Final Report to United Sorghum Checkoff Program

Energy Use and Associated Carbon Dioxide Emissions in US Sorghum Production

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Abstract

The Energy Independence and Security Act of 2007/Renewable Fuel Standard-2 (RFS-2) mandates production of 36 billion gallons of renewable fuel of which ethanol from grain sorghum can potentially qualify. All candidate feedstocks must meet certain greenhouse gas reductions versus their petroleum counterparts based on a 2005 baseline. For grain sorghum to quality as an RFS-2 feedstock it must demonstrate it can reduce all carbon dioxide equivalent emissions by at least 50% versus the 2005 petroleum baseline for gasoline.

An energy analysis, both direct and embodied with their associated carbon dioxide emissions, was performed for a continuous grain sorghum and a grain sorghum-wheat-fallow rotation both common to southwest Kansas as a function of inputs related to potential yield (bushels/acre) yield levels. Direct energy expenditures defined as energy consumed “in-field” (diesel fuel consumption) for planting, field maintenance including chemical and fertilizer application, and harvesting were approximately one-third to one-quarter less than energy required to manufacture fertilizers and herbicides (embodied/indirect). On a per gallon basis, both direct and embodied energy expenditures amounted to about 10% of the lower heating value of ethanol.

Introduction/Background

The Energy Independence and Security Act of 2007/Renewable Fuel Standard-2 (RFS-2) mandates production of 36 billion gallons of renewable fuel (e.g., ethanol, biomass-based diesel) by 2022 from a variety of biomass-based resources which represents an approximate three-fold increase over current (2010) renewable fuel volumes[1]. Figure 1 presents the RFS-2 in its original form.

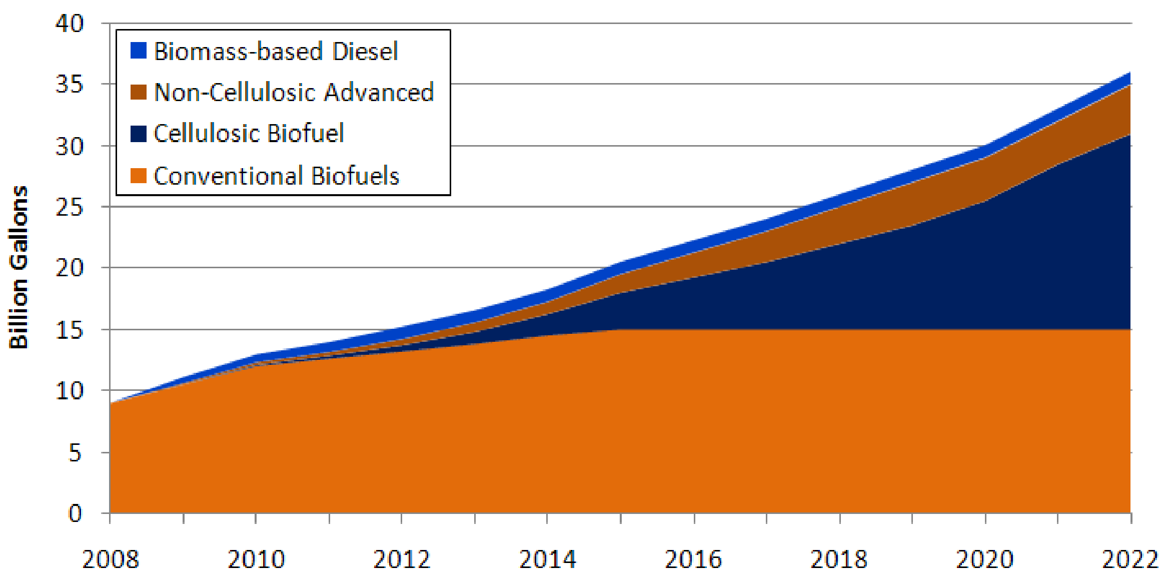

Figure 1. The Renewable Fuel Standard-2.

The RFS-2 also divided biofuels blended in the United States into the four categories shown in figure 1. All categories other than 'conventional biofuel' are termed 'advanced' biofuels. Each separate category has mandated life-cycle greenhouse gas emission reductions it must meet relative to its petroleum-based fuel produced in 2005 (e.g., ethanol to gasoline; biomass-based diesel to diesel). For a conventional biofuel, the greenhouse gas emissions must be 20% less than the life-cycle greenhouse gas emissions of gasoline, biomass-based diesel and cellulosic biofuels must be at least 50% less to qualify, and non-cellulosic advanced biofuel, the reduction must be at 60% less.

Grain sorghum for alternate liquid fuel production (ethanol) would qualify under the RFS-2 as an advanced biofuel, but its total fuel-cycle (e.g., bioenergy crop production to liquid fuel) carbon dioxide (CO_2) emissions must be at least 50% less than its equivalent petroleum counterpart. In addition, the California Air Resources Board (CARB) has its own emission regulations that need to be

[1] http://www.epa.gov/otaq/fuels/renewablefuels/index.htm

met to sell ethanol in the state. Therefore, a critical component of estimating carbon dioxide (CO_2) emissions of candidate feedstocks for biofuel production is ”in-field” energy consumption (diesel fuel or gasoline) and energy consumed “off-site” which is associated with the manufacture of fertilizers and chemicals and their resulting CO_2 emissions associated with the combustion of these fuels. The focus of this proposed project was to provide scientifically-acceptable values of all energy consumption/inputs and their associated CO_2 emissions attributable to on-farm grain sorghum production in southwest Kansas.

Project Objectives

The major project objective is to provide to the United Sorghum Checkoff Program (USCP) scientifically-based and peer-accepted estimates of quantities (gallons, MMBTU) of both direct and embodied/indirect energies and CO_2 emissions (tons per acre, tons per rotation) associated with their use from typical dryland (non-irrigated) grain sorghum-based cropping rotations in southwest Kansas. Specific objectives are to:

1. Provide estimates of the quantity of diesel fuel and gasoline consumed on-farm/on-site and CO_2 emissions resulting from their combustion for all agricultural operations in each candidate grain sorghum-based rotation in these three geographic areas.

2. Provide estimates of amounts of distillate fuel(s), natural gas, propane, and/or electricity used in the consumption of fertilizers and chemicals and their associated CO_2 emissions for each candidate cropping rotation.

Grain Sorghum Production in Southwest Kansas

Kansas is the number one grain sorghum producing state in the nation producing just under 50% of the total crop (bushels) and has over 43% of the total acres[2]. The southwest area of the state (USDA Crop Reporting District 30) has the highest number of planted and harvested grain sorghum acres.

Production scenarios (planting, field management including tillage, and harvesting) for grain sorghum production were obtained from Kansas State University and involved a continuous rotation

[2] http://www.nass.usda.gov/QuickStats/Create_County_All.jsp

and with wheat-fallow[3]. Both rotations are non-irrigated. Field operations for both rotations are presented in table 1. Table 2 presents amounts of fertilizer and herbicides used respectively for both rotations as a function of possible yields.

Table 1. Field operations for continuous grain sorghum and a grain sorghum-wheat-fallow rotation.

Continuous Grain Sorghum	Grain Sorghum-Wheat-Fallow
Surface plant	No-till plant
Fertilizer application	Fertilizer application
Herbicide application	Herbicide application
Harvest	Harvest

Table 2. Fertilizer and herbicide inputs to continuous grain sorghum and wheat-grain sorghum-fallow rotation in SW Kansas.

	Continuous Grain Sorghum	Wheat-Grain Sorghum-Fallow		
	45 bu/ac	60 bu/ac	80 bu/ac	100 bu/ac
Fertilizers (lbs/ac)				
N (11-52-0)	56	45	70	95
P		27	37	46
K	0	0	0	0
Lime	0	0	0	0
Herbicides (lb ai/ac)				
Atrazine 4L + crop oil	1.124			
Roundup Weather Max	0.869			
Dual II Magnum	1.140			
Atrazine 4L + crop oil		1.791	0	0
RT3		1.739	1.739	1.739
2,4-D		0	2.250	2.250

Energy and Carbon Dioxide Emissions Analyses

All cropping scenarios/systems such as corn, grain sorghum, wheat, and soybeans as well as cotton, rice, and hay all require energy primarily in the form diesel fuel for planting, fertilizer and

[3] http://www.ksre.ksu.edu/library/agec2/mf904.pdf

chemical application, tillage, and harvesting. Carbon dioxide (CO_2) emissions are directly related to the amount of fossil-based energy used in these operations.

Direct and Embodied (Indirect) Energy Use in Cropping Production Systems

Energy expenditures for agricultural and bioenergy crop production can be divided into those used on-site (e.g., within the field) and those used off-site for the manufacture of materials needed for production. On-site energies are typically referred to as direct energies and off-site are embodied or indirect energies. On-site energy use and emissions result from fossil-fuel combustion (i.e., primarily diesel fuel) occurring in the field directly related to crop production. Off-site energy are those energy expenditures from fuel oils, natural gas, electricity, etc. required to produce, manufacture, process, and/or distribute the raw materials, fuels, and/or chemicals needed to produce grain sorghum. This includes nitrogen, phosphorous, potash, and lime, and herbicides/insecticides such as Atrazine, Bicep, etc.

Direct Energy Consumption and Associated CO_2 Emissions for Grain Sorghum Production

Direct energy consumption for each rotation determined the amount (gallons) of diesel fuel combusted to perform each field operation on a per acre basis. Values for "in-field" consumption can and will vary due to crop yield, soil condition (e.g., clay versus loamy versus sandy soils), and field size. Values for typical consumption rates were solicited from a variety of sources in the literature and are considered to be the best representation of average energy consumption in these operations for grain sorghum in either rotation. Table 3 presents average diesel fuel consumption (gallons per acre) and its associated carbon dioxide (CO_2) emissions per acre for each operation for each reference[4,5,6,7]. CO_2 emissions from diesel fuel combustion are calculated as approximately 22 pounds per gallon of diesel fuel combusted.

Direct energy consumption (Btu/acre) was calculated as the product of the lower heating value of diesel fuel (128,450 Btu/gallon) and the average gallons used for each field operation as defined in table 1. For both rotations and at each yield level, table 4 contains all direct energies of each field operation.

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[4] http://www.extension.iastate.edu/Publications/PM709.pdf
[5] http://pubs.ext.vt.edu/442/442-073/442-073.html
[6] http://extension.missouri.edu/p/G1208
[7] http://ecat.sc.egov.usda.gov/

Table 3. Average "in-field" fuel consumption (gallons/acre) and resulting CO_2 emissions.

	Typical diesel fuel consumption and associated CO2 emissions by source									
	Hanna		Grisso		Frisby		NRCS		Average	
	diesel (gal/ac)	CO2 (lbs/ac)	diesel (gal/ac)	CO2 (lbs/ac)	diesel (gal/ac)	CO2 (lbs/ac)	diesel (gal/ac)	CO2 (lbs/ac)	diesel (gal/ac)	CO2 (lbs/ac)
Surface Plant	0.15	3.29	0.15	3.29	data n/a		0.13	2.85	0.14	3.14
No-till Plant	0.45	9.87	0.43	9.43	0.35	7.67	0.50	10.96	0.43	9.48
Fertilizer Application	0.15	3.29	0.19	4.17	data n/a		0.16	3.51	0.17	3.65
Herbicide Application	0.1	2.19	0.13	2.85	0.10	2.19	0.13	2.85	0.12	2.52
Harvest	1.45	31.79	1.49	32.67	1.60	35.08	1.60	35.08	1.54	33.65

Table 4. Direct energy consumption (Btu per acre) and associated CO_2 emissions.

	Continous Grain Sorghum - High Yield		Grain Sorghum-Wheat-Fallow Low Yield		Grain Sorghum-Wheat-Fallow Medium Yield		Grain Sorghum-Wheat-Fallow High Yield	
	Btu/acre	lbs CO2/acre	Btu/acre	lbs CO2/acre	Btu/acre	lbs CO2/acre	Btu/acre	lbs CO2/acre
Surface plant	18,411	3.14	0	0.00	0	0.00	0	0.00
No-till plant	0	0.00	55,555	9.48	55,555	9.48	55,555	9.48
Fertilizer application	21,408	3.65	21,408	3.65	21,408	3.65	21,408	3.65
Herbicide application	29,544	5.04	44,315	7.56	44,315	7.56	44,315	7.56
Harvest	197,171	33.65	197,171	33.65	197,171	33.65	197,171	33.65
	266,533.8	**45.5**	**318,449**	**54.4**	**318,449**	**54.4**	**318,449**	**54.4**

Embodied Energy Consumption and Associated CO_2 Emissions for Chemicals and Fertilizers used in Grain Sorghum Production

Energy consumed in the manufacture of nitrogen (N), potassium (P), phosphate (K), and herbicides was obtained from the GREET 1.8b worksheet[8]. The 'system' boundary for estimating energy consumption in the manufacture of each fertilizer type and herbicide and insecticide begins with the manufacture of each component including the 'feedstock' energy (e.g., the energy contained in the natural gas for nitrogen production) and concludes with distribution to an end retail market. Table 5 shows the equivalent quantities of coal, natural gas, and petroleum utilized (embodied energy, MMBtu per pound of finished product) and their corresponding CO_2 emissions for production/manufacture and distribution of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, and average national herbicides.

Table 5. Energy Inputs of Coal, Petroleum, and Natural Gas to Embodied Energy Values (Btu per pound of product).

	Coal Energy, mmBtu	Natural Gas Energy, mmBtu	Petroleum Energy, mmBtu	Total mmBtu per ton of product	Total Btu/pound of product	pounds CO2 equivalent per pound of product
N	3.091	44.751	1.924	49.77	24,883	3.63
P	3.043	6.743	4.136	13.92	6,961	1.24
K	3.283	2.579	2.577	8.44	4,220	0.82
Herbicide	61.20	78.69	137.40	277.30	138,649	25.85

[8] http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2005-0161-3174.10.

Nitrogen fertilizer for grain sorghum production in southwest Kansas is typically 11-52-0 (11% N; 52% P; 0% K). Phosphorus is P_2KO_5 and potassium and lime are not used. For each herbicide, the pounds of active ingredient applied were multiplied by the embodied energy value for herbicides. The following three equations demonstrate how the embodied energy values in terms of Btu per acre for nitrogen, phosphorus, and herbicides were calculated.

Nitrogen:	pounds of N (11-52-0) applied * (0.11* EEN +0.52*EEP)	(1)
	where: EEN = 24,883 Btu per pound (from table 4)	
	EEP = 6,961 Btu per pound (from table 4)	
Phosphorus:	pounds of P applied * EEP	(2)
Herbicides:	pounds of active ingredient applied per acre * EEH	(3)
	where: EEH = 138,649 Btu per pound active ingredient (from table 4)	

For the grain sorghum-wheat-fallow rotation at a yield level of 80 bushels per acre, the following outlines the total embodied energy.

Nitrogen:	70 pound per acre N (11-52-0) * (0.11 * 24,883 Btu per pound of N +		
	0.52 * 6,961 Btu per pound of P)	=	444,980
Phosphorus:	37 pounds per acre P * 6,961 Btu per pound P	=	257,557
Herbicides:	(1.739 + 2.250) pounds active ingredient		
	* 138,649 Btu per pound	=	553,027
Total Embodied Energy (Btu per acre)			1,255,564

The embodied energy values for the other three rotations were calculated in the same manner and all embodied energy calculations are presented in Appendix A.

Results

Table 6 presents both direct and embodied energies for all four rotations on a per acre and per bushel basis. The energy required in the continuous grain sorghum rotation is significantly lower for continuous grain sorghum versus the wheat-grain sorghum-fallow rotation and in all cases the embodied energy allocation is three to four times higher than direct energy expenditures.

Table 6. Direct and Embodied Energy Expenditures for Continuous Grain Sorghum and Grain Sorghum in a Wheat-Fallow Rotation Btu per acre and Btu/bushel.

	Energy per Acre					
	Direct Energy		Embodied Energy		Total Direct & Embodied Energy	
	Btu/acre	lbs CO2e/acre	Btu/acre	lbs CO2e/acre	Btu/acre	lbs CO2e/acre
Continuous Grain Sorghum Western Kansas High Yield	266,534	45	936,600	310	1,203,133	356
Grain Sorghum Western Kansas Wheat-Sorghum Low Yield	318,449	54	963,445	288	1,281,894	342
Grain Sorghum Western Kansas Wheat-Sorghum Medium Yield	318,449	54	1,255,564	403	1,574,013	457
Grain Sorghum Western Kansas Wheat-Sorghum High Yield	318,449	54	1,477,134	505	1,795,583	559

		Energy per Bushel					
		Direct Energy		Embodied Energy		Total Direct & Embodied Energy	
	Yield, bu/ac	Btu/bushel	lbs CO2e/bushel	Btu/bushel	lbs CO2e/bushel	Btu/bushel	lbs CO2e/bushel
Continuous Grain Sorghum Western Kansas High Yield	45	5,923	1.0	20,813	6.9	26,736	7.9
Grain Sorghum Western Kansas Wheat-Sorghum Low Yield	60	5,307	0.9	16,057	4.8	21,365	5.7
Grain Sorghum Western Kansas Wheat-Sorghum Medium Yield	80	3,981	0.7	15,695	5.0	19,675	5.7
Grain Sorghum Western Kansas Wheat-Sorghum High Yield	100	3,184	0.5	14,771	5.0	17,956	5.6

Conclusions

The amount of fossil-based energy consumed (both direct and embodied) in the production (planting, field maintenance, and harvesting) of grain sorghum in two separate cropping rotations in southwest Kansas was calculated. In addition, the quantities of carbon dioxide released through combustion were also determined from each operation or application of fertilizers and herbicides. Energy and the resulting CO_2 emissions consumed "off-site" in the manufacture of nitrogen and phosphorus fertilizers and herbicides was far greater than energy expenditures attributable to diesel fuel consumed and its CO_2 releases for "in-field" operations. Based on an average ethanol yield of nearly 200 gallons per acre across southwest Kansas using yields from 2008, 2009, and 2010 crop years, on a per gallon of ethanol basis (lower heating value), the total (direct and embodied) energy expenditures amount to an average of about 10%.

Appendix A

Embodied Energy Values

Continuous Grain Sorghum – High Yield

Grain Sorghum-Wheat-Fallow – Low Yield
Grain Sorghum-Wheat-Fallow – Medium Yield
Grain Sorghum-Wheat-Fallow – High Yield

Grain Sorghum Western Kansas High Yield

Chemical Input	Application Rate	units	Embodied Energy per pound of product (GREET)	units	Rotation Energy Inputs	units	CO2e	units	Application Rate	units	Application Rate	units	Btu/acre	CO2e	units
AA	0	lb/acre	20,404	Btu/lb	0	Btu/acre	3.6	lb/lb					0	0.0	lbs/acre
N	56	lb/acre	24,883	Btu/lb	355,984	Btu/acre	3.6	lb/lb					355,984	203.2	lbs/acre
P	21	lb/acre	6,961	Btu/lb	146,181	Btu/acre	1.2	lb/lb					146,181	26.0	lbs/acre
K	0	lb/acre	4,220	Btu/lb	0	Btu/acre	0.8	lb/lb					0	0.0	lbs/acre
Herbicide															
Atrazine 4L + crop oil			138,649	Btu/lb			25.8	lb/lb	0.28	gal/acre	1.12	lb ai/acre	155,841	29.1	lb/acre
Roundup Weather Max			138,649	Btu/lb			25.8	lb/lb	0.19	gal/acre	0.87	lb ai/acre	120,534	22.5	lb/acre
Dual II Magnum			138,649	Btu/lb			25.8	lb/lb	0.15	gal/acre	1.14	lb ai/acre	158,060	29.5	lb/acre
												Total	**936,600**	**310.2**	**lb/acre**

Grain Sorghum-Wheat-Fallow Low Yield

Chemical Input	Application Rate	units	Embodied Energy per pound of product (GREET)	units	Rotation Energy Inputs	units	CO_2e	units	Application Rate	units	Application Rate	units	Btu/acre	CO2e	units
AA	0	lb/acre	20,404	Btu/lb	0	Btu/acre	3.6	lb/lb					0	0	lbs/acre
N	45	lb/acre	24,883	Btu/lb	286,058	Btu/acre	3.6	lb/lb					286,058	163.3	lbs/acre
P	27	lb/acre	6,961	Btu/lb	187,947	Btu/acre	1.2	lb/lb					187,947	33.4	lbs/acre
K	0	lb/acre	4,220	Btu/lb	0	Btu/acre	0.8	lb/lb					0	0	lbs/acre
Herbicide															
Atrazine 4L			138,649	Btu/lb			25.8	lb/lb	0.447844	gal/acre	1.791	lb ai/acre	248,372	46.3	lb/acre
RT3			138,649	Btu/lb			25.8	lb/lb	0.386375	gal/acre	1.739	lb ai/acre	241,067	44.9	lb/acre
2,4-D			138,649	Btu/lb			25.8	lb/lb	0.25	gal/acre	0	lb ai/acre	0	0.0	lb/acre
												Total	**963,445**	**287.9**	**lb/acre**

Grain Sorghum-Wheat-Fallow Medium Yield														
Chemical Input	**Application Rate**	**units**	**Embodied Energy per pound of product (GREET)**	**units**	**Rotation Energy Inputs**	**units**	**CO_2e**	**units**	Application Rate	units	Application Rate	units	Btu/acre	CO_2e	units
AA	0	lb/acre	20,404	Btu/lb	0	Btu/acre	3.6	lb/lb					0	0.0	lbs/acre
N	70	lb/acre	24,883	Btu/lb	444,980	Btu/acre	3.6	lb/lb					444,980	254.0	lbs/acre
P	37	lb/acre	6,961	Btu/lb	257,557	Btu/acre	1.2	lb/lb					257,557	45.8	lbs/acre
K	0	lb/acre	4,220	Btu/lb	0	Btu/acre	0.8	lb/lb					0	0.0	lbs/acre
Herbicide															
RT3			138,649	Btu/lb			25.8	lb/lb	0.39	gal/acre	1.739	lb ai/acre	241,067	44.9	lb/acre
Bicep Lite II Magnum			138,649	Btu/lb			25.8	lb/lb	0.38	gal/acre	2.25	lb ai/acre	311,960	58.2	lb/acre
												Total	**1,255,564**	**403**	**lb/acre**

Grain Sorghum-Wheat-Fallow High Yield															
Chemical Input	**Application Rate**	**units**	**Embodied Energy per pound of product (GREET)**	**units**	**Rotation Energy Inputs**	**units**	**CO_2e**	**units**	Application Rate	units	Application Rate	units	Btu/acre	CO_2e	units
AA	0	lb/acre	20,404	Btu/lb	0	Btu/acre	3.6	lb/lb					0	0	lbs/acre
N	95	lb/acre	24,883	Btu/lb	603,901	Btu/acre	3.6	lb/lb					603,901	344.7	lbs/acre
P	46	lb/acre	6,961	Btu/lb	320,206	Btu/acre	1.2	lb/lb					320,206	57.0	lbs/acre
K	0	lb/acre	4,220	Btu/lb	0	Btu/acre	0.8	lb/lb					0	0	lbs/acre
Herbicide															
RT3			138,649	Btu/lb			25.8	lb/lb	0.386375	gal/acre	1.7386875	lb ai/acre	241,067	44.9	lb/acre
Bicep Lite II Magnum			138,649	Btu/lb			25.8	lb/lb	0.375	gal/acre	2.25	lb ai/acre	311,960	58.2	lb/acre
												Total	**1,477,134**	**504.7**	**lb/acre**