

# Supporting Information for the manuscript:

## WATER EMBODIED IN BIOETHANOL IN THE U.S.

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### SI Text

**Supporting note.** The EWe is a measure of water embedded in each liter of ethanol, from a standpoint of total life-cycle water consumption, whereas total consumptive water is used to represent the total water volume appropriated by ethanol production of a state. Detailed input data and calculation results are listed in Table S1 and S2, respectively. The data and research utilized for our study were provided by the USDA NASS, the USDA census of agriculture, the Minnesota Department of Agriculture, the EW model of Hoekstra (1) , as well as ethanol facility operations outlined by Pfromm (2), Patzek (3), as well as our own survey of the 17 ethanol plants found in the state of Minnesota.

16 **TABLE S1.** Irrigation input data, corn production data, and ethanol production data utilized in this study.

State	$r_{iw}$	$fc_{ia}$	$fc_{gwi}$	$fc_{swi}$	$h\nu_{05}$	$h\nu_{06}$	$h\nu_{07}$	$h\nu_{08}$	$yd_{05}$	$yd_{06}$	$yd_{07}$	$yd_{08}$	$EtOH_{05}$	$EtOH_{06}$	$EtOH_{07}$	$EtOH_{08}$
Alabama	0.21	7%	33%	67%	80	66	112	92	7557	4572	5017	5017	0.0	0.0	0.0	0.0
Arizona	1.37	99%	51%	49%	9	7	9	8	12383	10795	11748	11748	0.0	0.0	0.0	0.2
Arkansas	0.34	57%	82%	18%	92	72	236	180	8319	9271	10668	10668	0.0	0.0	0.0	0.0
California	0.88	112%	38%	62%	52	44	80	86	10922	10478	11430	11430	0.0	0.1	0.3	0.3
Colorado	0.49	88%	19%	81%	380	344	424	468	9398	9906	9017	9017	0.0	0.2	0.3	0.5
Delaware	0.12	26%	56%	44%	62	64	74	61	9081	9208	6160	6160	0.0	0.0	0.0	0.0
Florida	0.37	25%	51%	49%	11	12	14	16	5969	5207	6033	8255	0.0	0.0	0.0	0.0
Georgia	0.12	34%	66%	34%	92	90	180	128	8192	7112	8255	8255	0.0	0.0	0.0	0.0
Idaho	0.58	98%	22%	78%	24	26	42	42	10795	10795	10478	10478	0.0	0.0	0.0	0.2
Illinois	0.18	2%	97%	3%	4780	4460	5220	4600	9081	10351	11113	11113	2.9	2.9	3.5	3.9
Indiana	0.15	3%	55%	45%	2308	2152	2548	2140	9779	9970	9843	9843	0.4	0.4	1.0	2.2
Iowa	0.15	1%	95%	5%	5000	4940	5540	5120	10986	10541	10859	10859	3.7	4.9	6.9	8.0
Kansas	0.37	52%	92%	8%	1380	1200	1480	1560	8573	7303	8890	8890	0.4	0.7	0.8	1.8
Kentucky	0.15	1%	4%	96%	472	416	544	460	8382	9271	8192	8192	0.1	0.1	0.1	0.1
Louisiana	0.34	24%	77%	23%	132	116	292	200	8636	8890	10478	10478	0.0	0.0	0.0	0.0
Maryland	0.12	8%	70%	30%	160	170	182	164	8573	9017	6541	6541	0.0	0.0	0.0	0.0
Michigan	0.15	9%	64%	36%	804	784	940	832	9081	9335	7874	7874	0.2	0.2	0.6	0.8
Minnesota	0.21	3%	84%	16%	2740	2740	3120	2900	11049	10224	9271	9271	1.7	2.0	2.3	2.7
Mississippi	0.24	23%	93%	7%	146	130	376	304	8192	6985	9525	9525	0.0	0.4	0.0	0.0
Missouri	0.21	9%	97%	3%	1188	1052	1300	1000	7049	8763	9017	9017	0.4	0.0	0.6	0.9
Montana	0.40	90%	1%	99%	7	7	15	9	9398	9271	9208	9208	0.0	0.0	0.0	0.0
Nebraska	0.34	61%	84%	16%	3300	3100	3680	3500	9779	9652	10160	10160	2.0	2.1	2.5	4.7
New Jersey	0.24	6%	16%	84%	25	26	33	30	7747	8192	7938	7938	0.0	0.0	0.0	0.0
New Mexico	0.73	98%	43%	57%	22	18	22	24	11113	11748	11113	11113	0.1	0.1	0.1	0.1
New York	0.12	1%	66%	34%	184	192	220	256	7874	8192	8065	8065	0.0	0.0	0.0	0.2
North Carolina	0.15	3%	23%	77%	280	296	408	332	7620	8382	6350	6350	0.0	0.0	0.0	0.0
North Dakota	0.30	5%	50%	50%	480	560	940	860	8192	7049	7366	7366	0.1	0.1	0.5	0.5
Ohio	0.34	0%	44%	56%	1300	1184	1444	1260	9081	10097	9525	9525	0.0	0.0	0.0	1.3
Oklahoma	0.37	52%	79%	21%	100	88	108	128	7303	6668	9208	9208	0.0	0.0	0.0	0.0
Oregon	0.58	96%	13%	87%	10	12	14	12	10160	11430	12383	12383	0.0	0.0	0.0	0.2
Pennsylvania	0.12	0%	10%	90%	384	384	392	380	7747	7747	8128	8128	0.0	0.0	0.0	0.0
South Carolina	0.18	6%	39%	61%	114	116	148	132	7366	6985	6350	6350	0.0	0.0	0.0	0.0
South Dakota	0.76	4%	37%	63%	1580	1288	1800	1680	7557	6160	7684	7684	1.7	1.8	2.2	2.9
Tennessee	0.15	1%	33%	67%	238	200	314	256	8255	7938	6731	6731	0.3	0.3	0.3	0.3
Texas	0.37	37%	75%	25%	740	580	800	900	7239	7684	9398	9398	0.0	0.0	0.0	0.9
Utah	0.64	94%	12%	88%	5	7	9	9	10351	9970	9398	9398	0.0	0.0	0.0	0.0
Virginia	0.12	4%	14%	86%	144	138	162	144	7493	7620	5398	5398	0.0	0.0	0.0	0.0
Washington	0.67	104%	25%	75%	32	30	48	32	13018	13335	13335	13335	0.0	0.0	0.0	0.0
West Virginia	0.34	1%	50%	50%	11	10	11	10	6922	7620	7049	7049	0.0	0.0	0.0	0.0
Wisconsin	0.27	3%	99%	1%	1160	1120	1312	1240	9398	9081	8573	8573	0.6	0.7	1.1	1.9

Wyoming	0.46	98%	9%	91%	20	18	24	22	8890	8192	8192	8192	0.0	0.0	0.0	0.0
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$r_{iw}$  = irrigated water apply depth (meter)

$fc_{ia}$  = fraction of irrigated area in total corn harvested area

$fc_{gwi}$  = fraction of irrigated groundwater in total irrigated water

$fc_{swi}$  = fraction of irrigated surface water in total irrigated water

$EtOH_{05,06,07,08,17}$  = ethanol production in year 2005, 2006, 2007, 2008 and estimated 2017 (million cubic meters per year)

$hv_{05,06,07,08}$  = corn harvested area in year 2005, 2006, 2007 and 2008 (1000 hectares)

$yd_{05,06,07,08}$  = corn yield in year 2005, 2006, 2007 and 2008 (kg/hectare)

## Estimating climatic effects over evapotranspiration

We applied the potential evapotranspiration (ET<sub>0</sub>) equation proposed by Holdridge (4) along with the annual evapotranspiration (ET) equation of Budyko (5, 6) to estimate the change of ET from climate conditions for 1997 and 2002 Farm and Ranch Irrigation Survey. Required input data were derived from the National Climate Data Center (7) for the 19 states producing ethanol. Since irrigation most likely takes place during summer, we compiled the temperature and precipitation data from May to September of 1997 and 2002 for each listed state.

$$E_0 = 58.93 \times \left( \frac{\text{growing days}}{365 \text{ days}} \right) \times \text{average temperature during growing days (} ^\circ\text{C)}$$

$$ET = \left\{ P \left[ 1 - \exp(-E_0 / P) \right] \times E_0 \times \tanh(P / E_0) \right\}^{0.5}$$

where  $E_0$  and ET are in mm, and P is precipitation (mm).

30

31 ET is more sensitive to the change of precipitation than to that of temperature. The national average temperature increased 3.85% from 1997 to  
32 2002, while precipitation increased 3.64%. The change of temperature and precipitation resulted to ET's increase by 0.39% and 3.24%,  
33 respectively. Comparing additional ET and additional precipitation in 2002, we concluded that the changes in climate conditions did not  
34 significantly affect the irrigation volume between the two periods.

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36

**TABLE S2.** Computation results of water embodiment (*EWe*) and total consumptive water (*TCW*) of varied years. *EWe* indicated the sum of unit irrigated water (*EIR*) and process water appropriated by ethanol, in which *EIR* was further divided into groundwater (*EIR<sub>gw</sub>*) and surface water (*EIR<sub>sw</sub>*) based on the origin of extracted sources. *TCW*, on the other hand, represented the total volume of irrigated water (*TEIR*) and process water (*TPW*). Each category was computed from 2005 to 2008, and was projected to 2017. (m<sup>3</sup>w/m<sup>3</sup>e = cubic meters water per cubic meter ethanol; MCM = million cubic meters)

[illegible]

North Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Dakota	53.7	50.1	25.0	25.0	6.4	0.5	6.8	61.8	58.2	29.1	29.1	7.4	0.5	7.8
Ohio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.9	0.4	0.5	0.0	0.0	0.1
Oklahoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oregon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pennsylvania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Dakota	97.7	94.1	34.8	59.3	163.0	6.3	169.3	119.0	115.4	42.7	72.7	207.4	6.5	213.9
Tennessee	9.0	5.4	1.8	3.6	1.4	0.9	2.3	9.2	5.6	1.9	3.8	1.4	0.9	2.3
Texas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Utah	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Washington	1326.3	1322.7	330.7	992.0	3.5	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wisconsin	24.3	20.7	20.5	0.2	13.3	2.3	15.6	25.0	21.4	21.2	0.2	15.2	2.6	17.8
Wyoming	1247.5	1243.9	111.9	1131.9	23.5	0.1	23.6	1353.5	1349.9	121.5	1228.4	25.5	0.1	25.6

(TABLE S2. continued)

State	EWe07	EIR07	EIR <sub>GW</sub> 07	EIR <sub>SW</sub> 07	TEIR07	TPW07	TCW07	EWe08	EIR08	EIR <sub>GW</sub> 08	EIR <sub>SW</sub> 08	TEIR08	TPW08	TCW08
	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	MCM	MCM	MCM	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	MCM	MCM	MCM
Alabama	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	0.0	0.0	0.0	0.0	0.0	0.0	0.0	711.3	707.7	345.0	362.8	147.3	0.8	148.1
Arkansas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
California	2137.6	2134.0	810.9	1323.1	549.2	0.9	550.2	2137.6	2134.0	810.9	1323.1	642.1	1.1	643.2
Colorado	1175.7	1172.1	222.7	949.4	377.1	1.2	378.2	1175.7	1172.1	222.7	949.4	554.5	1.7	556.2
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Georgia	127.9	124.3	82.0	42.3	0.2	0.0	0.2	127.9	124.3	82.0	42.3	0.2	0.0	0.2
Idaho	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1211.2	1207.6	270.7	936.9	246.8	0.7	247.6
Illinois	11.5	7.9	7.6	0.2	27.4	12.6	40.0	11.5	7.9	7.6	0.2	30.8	14.1	44.9
Indiana	16.8	13.1	7.2	5.9	12.5	3.4	16.0	16.8	13.1	7.2	5.9	29.0	7.9	36.9
Iowa	6.1	2.5	2.4	0.1	17.3	24.7	42.0	6.1	2.5	2.4	0.1	20.1	28.8	48.9
Kansas	528.1	524.5	482.5	42.0	421.8	2.9	424.7	528.1	524.5	482.5	42.0	967.8	6.7	974.4

Kentucky	7.1	3.5	0.1	3.4	0.5	0.5	1.0	7.1	3.5	0.1	3.4	0.5	0.5	1.0
Louisiana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	194.6	191.0	147.0	43.9	1.1	0.0	1.1
Maryland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Michigan	46.5	42.9	27.5	15.4	25.2	2.1	27.3	46.5	42.9	27.5	15.4	34.8	2.9	37.7
Minnesota	18.7	15.1	12.7	2.4	34.6	8.3	42.9	18.7	15.1	12.7	2.4	40.6	9.7	50.3
Mississippi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Missouri	56.7	53.1	51.5	1.6	31.2	2.1	33.3	56.7	53.1	51.5	1.6	48.4	3.3	51.7
Montana	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nebraska	501.4	497.8	418.2	79.7	1235.1	9.0	1244.1	501.4	497.8	418.2	79.7	2320.5	16.8	2337.3
New Jersey	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New Mexico	1426.7	1423.0	611.7	811.4	161.6	0.4	162.0	1540.2	1536.6	660.7	875.9	174.5	0.4	174.9
New York	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	3.5	2.3	1.2	0.7	0.7	1.3
North Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Dakota	59.3	55.7	27.9	27.9	28.1	1.8	30.0	59.3	55.7	27.9	27.9	25.9	1.7	27.6
Ohio	4.6	1.0	0.4	0.5	0.0	0.0	0.1	4.6	1.0	0.4	0.5	1.2	4.7	6.0
Oklahoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oregon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	577.5	573.9	112.3	461.6	86.9	0.5	87.4
Pennsylvania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Dakota	96.1	92.5	34.2	58.3	203.8	7.9	211.7	96.1	92.5	34.2	58.3	268.5	10.5	279.0
Tennessee	10.2	6.6	2.2	4.4	1.7	0.9	2.6	10.2	6.6	2.2	4.4	1.7	0.9	2.6
Texas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	355.8	352.2	264.1	88.0	319.9	3.3	323.2
Utah	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Washington	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wisconsin	26.3	22.7	22.5	0.2	24.2	3.9	28.1	26.3	22.7	22.5	0.2	42.8	6.8	49.6
Wyoming	1353.5	1349.9	121.5	1228.4	25.5	0.1	25.6	1353.5	1349.9	121.5	1228.4	33.2	0.1	33.3

(TABLE S2. continued)

State	EWe17	EIR17	EIR_GW17	EIR_SW17	TEIR17	TPW17	TCW17
	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	m <sup>3</sup> w/m <sup>3</sup> e	MCM	MCM	MCM
Alabama	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	711.3	707.7	345.0	362.8	147.3	0.8	148.1

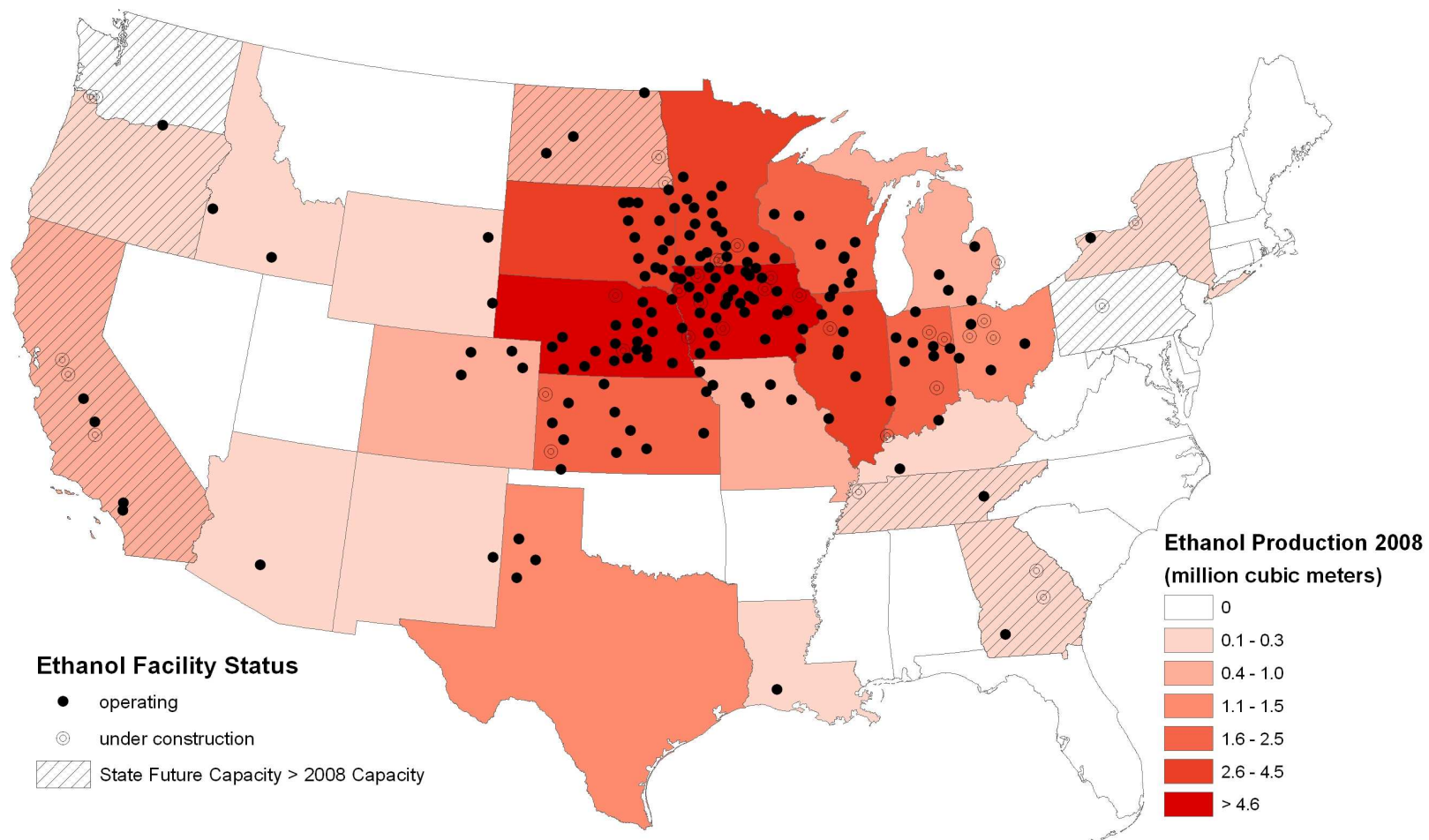
Arkansas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
California	1093.9	1090.3	419.1	671.2	967.7	3.2	970.9
Colorado	1175.7	1172.1	222.7	949.4	554.5	1.7	556.2
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Georgia	132.3	128.7	82.5	46.2	58.7	1.6	60.3
Idaho	1211.2	1207.6	270.7	936.9	246.8	0.7	247.6
Illinois	11.5	7.9	7.6	0.2	33.8	15.5	49.3
Indiana	16.8	13.1	7.2	5.9	53.4	14.7	68.1
Iowa	6.1	2.5	2.4	0.1	33.7	48.3	82.0
Kansas	528.1	524.5	482.5	42.0	1086.9	7.5	1094.3
Kentucky	7.1	3.5	0.1	3.4	0.5	0.5	1.0
Louisiana	194.6	191.0	147.0	43.9	1.1	0.0	1.1
Maryland	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Michigan	46.5	42.9	27.5	15.4	42.9	3.6	46.5
Minnesota	18.7	15.1	12.7	2.4	62.8	15.1	77.9
Mississippi	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Missouri	56.7	53.1	51.5	1.6	48.4	3.3	51.7
Montana	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nebraska	501.4	497.8	418.2	79.7	3138.2	22.8	3161.0
New Jersey	0.0	0.0	0.0	0.0	0.0	0.0	0.0
New Mexico	1540.2	1536.6	660.7	875.9	174.5	0.4	174.9
New York	7.1	3.5	2.3	1.2	2.1	2.2	4.4
North Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Dakota	59.3	55.7	27.9	27.9	70.2	4.5	74.8
Ohio	4.6	1.0	0.4	0.5	1.9	7.2	9.1
Oklahoma	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oregon	317.9	314.3	97.2	217.1	176.0	2.0	178.1
Pennsylvania	5.0	1.4	0.1	1.3	0.6	1.5	2.1
South Carolina	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Dakota	96.1	92.5	34.2	58.3	312.3	12.2	324.5
Tennessee	28.7	25.1	10.0	15.1	19.4	2.8	22.2
Texas	355.8	352.2	264.1	88.0	473.2	4.8	478.1
Utah	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Washington	1125.9	1122.3	286.4	835.9	233.6	0.8	234.4
West Virginia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wisconsin	26.3	22.7	22.5	0.2	42.8	6.8	49.6
Wyoming	1353.5	1349.9	121.5	1228.4	33.2	0.1	33.3

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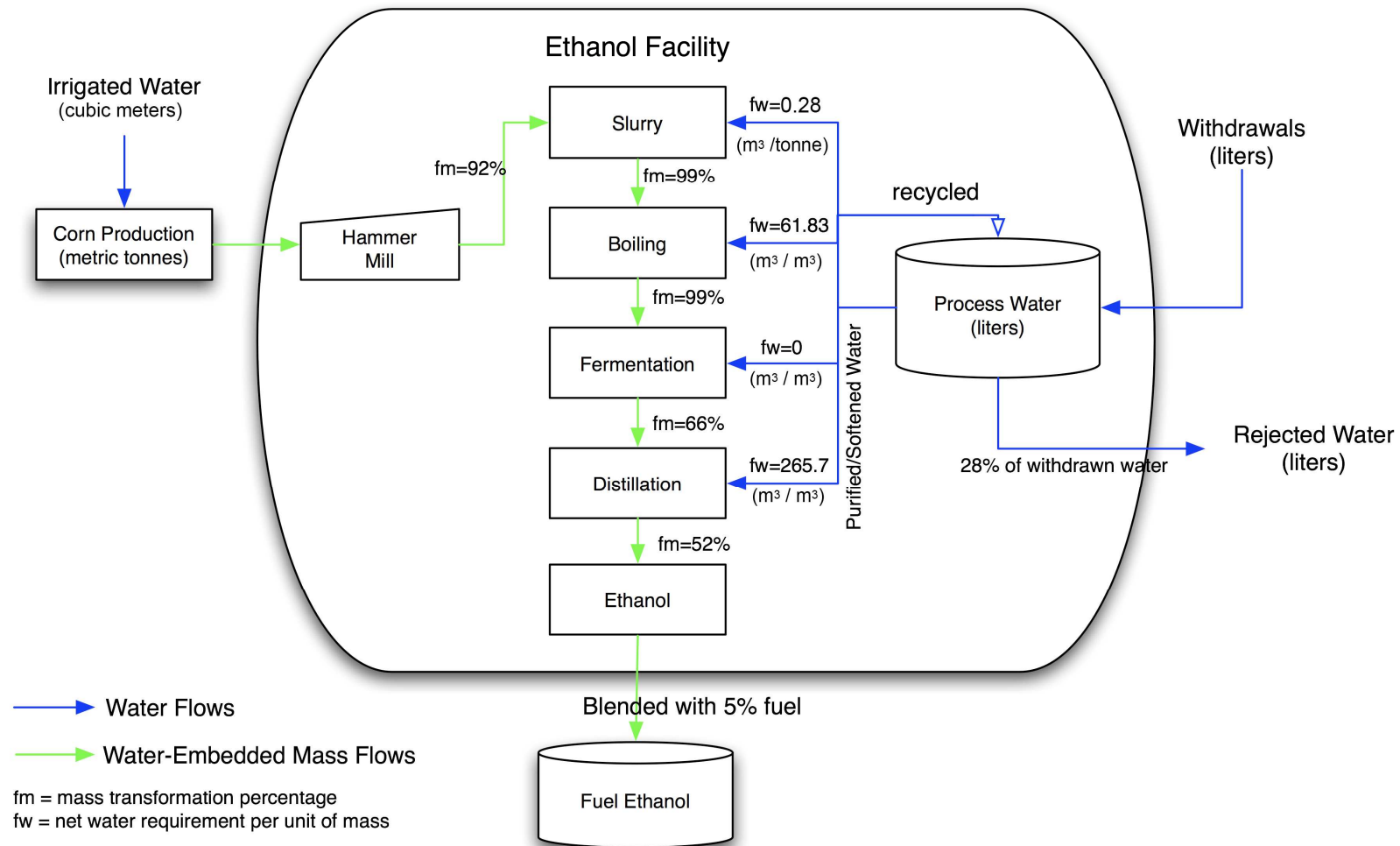
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**FIGURE S1.** Ethanol facilities location of each state and the operational status of each as of June, 2008. Data was compiled based on the reports of both Nebraska Energy Statistics ([http://www.neo.ne.gov/statshtml/122\\_archive.htm](http://www.neo.ne.gov/statshtml/122_archive.htm)) and Renewable Fuels Association (RFA, <http://www.ethanolrfa.org/>)



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 54 **FIGURE S2.** The study boundary, corn mass transfer with water flows, and the various coefficients used in this study. Overall mass balance is set  
 55 to 0.01 m<sup>3</sup> of ethanol generated from one bushel (or 25.4 kg) of corn. The water usage of each phase accounts only the net balance of input  
 56 (intake) and output (recycled, treated, or evaporated). The overall system balance is adjusted to be 3.6 m<sup>3</sup>w/m<sup>3</sup>e.

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