Harvest method		Mower-conditioner, large rectangular baler, bale wagon	Mower-conditioner, large rectangular baler, bale wagon	Billet harvester, 3 sugar cane high-dump wagons	Forage harvester, 2 high-dump forage wagons	Shredder, large rectangular baler, bale wagon	Large rectangular baler, bale wagon
Harvest costs	$/acre	41-46	41–45	285	240–250	36–40	28–30
Harvest costs	$/dt	2.90	2.90	N/A	N/A	2.90	2.90

Table C-8 | Summary of Production Inputs and Costs for Woody Energy Crops

Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Rotation	years	8	8	8 years (2 harvests at years 4 and 8); model assumes replanting for up to 32 years	32 years (8 harvests, occurring every 4 years)
Spacing	square feet	60	60	28	7.9
Spacing	trees/acre	726	762	1,575	5,500
Establishment – year 1					
Cuttings	$/tree	0.12	0.065	0.60	0.12
Planting	$/tree	0.09	0.12	0.118	822/acre
Replants	%	0.05	0.05	0	0
Bushog	frequency	N/A	N/A	N/A	1 time
Moldboard plow	frequency	1 time	1 time	1 time	1 time
Disk	frequency	1 time	1 time	1 time	1 time
Plant cover crop	frequency	N/A	N/A	N/A	1- 50/acre

Table C-8 *(continued)*

Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Kill cover crop	frequency	N/A	N/A	N/A	1- 30/acre
Cultivate	frequency	2 times	2 times	2 times	1-weed control 15/acre
Herbicide	herbicide name quantity	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	2-Roundup (1.5 pt/acre each), Goal (2.5 pt/ac), Prowl (2.4 pt/acre)
Herbicide	herbicide name quantity	1-Prowl 0.21 gal/acre	1-Lorox 0.75 lb/acre	1-SFM 0.1406 lb/acre	1-preemergent after planting 45/acre
Nitrogen	lb N/acre	N/A	N/A	150	N/A
Phosphorous	lb P_2O_5/acre	N/A	40	50	N/A
Potassium	lb K_2O/acre	18–60	N/A	48	N/A
Limestone	tons/acre	1	1	1	N/A
Coppice	cut back/acre	N/A	N/A	N/A	1- 10/acre
Establishment costs	$/acre	295–435	425–490	1,565–1,620	N/A
Maintenance years					
Cultivate—year 2		2 times	2 times	0	N/A
Cultivate—year 3		1 time	1 time	0	N/A
Herbicide	years	2,3	2,3	2,6	N/A
	herbicide name quantity	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	1-Roundup 4S 0.375 gal/acre	N/A
Nitrogen	years	3,6	2,4,6	6,11,16,21	2,4,8,16,20,24,28,32
	lb N/acre	90	90	150	45
Phosphorous	years	3	3	6,11,16,21	2,4,8,16,20,24,28,32
	lb P_2O_5/acre	15–30	92 (includes 36 lb N/acre)	115	20
Potassium	years	N/A	N/A	6,11,16,21	2,4,8,16,20,24,28,32
	lb K_2O/acre	N/A	N/A	40	45
Insecticide	years	4	N/A	2,6	N/A
	Name	Poplar insecticide	N/A	N/A	N/A
	lb/acre	1	N/A	N/A	N/A
Maintenance costs					
Year 2	$/acre	22.55–25.70	77.40–85.10	10.40–10.80	N/A
Year 3	$/acre	110–135	100–105	170–180	N/A

Table C-8 *(continued)*

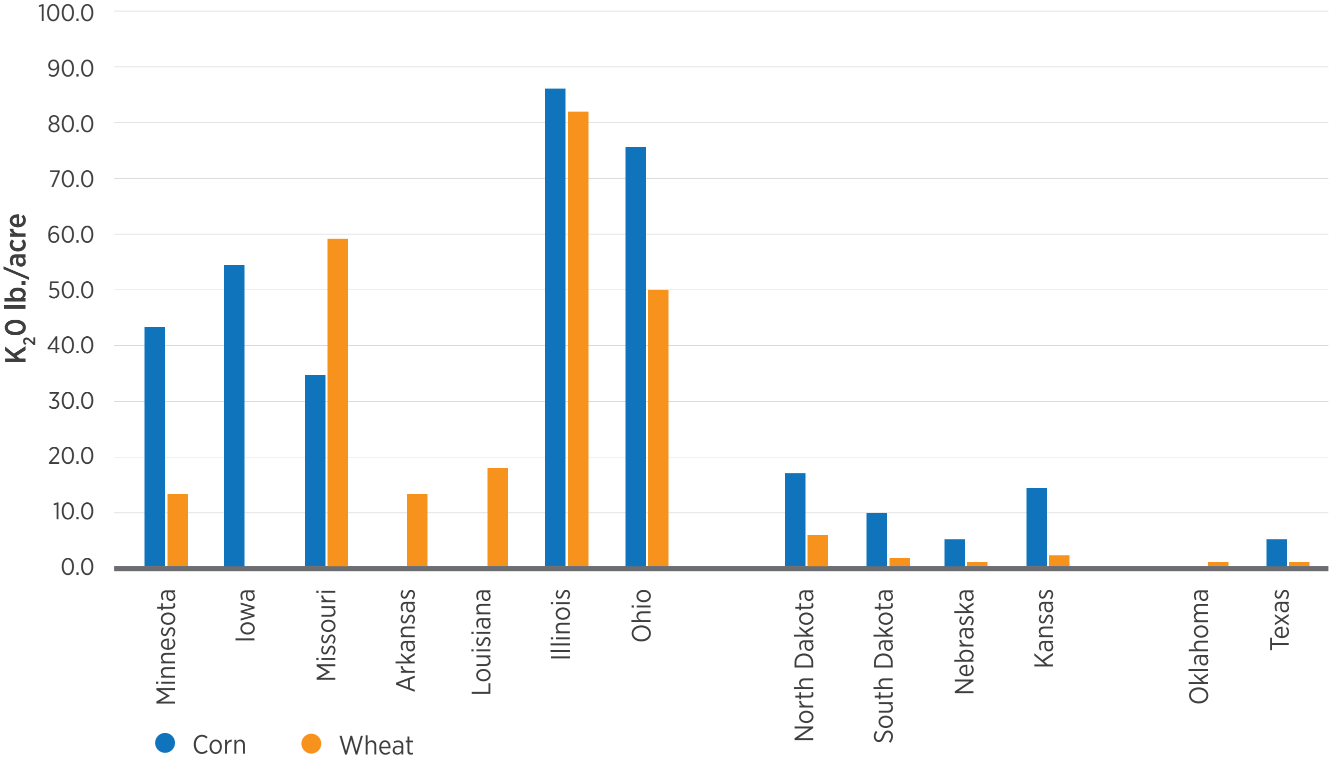
Item	Units	Hybrid poplar	Pine	Eucalyptus	Willow
Year 4	$/acre	22.20	71.95–73.70		N/A
Year 6	$/acre	71.20–82.90	71.95–73.70	190	N/A
Years 8,13,18,23	$/acre			185–190	N/A
Years 11,16,21	$/acre			180	N/A
Remove stumps		N/A	N/A	N/A	Year 22: 400/acre
Harvest					
Harvest method		feller buncher, skidder, chipper and chip van.	feller buncher, skidder, chipper and chip van	feller buncher, skidder, chipper and chip van	Self-propelled forage harvester equipped with a willow cutting head that cuts and chips the stems; the chips are blown into forage wagons transported to the road side; at the roadside, the chips are transferred to a chip van
Harvest costs	$/dt	23.00–24.70	24.50	24.50	N/A

3. Nutrient Costs and How the Inclusion or Exclusion of K_2O Affects Residues and Herbaceous Energy Crops

Biomass production budgets nutrients (nitrogen, phosphorus, and potassium) are removed in crop residues. Data from Nielsen (1995), Lang (2002), Gallagher et al. (2003), Schechinger and Hettenhaus (2004), and Fixen (2007) were used to estimate an average nutrient composition of removed corn stover. Nutrient values used were 14.8 pounds nitrogen per dry ton, 5.1 pounds P_2O_5 (phosphate) per dry ton, and 27.2 pounds K_2O per dry ton. Data from Larson et al. (1978), Jurgens (1978), and Gallagher et al. (2003) were used to estimate average nutrient composition of removed wheat straw. Nutrient values used were 11.0 pounds nitrogen per dry ton, 2.8 pounds P_2O_5 per dry ton, and 24.7 pounds K_2O per dry ton.

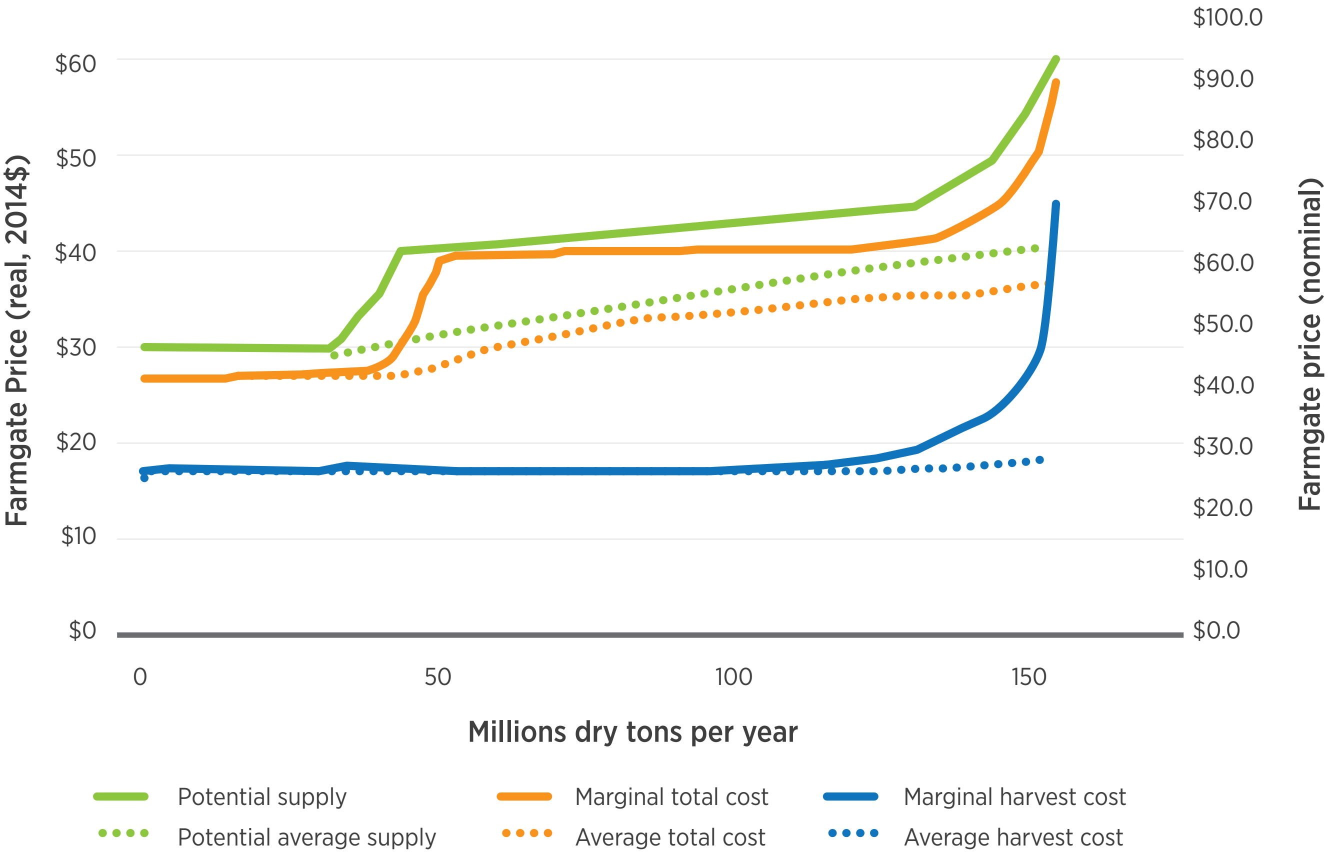
In regions in the western half of the United States potassium is only applied at very low rates (potassium is applied to less of the crop acres and at lower rates) compared to the eastern half of the United States, as shown in figure C.10 for corn and wheat. It is assumed that in calculating grower payments in regions including North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas and further west (i.e., west of Minnesota, Iowa, Missouri, Arkansas, and Louisiana), potassium would not be costed as part of the grower payment reflecting the fact that potassium is applied at low rates.

Figure C-10 | Potassium application rates for corn and wheat for selected states



Using a national average price of $0.513 per lb of K_2O, for corn stover and wheat straw the exclusion of potassium replacement from the grower payment results in a $13.95 per dry ton of stover and straw lower payment, respectively. Corn stover and wheat straw from regions in the western United States have a cost advantage at equal yields over stover and straw from regions in the eastern United States. In addition, because switchgrass and miscanthus translocate nutrients into their roots and have lower nutrient replacement requirements, they have lower nutrient replacement costs, $10 (4) and $15 (6) per dry ton than corn stover when potassium is included (excluded) from the nutrient replacement cost.

Figure C-11 | Harvest and nutrient costs and potential supply curves for corn stover



4. Costs Associated with Management-Intensive Grazing and Pasture Transition

Displacement of livestock grazing occurs when energy crops are established on permanent pasture and cropland used as pasture. In order for stocking rates to be maintained throughout the projection period, this externality is internalized to the bioenergy crop producer by implementation of management intensive grazing of remaining pastureland acreage. This report assumes yield increases of up to 50% from baseline pastureland yields defined in Hellwinckel et al. (2016).

The costs to intensify pastureland for improved forage yields while maintaining same stocking rates include additional fencing, watering, and labor at following rates:

- **Permanent Pasture:** $100/acre in initial intensification year, $15/acre per year for maintenance
- **Cropland Used as Pasture:** $100/acre in initial intensification year, $10/acre per year for maintenance.

Table C-9 | Economic Impacts of the Extended USDA Baseline and *BT16* Base-Case Scenarios (at $60 per dry ton)

Crop	Extended USDA baseline				*BT16* base case			
Crop prices ($/bu)	**2017**	**2022**	**2030**	**2040**	**2017**	**2022**	**2030**	**2040**
Corn	3.5	3.65	3.7	3.7	3.49	3.74	3.83	4.03
Grain sorghum	3.4	3.55	3.68	3.73	3.41	3.87	4.22	4.94
Oats	2.28	2.4	2.4	2.34	2.27	2.59	2.55	2.75
Barley	4.08	4.06	4.02	3.94	4.1	4.29	4.22	4.32
Wheat	4.75	4.85	5.01	5.28	4.72	5.35	5.68	6.48
Soybeans	8.8	9.4	9.36	9.17	8.83	9.86	10.08	10.97
Cotton ($/lb)	0.62	0.69	0.724	0.752	0.621	0.746	0.782	0.826
Rice ($/cwt)	14.9	15.8	16.69	18.29	14.9	15.82	16.86	18.94
Crop acres (millions)								
Corn	90	89	89.09	89.1	89.85	87.6	86.92	84.76
Grain sorghum	7.4	7.1	7.01	7.02	7.39	6.77	6.57	6.16
Oats	2.5	2.5	2.47	2.44	2.5	2.26	2.16	2.09
Barley	3.2	3	2.96	2.9	3.16	2.91	2.92	2.83
Wheat	52.5	52	52.58	54.07	52.74	47.78	47.43	45.83
Soybeans	78	79	78.37	76.87	77.97	75.63	72.85	66.12
Cotton	9.8	10.2	10.38	10.53	9.79	8.91	8.88	8.63
Rice	2.94	3.03	3.06	3.06	2.94	3.02	3.03	2.97
Crop net returns (% relative to 2015)								
Corn	24%	43%	39%	10%	23%	58%	63%	71%
Grain sorghum	16%	-25%	-135%	-333%	18%	103%	91%	111%
Oats	4%	13%	37%	76%	4%	-9%	9%	35%
Barley	-56%	-78%	-124%	-194%	-54%	-55%	-101%	-146%
Wheat	-20%	-26%	-46%	-77%	-21%	22%	23%	42%
Soybeans	3%	21%	14%	-5%	4%	30%	28%	29%
Cotton	8%	23%	66%	148%	8%	-29%	2%	56%
Rice	3%	18%	21%	26%	3%	18%	23%	36%
Livestock								
Total production (million lbs)	22607	25417	26023	26025	22601	25409	26016	25998
Price ($/cwt)	163	156	156	156	163	151	156	157
Inventory (1,000 head)	88,281	93,634	112,981	132,168	88,316	93,581	112,928	132,000
Total crop net returns (% relative to 2015)	8%	24%	15%	-13%	8%	42%	41%	44%
Total livestock net returns (% relative to 2015)	-2%	-2%	11%	11%	-2%	-2%	11%	11%
Total agriculture net returns (% relative to 2015)	1%	5%	12%	5%	1%	9%	19%	19%

Table C-10 | Economic Impacts of Extended USDA Baseline and *BT16* High-Yield Scenarios (at $60 per dry ton)

Crop	Extended USDA baseline				*BT16* base case			
Crop prices ($/bu)	**2017**	**2022**	**2030**	**2040**	**2017**	**2022**	**2030**	**2040**
Corn	3.5	3.65	3.7	3.7	3.33	3.34	3.03	2.86
Grain sorghum	3.4	3.55	3.68	3.73	3.42	3.97	4.38	5.19
Oats	2.28	2.4	2.4	2.34	2.25	2.46	2.35	2.28
Barley	4.08	4.06	4.02	3.94	4.1	4.08	3.98	3.9
Wheat	4.75	4.85	5.01	5.28	4.68	5.32	5.75	7.27
Soybeans	8.8	9.4	9.36	9.17	8.91	9.79	10.29	12.24
Cotton ($/lb)	0.62	0.69	0.724	0.752	0.621	0.764	0.817	0.864
Rice ($/cwt)	14.9	15.8	16.69	18.29	14.9	15.87	16.9	20.39
Crop acres (millions)								
Corn	90	89	89.09	89.1	90.36	84.55	79.67	74.33
Grain sorghum	7.4	7.1	7.01	7.02	7.37	6.63	6.27	5.81
Oats	2.5	2.5	2.47	2.44	2.49	2.21	2.04	1.94
Barley	3.2	3	2.96	2.9	3.15	2.88	2.78	2.69
Wheat	52.5	52	52.58	54.07	52.86	47	45.26	42.04
Soybeans	78	79	78.37	76.87	77.39	75.68	71.06	59.85
Cotton	9.8	10.2	10.38	10.53	9.78	8.49	8.07	7.74
Rice	2.94	3.03	3.06	3.06	2.94	3.01	3.02	2.81
Crop net returns (% relative to 2015)								
Corn	24%	43%	39%	10%	9%	32%	15%	2%
Grain sorghum	16%	-25%	-135%	-333%	23%	162%	213%	272%
Oats	4%	13%	37%	76%	5%	-3%	11%	41%
Barley	-56%	-78%	-124%	-194%	-55%	-77%	-125%	-193%
Wheat	-20%	-26%	-46%	-77%	-22%	27%	41%	117%
Soybeans	3%	21%	14%	-5%	5%	30%	33%	47%
Cotton	8%	23%	66%	148%	8%	-47%	-33%	11%
Rice	3%	18%	21%	26%	3%	19%	24%	56%
Livestock								
Total production (million lbs)	22,607	25,417	26,023	26,025	22,605	25,409	26,016	25,998
Price ($/cwt)	163	156	156	156	163	150	155	155
Inventory (1,000 head)	88,281	93,634	112,981	132,168	88,307	93,814	113,392	132,779
Total crop net returns (% relative to 2015)	8%	24%	15%	-13%	3%	33%	29%	37%
Total livestock net returns (% relative to 2015)	-2%	-2%	11%	11%	-2%	-2%	11%	11%
Total agriculture net returns (% relative to 2015)	1%	5%	12%	5%	-1%	7%	15%	18%

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Appendix D

Appendix to Chapter 7 - Microalgae

D.1 Calculation of Gas Flow Rate

For practical pipeline purposes, in this analysis, we use Eq. (D.1) (SPE 2015) to calculate gas flow rate:

$$P_1^2 - P_2^2 = 25.2\left[\frac{SQ_g^2 ZTfL}{d^5}\right] \tag{D.1}$$

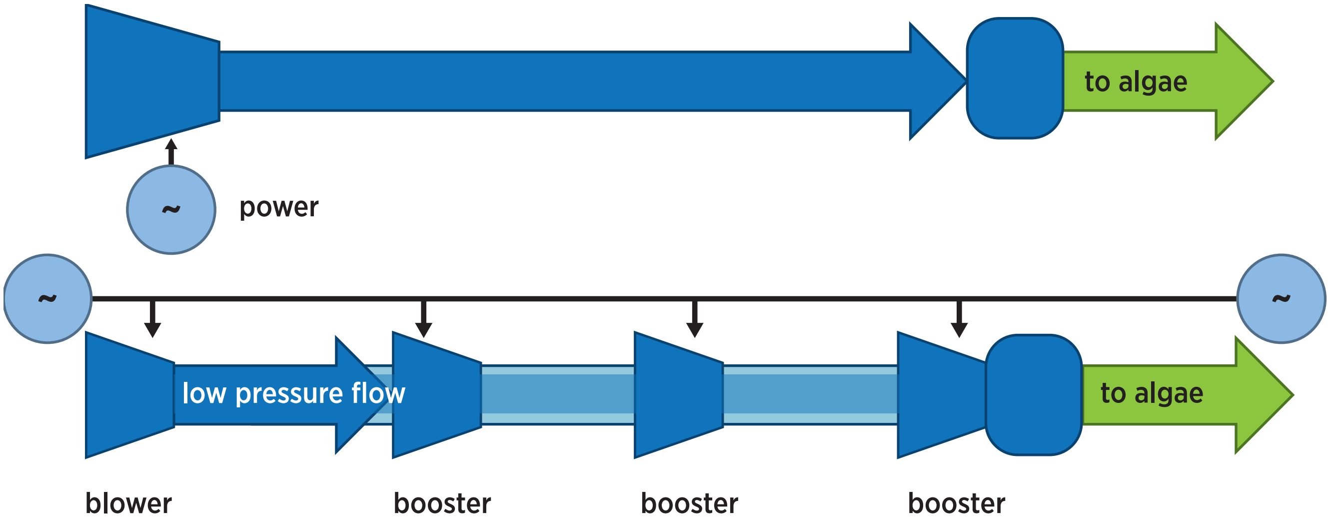
where:

P_1 = upstream pressure (psia)
P_2 = downstream pressure (psia)
S = specific gravity of gas
Q_g = gas flow rate, MMscf/day,
Z = compressibility factor for gas (dimensionless)
T = flowing temperature (°R)
f = Moody friction factor (dimensionless)
d = pipe ID (inches)
L = length (feet)

The Moody friction factor is a function of Reynolds number.

Two configurations were considered: (1) a high-pressure compressor (>100 psig) at the source and (2) low-pressure (20 psig) boost compressors at intervals along the pipe (figure D.1). For the case of intermediate boost compressors, there is a trade-off between the spacing of the compressors and the diameter of the pipeline to optimize the pressure drop. This in turn leads to a trade-off between the cost of compressors and the cost of piping.

Figure D-1 | Alternative configurations for pipeline transport of CO_2 or flue gas



A review of Eq. (D.1) shows that the required pipe diameter for a given pressure drop does not scale linearly with mass flow rate. Furthermore, the cost of piping does not scale linearly with diameter. Consequently, the ideal resource for algae would be a modest-sized facility using pure CO_2 from a relatively close site.

D.2 Description of Growth Model in the Biomass Assessment Tool from Wigmosta et al. (2011)

The growth model of Wigmosta et al. (2011) is used to describe key components in the conversion of solar energy to algal biomass, with the rate of biomass production (P_{mass} in mass per unit area per unit time) given by

$$P_{mass} = \left(\tau_p C_{PAR} E_s\right)\left[\frac{E_c \varepsilon_b}{E_a Q_r E_p}\right]\left(\varepsilon_s \varepsilon_t\right) \qquad \text{(D.2)}$$

The first term on the right-hand side of Eq. (D.1) represents the amount of photosynthetically active radiation (PAR) available, where E_s is the full-spectrum solar energy at the land surface (MJ/m^2), C_{PAR} is the fraction of PAR, and τ_p is the transmission efficiency of incident solar radiation to the pond microalgae. The middle term on the right-hand side is a strain-specific term representing the conversion of PAR to biomass under optimal light and water temperature, where E_a is the energy content per unit biomass (MJ/kg), the photon energy (E_p) (MJ/mol) converts PAR as energy to the number of photons, and ε_p accounts for reductions in photon absorption due to suboptimal light and water temperature. The quantum requirement (Q) is the number of photons required to liberate one mol of O_2 and, together with the carbohydrate energy content (E_c), represents the conversion of light energy to chemical energy through photosynthesis (Weyer et al. 2010). The biomass-accumulation efficiency ($\mathcal{E}_b$) is a poorly understood function of species, water temperature, and other growing conditions accounting for energy required for cell functions that do not produce biomass (e.g., respiration). The final term in Eq. (D.2) represents a reduction in photon absorption from suboptimal light ($\mathcal{E}_s$) and/or water temperature ($\mathcal{E}_t$).

The light utilization efficiency ($\mathcal{E}_s$), including light saturation and photo inhibition, was modeled using the Bush equation (Huesemann et al. 2009):

with E_s and the light saturation constant (E_s) expressed in µmoles/m²•sec.

$$\varepsilon_s = \frac{S_o}{E_s}\left(\ln\left(\frac{E_s}{S_o}\right)+1\right) \tag{D.3}$$

The correction for water temperature ($\mathcal{E}_t$) in Eq. (D.2) is given by

$$\begin{array}{l} 0 \text{ for } T < T_{\min} \\ (T - T_{\min}) / (T_{opt\_low} - T_{\min}) \text{ for } T_{\min} \leq T \leq T_{opt\_low} \\ \varepsilon_t = 1.0 \text{ for } T_{opt\_low} \leq T \leq T_{opt\_high} \\ (T_{\max} - T) / (T_{\max} - T_{opt\_high}) \text{ for } T_{opt\_high} \leq T \leq T_{\max} \\ 0 \text{ for } T > T_{\max} \end{array} \tag{D.4}$$

where T is the minimum water temperature for zero productivity (°C), T_{opt_low} is the lower water temperature for optimal productivity (°C), T_{opt_high} is the upper water temperature for optimal productivity (°C), and T_{max} is the maximum water temperature for zero productivity (°C).

Growth model parameters for the two selected algal strains are shown in Table D.1.

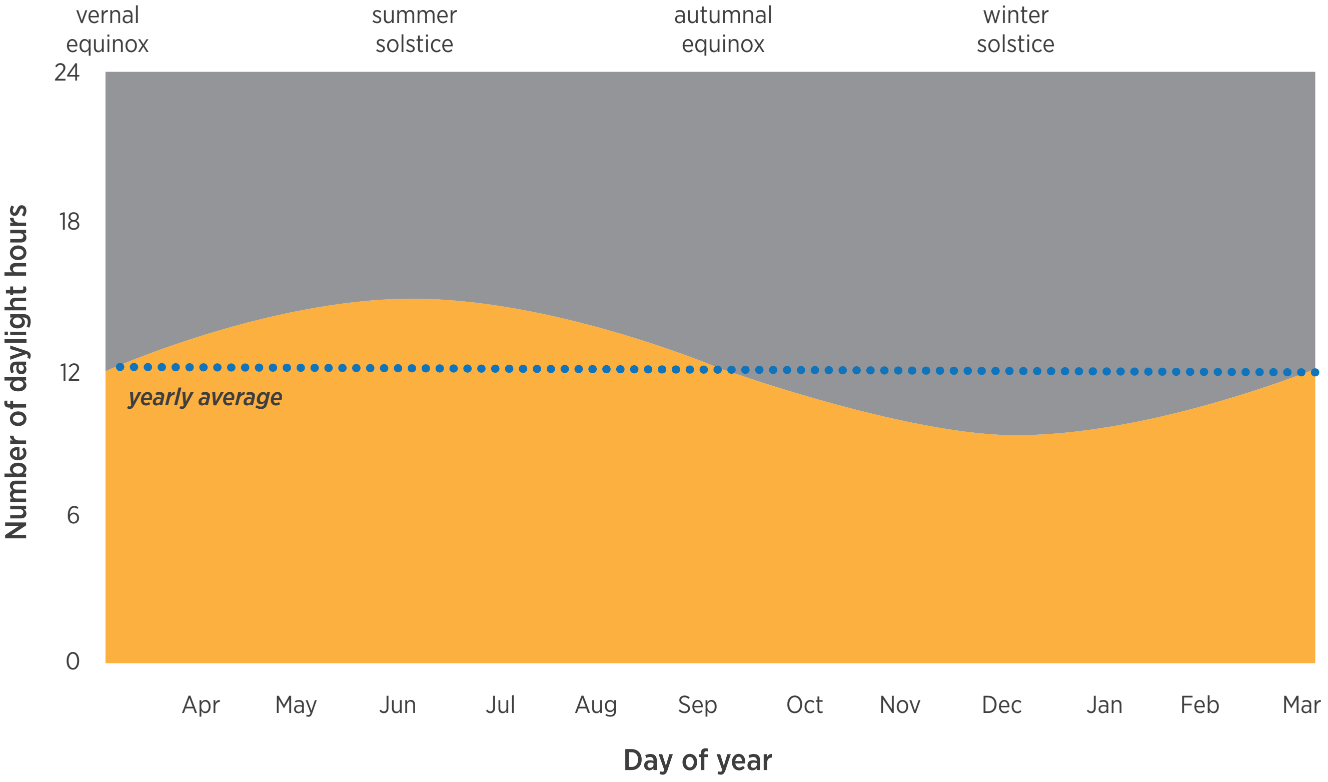
Table D-1 | Growth Model Parameters for Two Selected Algal Strains

	Freshwater-brackish	Saline
	Chlorella sorokiniana	***Nannochloropsis salina***
S_o	250 µmoles/m²•sec	250 µmoles/m²•sec
$\mathcal{E}_b$	0.61°	0.21
T_{min}	12.8°C	11°C
T_{opt_low}	36.0°C	26.3°C
T_{opt_high}	36.2°C	28°C
T_{max}	45.0°C	36°C

D.3 Hours of Daylight

A 12-hour daylight day is assumed for CO_2 demand and delivery based on the geographic center latitude of the conterminous United States, at 39.82°N.

Figure D-2 | Monthly and annual average daylight available at the geographic center latitude for the conterminous United States



D.4 Cost of Transporting CO_2 from Co-Located Industrial Facilities to Algae Production Facilities

D.4.1 Coal-Fired Power Plants

Cost of Transport of CO_2 to Algae Growth Facilities

Delivering flue gas from a coal-fired power plant to feed a 1,000-acre algae facility (open pond) was modeled assuming two identical transport systems of compressor, pipeline, and small buffer storage. The capital cost was calculated for this equipment. The operating cost consists primarily of purchasing electricity to run the compressors. A trade-off between capital and operating cost is possible by selecting a larger- or smaller-diameter pipe. The larger pipe is more expensive but requires less compressor power.

The results of the cost analysis for transporting flue gas from a coal-fired power plant to feed a 1,000-acre algae facility (open pond) are shown in figures D.3 and D.4. The results are shown to highlight the effect of distance (pipeline length) from the co-located source. This information is then used in the Pacific Northwest National Laboratory Biomass Assessment Tool analysis to search for potential algae growth sites.

The distinction between the two figures is as follows: in figure D.3, the analysis is carried out to minimize the energy requirement; whereas in figure D.4, the analysis is carried out to minimize the capital cost. In both figures, an estimate of the annual electricity cost plus an annualized capital cost (labeled "sum") is compared with the annual cost of the required CO_2 at both \$30/ton and \$40/ton. The economic analysis for the CO_2 transport assumes a 20-year life for the capital equipment and a 10% cost of money.

Figure D-3 | Equipment and electricity costs for coal flue gas transport system, including two parallel sets of pipelines and blowers. The system supports a 1,000-acre open pond and is designed to minimize energy requirements for the blowers.

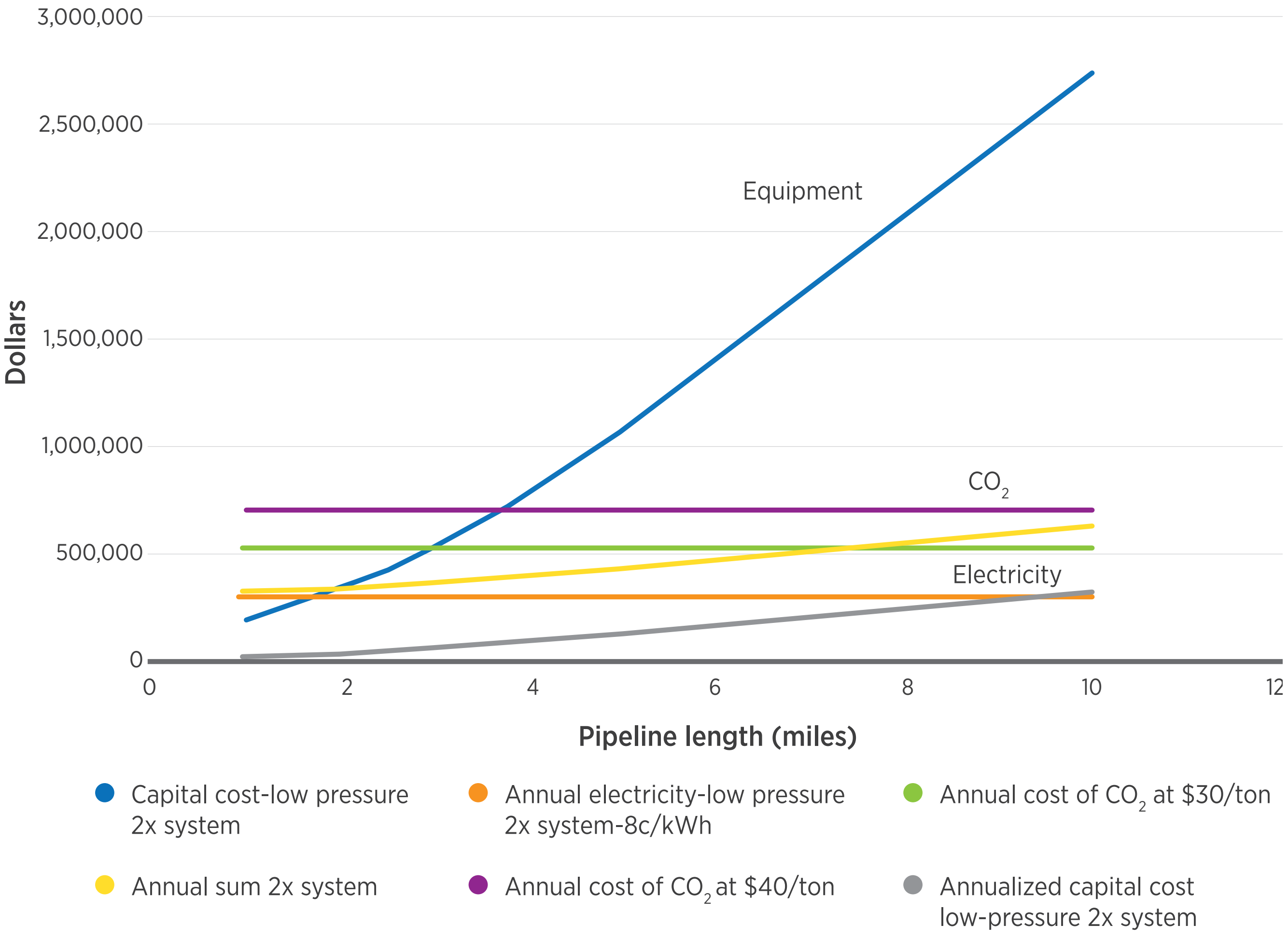
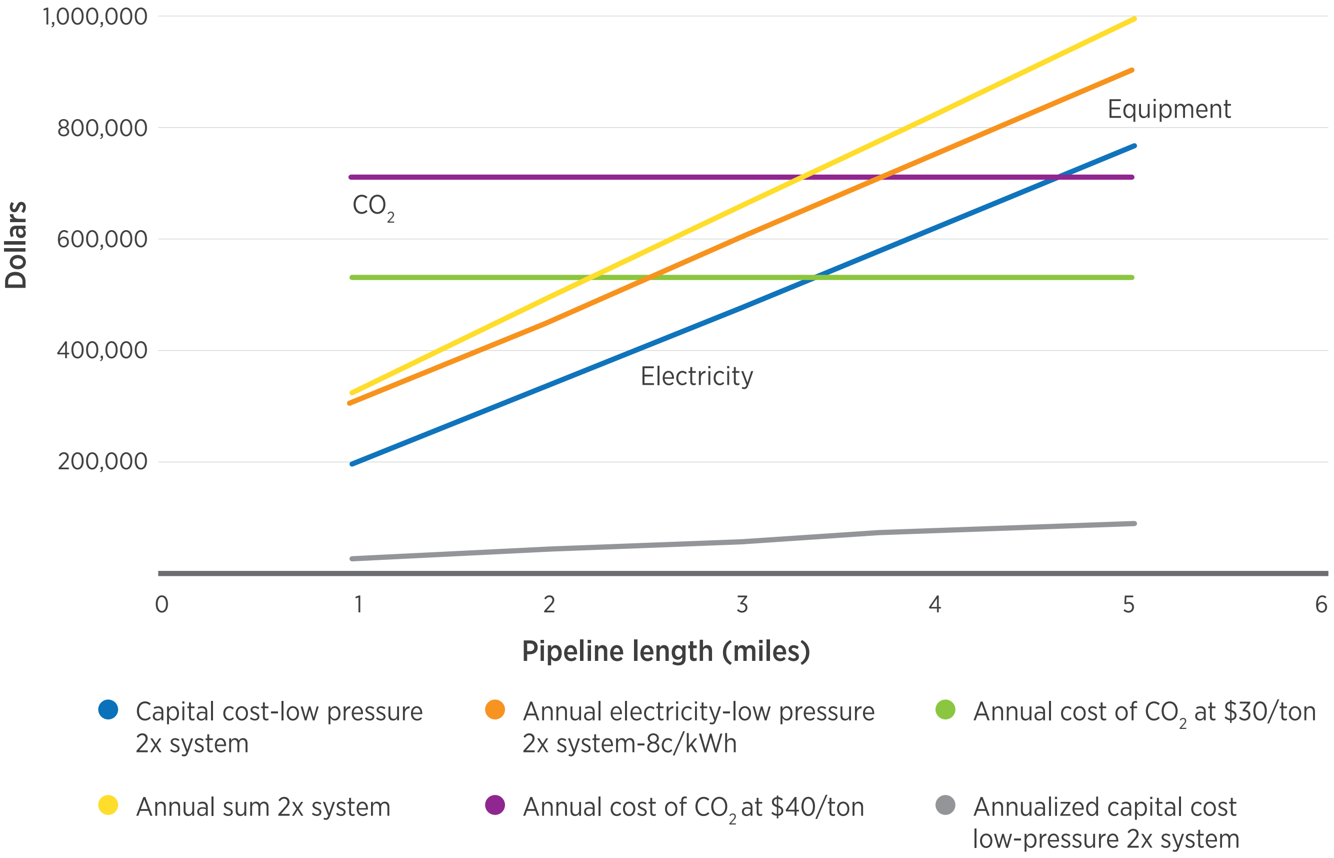


Figure D-4 | Equipment and electricity costs for coal flue gas transport system, including two parallel sets of pipelines and blowers. The system supports a 1,000-acre open pond and is designed to minimize cost.



Cost-Effective Distance

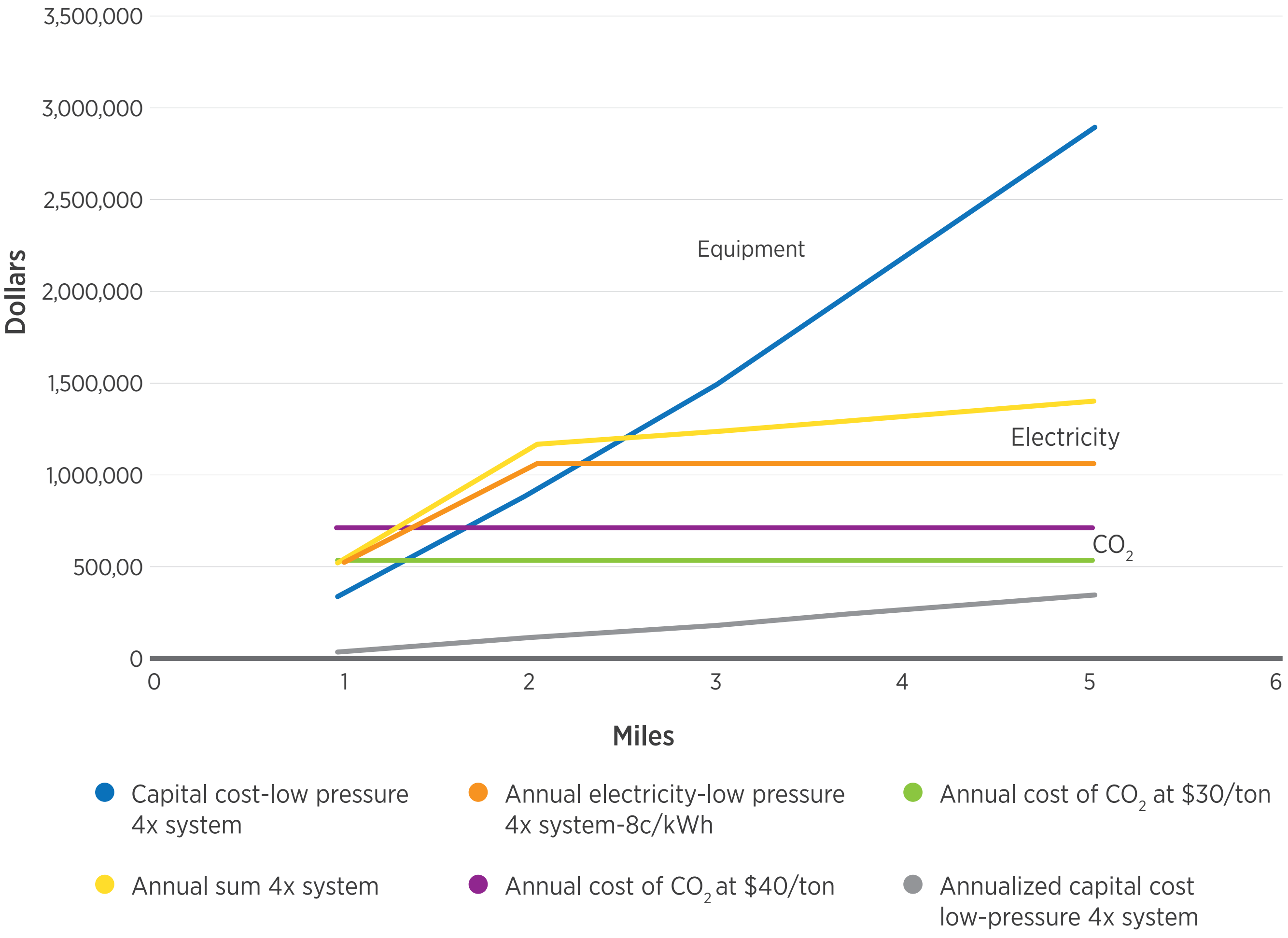
The cost-effective distance is less than about 7 miles to minimize blower energy. The cost-effective distance is less than about 3 miles to minimize capital cost. These results are subject to the assumptions of farm size and the various cost and economic factors. They suggest that the algae facility would need to be very close to the power plant.

D.4.2 Natural Gas–Fired Plants

Cost of Transport of CO_2 to Algae Growth Facilities

Similar to the scenario for coal-fired plant flue gas, the case for using flue gas from a natural gas-fired power plant requires large pipes to move the gas to the algae. This case is even more difficult because the CO_2 is more dilute in the emission stream of a natural gas-fired plant. For a 1,000-acre algae farm, a four-pipe system was assumed. In this case, the system must be designed to minimize compressor power, or else there is no other opportunity to reduce operating costs than to simply purchase CO_2. The results of the cost analysis are shown in figure D.5.

Figure D-5 | Equipment and electricity costs for a natural gas–fired power plant flue gas transport system include (4x) pipeline and blower; 1,000-acre open pond. For transport more than 1 mile, only one blower per pipeline is needed.



Cost-Effective Distance

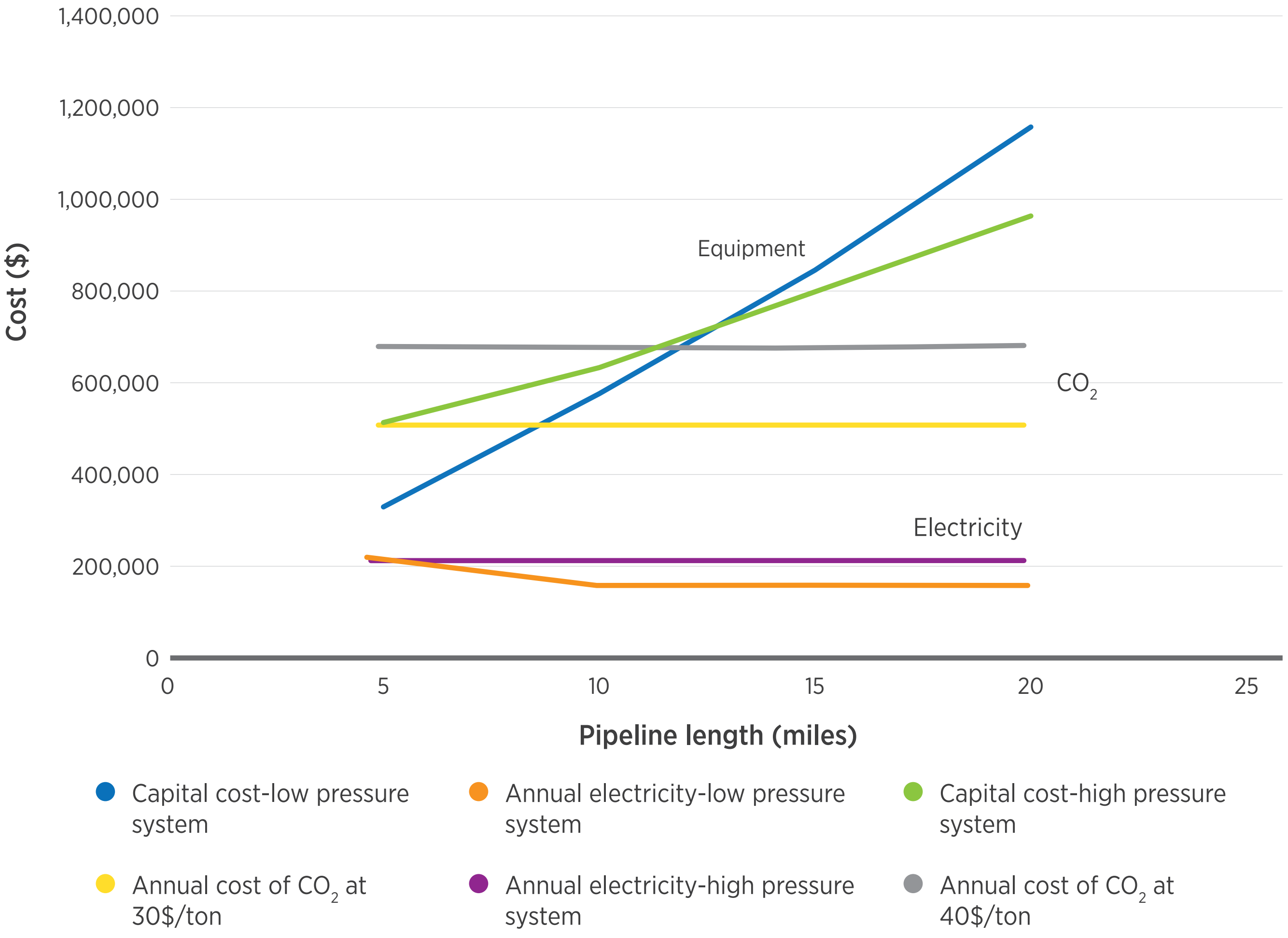
The cost-effective distance for co-location of an algae facility with a natural gas–fired power plant is less than 2 miles. The cost of a pipeline, plus the power to move the very dilute gas, suggests that the algae facility must be located at the same site as the power plant.

D.4.3 Corn Ethanol Plants

Cost of Transport of CO_2 to Algae Growth Facilities

The transport of the gas stream from a corn ethanol plant is much simpler than transport from a power plant because the output gas is more than 99% pure. The pipes can be smaller in diameter and the blowers can be lower in power and less expensive. The results of the cost analysis for equipment and electricity for transporting CO_2 to a 1,000-acre algae facility (open pond) are shown in figure D.6.

Figure D-6 | Equipment and electricity costs for a CO_2 transport system from a corn ethanol plant to an open pond facility include pipeline, compression, and storage



Cost-Effective Distance

For the base ethanol case, the results suggest it is easily cost-effective to pipe CO_2 from a corn ethanol plant to an algae facility up to 20 miles away. This makes it easier to find suitable land for the algae farm that does not compete with land for growing the corn.

D.5 Detailed Scenario Results from Biophysically Based Production Estimates

The tables provided in this appendix provide Biomass Assessment Tool (BAT) model analysis results for site-specific biomass production supported by CO_2-based co-location constrained by available supply and transport economics. In total, 12 scenarios are evaluated. Both current and future productivities are modeled for both *Chlorella sorokiniana* and *Nannochloropsis salina*, each considering three CO_2 co-location options (i.e., ethanol, coal electric generating unit [EGU], natural gas EGU). A summary table of these results is provided in section 7.6.3, Biophysically Based Production Estimates.

Ethanol Production Plant Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-2 | Ethanol Plant Co-Location Results Under Chlorella sorokiniana Freshwater Scenario

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.3	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available		
for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	29.21	million tons/year
Percentage of supply used in co-location	19.3%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.40	million tons/year
Number of ethanol CO_2 plants sourced for co-location	117	
Number of algae production sites	904	unit farm (1,000 acres)
Total algae production area	904,699	acres
Average distance from CO_2 source to algae facility	15.2	miles
Total biomass produced with available co-located CO_2	11.88	million tons/year
Percentage of sites favoring low-pressure system	82.7%	
Percentage of sites favoring high-pressure system	17.3%	
Average cost of co-located CO_2 (CapEx and OpEx)	$10.67	$/ton of CO_2
Total cost per year of all co-located CO_2	$239.88	total million $
Average site cost per year of co-located CO_2	$265.35	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.17	total million $

Table D-2 ***(continued)***

Description	Value	Units
Co-located cost savings	\$907.15	total thousand \$
Percentage of co-located cost savings	77.4%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-3 | Coal EGU Plant Co-Location Results Under *Chlorella sorokiniana* Freshwater Scenario

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	671.61	million tons/year
Percentage of coal CO_2 stream available for co-location	24.7%	
Total CO_2 available during daylight hours	201.48	million tons/year
Percentage of daylight supply used in co-location	7.4%	
Total CO_2 used in co-location scenario (transport to production sites ≤\$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	45.61	million tons/year
Percentage of supply used in co-location	1.7%	
Largest single plant CO_2 output	17.52	million tons/year
Average plant CO_2 output	2.08	million tons/year
Number of coal CO_2 plants sourced for co-location	189	
Number of algae production sites	1,256	unit farm (1,000 acres)
Total algae production area	1,256,971	acres
Average distance from CO_2 source to algae facility	6.2	miles
Total biomass produced with available co-located CO_2	18.54	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	\$19.48	\$/ton of CO_2
Total cost per year of all co-located CO_2	\$612.91	total million \$
Average site cost per year of co-located CO_2	\$487.9	total thousand \$
Average site cost of commercially purchased CO_2 (\$40/ton) for same co-located biomass amount	\$1.32	total million \$
Co-located cost savings	\$829.6	total thousand \$
Percentage of co-located cost savings	63.0%	
Percentage of sites ≤2 miles	4.4%	
Percentage of sites >2 miles	95.6%	

CapEx = capital expense; OpEx = operating expense.

Natural Gas EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Current Productivity

Table D-4 | Natural Gas EGU Plant Co-Location Results Under *Chlorella sorokiniana* Freshwater Scenario

Description	Value	Units
Total U.S. natural gas CO_2 supply	414.54	million tons/year
Total CO_2 potentially available for co-location	240.42	million tons/year
Percentage of coal CO_2 stream available for co-location	58.0%	
Total CO_2 available during daylight hours	96.17	million tons/year
Percentage of daylight supply used in co-location	23.2%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	36.87	million tons/year
Percentage of supply used in co-location	8.9%	
Largest single plant CO_2 output	740.1	K tons/year
Average plant CO_2 output	96.4	K tons/year
Number of CO_2 plants sourced for co-location	176	
Number of algae production sites	789	unit farm (1,000 acres)
Total algae production area	789,610	acres
Average distance from CO_2 source to algae facility	4.8	miles
Total biomass produced with available co-located CO_2	14.99	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$31.58	$/ton of CO_2
Total cost per year of all co-located CO_2	$781.91	total million $
Average site cost per year of co-located CO_2	$991.01	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.70	total million $
Co-located cost savings	$704.69	total thousand $
Percentage of co-located cost savings	41.6%	
Percentage of sites ≤1 mile	3.9%	
Percentage of sites >1 mile	96.1%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-5 | Ethanol Plant Co-Location Results Under *Nannochloropsis salina* Saline Water Scenario

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.33	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ \$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	25.45	million tons/year
Percentage of supply used in co-location	16.8%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.38	million tons/year
Number of ethanol CO_2 plants sourced for co-location	134	
Number of algae production sites	792	unit farm (1,000 acres)
Total algae production area	792,612	acres
Average distance from CO_2 source to algae facility	16.0	miles
Total biomass produced with available co-located CO_2	10.35	million tons/year
Percentage of sites favoring low-pressure system	80.3%	
Percentage of sites favoring high-pressure system	19.7%	
Average cost of co-located CO_2 (CapEx and OpEx)	$10.92	$/ton of CO_2
Total cost per year of all co-located CO_2	$213.26	total million $
Average site cost per year of co-located CO_2	$269.3	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.17	total million $
Co-located cost savings	$896.6	total thousand $
Percentage of co-located cost savings	76.9%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-6 | Coal EGU Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	912.33	million tons/year
Percentage of coal CO_2 stream available for co-location	33.5%	
Total CO_2 available during daylight hours	273.70	million tons/year
Percentage of daylight supply used in co-location	10.1%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ $40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	133.80	million tons/year
Percentage of supply used in co-location	4.91%	
Largest single plant CO_2 output	22.7	million tons/year
Average plant CO_2 output	6.77	million tons/year
Number of coal CO_2 plants sourced for co-location	246	
Number of algae production sites	3,346	unit farm (1,000 acres)
Total algae production area	3,348,586	acres
Average distance from CO_2 source to algae facility	8.9	miles
Total biomass produced with available co-located CO_2	54.40	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$21.67	$/ton of CO_2
Total cost per year of all co-located CO_2	$2.765	total billion $
Average site cost per year of co-located CO_2	$826.4	total 100 thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$1.45	total million $
Co-located cost savings	$624.7	total thousand $
Percentage of co-located cost savings	43.0%	
Percentage of sites $\leq$2 miles	1.2%	
Percentage of sites >2 miles	98.8%	

CapEx = capital expense; OpEx = operating expense.

Natural Gas EGU Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Current Productivity

Table D-7 | Natural Gas EGU Plant Co-Location Results Under *Nannochloropsis salina* Saline Water Scenario

Description	Value	Units
Total U.S. natural gas CO_2 supply	414.54	million tons/year
Total CO_2 potentially available for co-location	218.67	million tons/year
Percentage of coal CO_2 stream available for co-location	52.8%	
Total CO_2 available during daylight hours	87.47	million tons/year
Percentage of daylight supply used in co-location	12.6%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ \$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	52.23	million tons/year
Percentage of supply used in co-location	12.6%	
Largest single plant CO_2 output	740.1	K tons/year
Average plant CO_2 output	64.2	K tons/year
Number of CO_2 plants sourced for co-location	151	
Number of algae production sites	1,095	unit farm (1,000 acres)
Total algae production area	1,095,846	acres
Average distance from CO_2 source to algae facility	6.7	miles
Total biomass produced with available co-located CO_2	21.24	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	\$34.43	\$/ton of CO_2
Total cost per year of all co-located CO_2	\$1.246	total billion \$
Average site cost per year of co-located CO_2	\$1.14	total million \$
Average site cost of commercially purchased CO_2 (\$40/ton) for same co-located biomass amount	\$1.73	total million \$
Co-located cost savings	\$592.5	total thousand \$
Percentage of co-located cost savings	34.2%	
Percentage of sites $\leq$1 mile	2.28%	
Percentage of sites >1 mile	97.72%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Future Productivity

Table D-8 | Ethanol Plant Co-Location Results Using *Chlorella sorokiniana* Fresh Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.32	million tons/year
Total CO_2 potentially available for co-location	76.77	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	50.7%	
Total CO_2 available during daylight hours	38.38	million tons/year
Percentage of daylight supply used in co-location	25.4%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$\$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	32.24	million tons/year
Percentage of supply used in co-location	21.3%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.48	million tons/year
Number of ethanol CO_2 plants sourced for co-location	141	
Number of algae production sites	508	unit farm (1,000 acres)
Total algae production area	508,393	acres
Average distance from CO_2 source to algae facility	14.5	miles
Total biomass produced with available co-located CO_2	13.11	million tons/year
Percentage of sites favoring low-pressure system	82.7%	
Percentage of sites favoring high-pressure system	17.3%	
Average cost of co-located CO_2 (CapEx and OpEx)	$7.79	$/ton of CO_2
Total cost per year of all co-located CO_2	$185.97	total million $
Average site cost per year of co-located CO_2	$366.1	total $100 thousand
Average site cost of commercially purchased CO_2 (\$40/ton) for same co-located biomass amount	$2.30	total million $
Co-located cost savings	$1.94	total million $
Percentage of co-located cost savings	84.1%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-Location: Freshwater Open-Pond Scenario (*Chlorella sorokiniana*)—Future Productivity

Table D-9 | Coal EGU Plant Co-Location Results Using *Chlorella sorokiniana* Freshwater Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	671.61	million tons /year
Percentage of coal CO_2 stream available for co-location	24.7%	
Total CO_2 available during daylight hours	201.48	million tons/year
Percentage of daylight supply used in co-location	7.4%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$ \$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	24.66	million tons/year
Percentage of supply used in co-location	0.9%	
Largest single plant CO_2 output	2.68	million tons/year
Average plant CO_2 output	7.63	million tons/year
Number of coal CO_2 plants sourced for co-location	68	
Number of algae production sites	257	unit farm (1,000 acres)
Total algae production area	257,199	acres
Average distance from CO_2 source to algae facility	3.8	miles
Total biomass produced with available co-located CO_2	10.03	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	\$24.04	\$/ton of CO_2
Total cost per year of all co-located CO_2	\$1.390	total billion \$
Average site cost per year of co-located CO_2	\$2.70	total million \$
Average site cost of commercially purchased CO_2 (\$40/ton) for same co-located biomass amount	\$3.48	total million \$
Co-located cost savings	\$782.8	total thousand \$
Percentage of co-located cost savings	22.5%	
Percentage of sites $\leq$4 miles	41.4%	
Percentage of sites >4 miles	58.6%	

CapEx = capital expense; OpEx = operating expense.

Ethanol Production Plant Co-Location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Future Productivity

Table D-10 | Ethanol Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. ethanol CO_2 supply	151.33	million tons/year
Total CO_2 potentially available for co-location	63.55	million tons/year
Percentage of total ethanol CO_2 stream available for co-location	42.0%	
Total CO_2 available during daylight hours	31.77	million tons/year
Percentage of daylight supply used in co-location	21.0%	
Total CO_2 used in co-location scenario (transport to production sites ≤$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	27.91	million tons/year
Percentage of supply used in co-location	18.5%	
Largest single plant CO_2 output	5.47	million tons/year
Average plant CO_2 output	1.42	million tons/year
Number of ethanol CO_2 plants sourced for co-location	127	
Number of algae production sites	435	unit farm (1,000acres)
Total algae production area	435,336	acres
Average distance from CO_2 source to algae facility	14.6	miles
Total biomass produced with available co-located CO_2	11.35	million tons/year
Percentage of sites favoring low-pressure system	72.2%	
Percentage of sites favoring high-pressure system	27.8%	
Average cost of co-located CO_2 (CapEx and OpEx)	$8.01	$/ton of CO_2
Total cost per year of all co-located CO_2	$159.39	total million $
Average site cost per year of co-located CO_2	$366.4	total thousand $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$2.33	total million $
Co-located cost savings	$1.96	total million $
Percentage of co-located cost savings	84.3%	

CapEx = capital expense; OpEx = operating expense.

Coal EGU Co-location: Saline Water Open-Pond Scenario (*Nannochloropsis salina*)—Future Productivity

Table D-11 | Coal EGU Plant Co-Location Results Using *Nannochloropsis salina* Saline Water Strain Under Future Productivity Conditions

Description	Value	Units
Total U.S. coal CO_2 supply	2.725	billion tons/year
Total CO_2 potentially available for co-location	912.33	million tons/year
Percentage of coal CO_2 stream available for co-location	33.5%	
Total CO_2 available during daylight hours	273.70	million tons/year
Percentage of daylight supply used in co-location	10.1%	
Total CO_2 used in co-location scenario (transport to production sites $\leq$$40/ton and/or sufficient pond areas/biomass production to support available CO_2 supply)	30.38	million tons/year
Percentage of supply used in co-location	1.1%	
Largest single plant CO_2 output	22.68	million tons/year
Average plant CO_2 output	8.12	million tons/year
Number of coal CO_2 plants sourced for co-location	70	
Number of algae production sites	299	unit farm (1,000 acres)
Total algae production area	299,231	acres
Average distance from CO_2 source to algae facility	4.4	miles
Total biomass produced with available co-located CO_2	12.35	million tons/year
Average cost of co-located CO_2 (CapEx and OpEx)	$33.43	$/ton of CO_2
Total cost per year of all co-located CO_2	$1.869	total billion $
Average site cost per year of co-located CO_2	$1.10	total million $
Average site cost of commercially purchased CO_2 ($40/ton) for same co-located biomass amount	$3.69	total million $
Co-located cost savings	$2.59	total million $
Percentage of co-located cost savings	70.2%	
Percentage of sites $\leq$4 miles	10.7%	
Percentage of sites >4 miles	89.3%	

CapEx = capital expense; OpEx = operating expense.

D.6 Productivities Associated with Costs

Table D-12 | Productivities (g/m²/d) of *Chlorella sorokiniana* (freshwater media) and *Nannochloropsis salina* (saline media) associated with minimum, median, and maximum costs for each scenario. The 5-digit FIPs code (county identifier) associated with the productivity is given in each cell, following the productivity.

Scenario—time	Scenario—culture medium	Source of CO_2	Productivities (g/m²/d); FIPs code		
			Minimum	Median	Maximum
Present productivity	Freshwater media	Coal	15.87; 12099	11.63; 22011	3.21; 55003
		Natural gas	16.77; 12071	13.63; 48201	7.17; 35029
		Ethanol	14.46; 48057	11.54; 48401	3.25; 55099
	Saline media	Coal	17.23; 12011	11.07; 01091	3.49; 32013
		Natural gas	16.77; 12071	13.30; 48361	4.64; 32019
		Ethanol	14.46; 48057	11.31; 22067	3.23; 41057
Future productivity	Freshwater media	Coal	29.81; 12009	27.66; 12107	6.88; 32013
		Ethanol	28.49; 48057	22.74; 48401	6.36; 41057
	Saline media	Coal	31.02; 12009	21.19; 12017	7.16; 32013
		Ethanol	29.31; 22057	28.67; 31121	5.30; 36063

D.7 References

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Glossary of Key Terms

Glossary of Key Terms

advanced supply system – Feedstock supply system with advanced preprocessing to transform raw biomass into a tradeable commodity. In this analysis, advanced systems feature preprocessing depots to convert biomass bales or wood chips into pellets, which can then be blended and accepted by any biorefinery.

AFDW – ash-free dry weight

ASD – Agricultural Statistic District

algal biofuels – Utilization of primarily microalgae to produce high quantities of biomass per unit land area. The lipids in the microalgae can be used to produce biodiesel.

bcf – billion cubic feet

BGY – billion gallons per year

BT2 – Billion-Ton Update – *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (2011); the second of the Billion-Ton reports; expanded and updated analyses of the 2005 *Billion-Ton Study* to provide a more comprehensive assessment of U.S. biomass resources; evaluated the potential economic availability of biomass feedstocks under a range of offered prices and yield scenarios between 2012 and 2030.

BT16 – Billion-Ton Report—*U.S. Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (2016); the third of the Billion-Ton reports; provides the most recent estimates of potential biomass that could be available for biorefining and consists of two volumes: volume 1 (this report), focusing on biomass potentially available at specified prices, and volume 2, changes in environmental sustainability indicators associated with select production scenarios in volume 1.

BTS – Billion-Ton Study—*Biomass as a Feedstock for Bioenergy and Bioproducts: The Feasibility of a Billion Ton Annual Supply* (2005); the first of the Billion-Ton reports; a national-level, strategic assessment of the potential biophysical availability of biomass; identified more than one billion tons of biomass resources in the United States from agricultural land and forestland.

biobased product – The term biobased product, as defined by the Farm Security and Rural Investment Act of 2002 (FSRIA), means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.

biodiesel – Fuel derived from vegetable oils or animal fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol, typically methanol. It is mixed with petroleum-based diesel.

BAT – Biomass Assessment Tool

bioenergy – Energy derived from biomass.

bioenergy equivalent – Conversion estimate for the quantity of raw biomass on a dry ton basis, assuming a particular heating content and thermal conversion efficiency. For example, wood biopower for electric generation is assumed to be 13 million Btu per bone dry ton and municipal solid waste (MSW)-derived biopower is assumed to be 8 million Btu per bone dry ton.

biofuels – Fuels made from biomass resources, or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

biomass – Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants, algae, grasses, animal manure, municipal residues, and other residue materials.

biomass resource analysis – The quantification of a supply of biomass that under specified conditions (e.g., availability of land, water, and fertilizer; spatial resolution and extent; timeframe) can be used to generate biofuel or biopower.

biopower – The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.

biorefinery – A facility that processes and converts biomass into value-added products (e.g., renewable fuels, power, chemical products, and intermediates). The biorefinery concept is analogous to a petroleum refinery, which produces a slate of multiple fuels, intermediates, and products from a petroleum feedstock.

black liquor – Solution of lignin residue and the pulping chemicals used to extract lignin during the manufacture of paper.

Btu – British Thermal Unit – A unit of energy equal to approximately 1,055 Joules. It is the amount of energy required to heat 1 pound (0.454 kg) of water from 39˚ to 40˚ F.

Bu – bushels

C&D – Construction and demolition materials – Wood waste generated during the construction of new buildings and structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures.

CHP – combined heat and power

CNG – compressed natural gas

CONUS – conterminous United States

CORRIM – Consortium for Research on Renewable Industrial Materials

conventional supply system – Feedstock supply system using traditional agricultural and forestry systems to deliver biomass bales or wood chips to the refinery. In this analysis, conventional systems have little to no active quality control and biorefineries can only accept one feedstock type.

conventionally sourced wood – Wood that has commercial uses other than fuel (e.g. pulpwood) but is used for energy because of market conditions. This would probably only include smaller diameter pulpwood-sized trees.

coppice – To regrow from a (tree) stump after harvest.

cotton gin trash – Residue available at a processing site, including seeds, leaves, and other material.

cotton residue – Cotton stalks available for collection after cotton harvest.

CRM – component ratio method – A method introduced in 2009 used to estimate non-merchantable volumes from merchantable trees by the USDA Forest Service.

CRP – Conservation Reserve Program – A land conservation program administered by the Farm Service Agency (FSA) that pays a yearly rental payment in exchange for farmers removing environmentally sensitive land from agricultural production and planting species that will improve environmental quality (Definition from U.S. Department of Agriculture Farm Service Agency Conservation Programs).

crop residues – The portion of a crop remaining after the primary product is harvested.

cropland – Similar to the 2012 USDA Census of Agriculture definition of "total cropland," this land category includes planted and harvested acres of corn, wheat, grain sorghum, barley, soybeans, rice, cotton, barley and hay (see Natural Resources Conservation Service definition of cropland and appendix C for more details).

cropland pasture, or cropland used for pasture or grazing – Defined in the 2012 USDA Census of Agriculture Appendix B as "land used only for pasture or grazing that could have been used for crops without additional improvement. Also included are acres of crops hogged or grazed but not harvested prior to grazing" (Adapted from the U.S. Department of Agriculture; see appendix C for more details).

cull tree – A live tree, 5.0 inches dbh or larger that is non-merchantable for saw logs, now or prospectively, because of rot, roughness, or species.

CTL – cut-to-length

delivered cost – An estimate of all costs—including production, harvest, storage, handling, preprocessing, and transportation—to deliver biomass feedstocks to the reactor throat.

dbh – diameter at breast height – The common measure of wood volume approximated by the diameter of trees measured at approximately breast height from the ground.

DOE – United States Department of Energy

EGU – electric generating unit

EISA – The Energy Independence and Security Act of 2007

EPA – United States Environmental Protection Agency

ethanol – Also known as ethyl alcohol or grain alcohol, this volatile, flammable, and colorless liquid with the chemical formula C_2H_6O is produced by the fermentation of sugars.

EU – European Union

feedstock – A product used as the basis for manufacture of another product.

FIA – Forest Inventory and Analysis – A program of the U.S. Forest Service of the U.S. Department of Agriculture that collects, analyzes, and reports information on the status and trends of America's forests: how much forest exists, where it exists, who owns it, and how it is changing. It has been in continuous operations since 1928. The latest technologies are used to acquire a consistent core set of ecological data about forests through remote sensing and field measurements. The data in this report are summarized from more than 100,000 permanent field plots in the United States.

fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

forest land – Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. (Adapted from the U.S. Forest Service of the U.S. Department of Agriculture)

ForSEAM – Forest Sustainable and Economic Analysis Model

FRCS – Fuel Reduction Cost Simulator – A forest harvesting costing model utilized in this report to estimate the cost of harvesting small diameter trees for biomass.

fuelwood – Wood used for conversion to some form of energy, primarily for residential use.

GDP – gross domestic product

GFPM – Global Forest Products Module

GHG – greenhouse gas – Natural or anthropogenic gas that can absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere, and the clouds. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. (Adapted from the Intergovernmental Panel on Climate Change and the International Organization for Standardization 13065 sustainability criteria for bioenergy)

growing stock – A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, growing stock includes only trees 5.0 inches dbh and larger.

HI – harvest index – For conventional crops, the ratio of residue to grain.

idle land – A land class defined as cropland used for cover crops or soil improvement, but not harvested and not pastured or grazed (Adapted from the U.S. Department of Agriculture; see also appendix C for more details).

IMPLAN – Impact analysis for planning

industrial wood – All commercial roundwood products except fuelwood.

irrigated pasture – Irrigated pasture is defined to be any pasture land that falls under the “irrigated land” land class defined by the U.S. Department of Agriculture (USDA 2012; see also appendix C for more details).

KDF – Bioenergy Knowledge Discovery Framework – Online collection of bioenergy-related research, data sets, applications, and maps for bioenergy researchers, policymakers, and industry; hosts U.S. Billion-Ton Report interactive data and visualizations

kwh – kilowatt hour

LHW – lowland hardwood

LNG – liquefied natural gas

logging residues – The unused portions of growing-stock and non-growing-stock trees cut or killed by logging and left in the woods.

MGD – million gallons per day

MiG – management-intensive grazing – Management of grazing land that can increase the carrying capacity, whereby animal nutrient demand through the grazing season is balanced with forage supply based on animal requirements (Adapted from *Management-Intensive Grazing* by Jim Gerrish, 2004).

mill residues – Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials) but excludes logging residues. May include both primary and secondary mills.

MSW – municipal solid waste – Wastes (garbage) collected from municipalities consisting mainly of yard trimmings and paper products.

MW – megawatt

nonforest land – Land that has never supported forests and lands formerly forested where use of timber management is precluded by development for other uses. Nonforest land includes area used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Bureau of the Census as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120 feet wide, and clearings, etc., must be more than 1 acre in area to qualify as nonforest land.

other forestland – Forest land other than timberland and reserved forest land. It includes available forest land, which is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

other removals and residues – Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing for other uses (i.e., cropland, pastureland, roads, urban settlement). It does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

PBR – photobioreactor

perennial – A crop that lives for more than two years. Well-established perennial crops have a good root system and provide cover that reduces erosion potential. They generally have reduced fertilizer and herbicide requirements compared to annual crops.

permanent pastureland, or rangeland, other than cropland and woodland pastured – Defined in the 2012 USDA Census of Agriculture Appendix B as a land category which "encompasses grazable land that does not qualify as woodland pasture or cropland pasture. It may be irrigated or dry land. In some areas, it can be a high quality pasture that could not be cropped without improvements. In other areas, it is barely able to be grazed and is only marginally better than wasteland." (USDA 2012; see also appendix C for more details).

POLYSYS – Policy Analysis System – An agricultural policy modeling system of U.S. agriculture, including both crops and livestock. It is based at the University of Tennessee Institute of Agriculture, Agricultural Policy Analysis Center.

PVC – polyvinyl chloride

primary agricultural resources – Resources included within this category include energy feedstocks (annual energy crops, coppice and non-coppice woody crops, perennial grasses), crop residues (barely straw, corn stover, oat straw, sorghum stubble, wheat straw), and conventional crops (barley, born, cotton, hay, oats, rice, sorghum, soybeans, wheat). The projections included for this category of feedstocks are two baseline scenarios (one with no energy crops—e.g., feedstock price of zero—and another including energy crops) and four high-yield scenarios with estimated biomass prices ranging between $30 and $100.

primary wood-using mill – A mill that converts roundwood products into other wood products. Common examples are sawmills that convert saw logs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

PS – planted softwood

psig – pounds per square inch gauge

PSU – practical salinity units

pulpwood – Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp (also referred to as conventional wood within the database).

renewable fuel – liquid fuels (e.g., ethanol or biodiesel as a replacement for gasoline, jet fuel, kerosene, or diesel) or other fuels (e.g., pellets as a substitute for fossil based power production). Note: the generation of renewable fuels can also produce valuable biomass based products or chemicals.

RFS – Renewable Fuel Standard – The RFS was established by the Energy Policy Act of 2005. It required 7.5 billion gallons of renewable-based fuel (which was primarily ethanol) to be blended into gasoline by 2012. This original RFS (referred to sometimes as RFS1) was expanded upon (RFS2) by the Energy Independence and Security Act of 2007 (EISA) to include diesel in addition to gasoline as well as to increase the volume of renewable fuel to be blended into fossil-based fuel to 9 billion and ultimately 36 billion gallons by 2022. RFS2 established life-cycle greenhouse gas requirements (less than fossil fuels they replace) for renewable fuels.

RIN – Renewable Identification Number

roundwood products – Logs and other round timber generated from harvesting trees for industrial or consumer use.

RPA – Resources Planning Act – The Forest and Rangeland Renewable Resources Planning Act of 1974 requires periodic assessments and reports the status and trends of the nation's renewable resources on all forest and rangelands.

RPS – renewable portfolio standard – A standard or regulation that requires electricity utilities and other retail electricity suppliers to obtain a certain percent of their electricity from certified renewable sources.

RUSLE2 – Revised Universal Soil Loss Equation – A computer program that estimates erosion and sediment delivery for conservation planning in crop production.

RVO – renewable volume obligation

SCM – Supply Characterization Model

SRTS – Subregional Timber Supply

Soil Conditioning Index – An index indicating the impact of crop management activities on soil organic matter.

starch – A carbohydrate consisting of many glucose units. It is the most common carbohydrate in the human diet.

stumpage value – The sale value of the products that can be obtained from a stand of trees. This is the value of the wood products at a processing or end use facility minus transport and harvest costs and a profit for the harvester.

SUNY – State University of New York

sustainability – Aspirational concept denoting the capacity to meet current needs while maintaining options for future generations to meet their needs. To make the concept of sustainability operational, consistent approaches are required that facilitate comparable, science-based assessments using measurable indicators of environmental, economic, and social processes (Hecht et al. 2009; McBride et al. 2011; Dale et al. 2015). Notes: Conceptual sustainability and sustainable development goals are described in the Brundtland Report (1987) and the National Environmental Policy Act (U.S. Government 1969), the latter of which committed "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations." Sustainability does not imply a steady state or an absolute value, but instead is a relative and comparative term that must have a defined context, based on clear objectives (Efroymson et al. 2013).

thinnings (other forestland treatment thinnings) – The practice of reducing the number of plants in an area of the quantity of vegetative or reproductive structures on individual plants. Thinnings can come from operations to reduce fuel load (i.e., removal of small trees to reduce the fire danger) and from composite integrated operations on forestland (activities to harvest merchantable commercial wood and low-quality wood for bioenergy applications simultaneously). Thinnings can also come from pre-commercial operations and from other forestland to improve forest health.

timberland – Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.

TPO – Timber Product Output Database Retrieval System – System that acts as an interface to a standard set of consistently coded TPO data for each state and county in the country; developed in support of the 1997 Resources Planning Act (RPA) Assessment. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, the logging residues left behind, the timber otherwise removed, and the wood and bark residues generated by its primary wood-using mills.

urban wood wastes – Wastes coming from municipal solid waste (MSW) and construction and demolition (C&D) debris. In the MSW portion, there is a wood component in containers, packaging, and discarded durable goods (e.g., furniture) and yard and tree trimmings.

UK – United Kingdom

UHW – upland hardwood

USDA – United States Department of Agriculture

USFPM – U.S. Forest Products Module

WWTP – wastewater treatment plants

WEF – Water Environment Federation

wheat dust – Portion of wheat left after processing, known as dust and chaff.

yield – The volume of feedstock on a designated land unit at a specific point in time.

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