The Texas Journal of Agriculture and Natural Resources 26:1-13 (2013)

Suitability of Biodiesel from Winter Safflower on the Southern High Plains

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ABSTRACT

Winter safflower is considered a potential feedstock for biodiesel production that can be grown on the Texas High Plains. It requires fewer inputs than current irrigated crops, and could be grown on semi-arid or marginal land. The potential of winter safflower for biofuel production is analyzed using a life-cycle assessment of the energy inputs and greenhouse gas (GHG) emission impacts during the seed and biodiesel production processes. In addition, this study identifies the factors that have the greatest impact on GHG emissions and the likelihood that winter safflower would be adopted by farmers on the High Plains. Finally, a safflower production model that includes GHG emissions was developed, and this model was used to determine how potential GHG emissions policies might change resource use by farmers. It was found that expected carbon prices are not likely to affect demand for irrigation by safflower farmers.

KEY WORDS: winter safflower, life-cycle greenhouse gas emission, biofuel

INTRODUCTION

The increasing emission of greenhouse gases (GHG), like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) has raised great concerns about potential global warming effects, which has led to recognition of the need to reduce anthropogenic GHG emissions worldwide. Transportation through the combustion of fossil fuels is a major source of GHG emissions, accounting for about 26% of total U.S. greenhouse gas emissions in 2010 (EPA 2010). Biofuel derived from biomass is often advocated as a significant contributor to possible solutions to the need for a sustainable transportation fuel. Such a substitution immediately addresses the issue of reducing the use of non-renewable resources like fossil fuels and the impact on climate change, especially carbon dioxide and the resulting greenhouse effect. However, biofuels must be derived from feedstocks produced with much lower life-cycle GHG emissions than traditional fossil fuels and with little or no competition with food production if biofuel use is to realize local environmental and societal benefits (Tilman et al. 2009).

Winter safflower is a potential feedstock for biodiesel production that could be grown on the Texas High Plains. It requires fewer inputs in terms of irrigation and fertilizer than current irrigated crops, and could be grown on marginal or semi-arid land. Use and development of winter safflower biodiesel is believed to reduce GHG emissions.

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In addition, it could also benefit agricultural economies by providing an important new source of income for farmers while lowering dependence on fossil fuel supplies. However, the production of winter safflower requires fossil fuel inputs and emits greenhouse gases. Thus, it is crucial to measure the greenhouse gas emissions over the entire life-cycle of biodiesel production to assess the overall environmental benefits. Generally, the less a biofuel depends on fossil energy, the more potential it has for diversifying the total fuel supply. On the other hand, the degree to which a biofuel relies on fossil energy for its production is one of many criteria that may be used by policymakers and others to evaluate and compare various biofuels.

This report presents a life-cycle assessment (LCA) of the energy inputs and GHG emission impacts of safflower biodiesel relative to those of petroleum diesel and gasoline. The LCA of safflower biodiesel is a cradle-to-grave analysis of the energy and environmental impacts of making a product, which provides a tool to quantify the total required energy from different sources and the overall energy efficiency of safflower biodiesel production processes. This analysis estimates the consumption of total energy, fossil energy, petroleum oil and emissions of GHGs. The LCA of safflower biodiesel in this analysis accounts for emissions in four stages of production:

(1) feedstock cultivation, including energy inputs to produce fertilizer and other chemicals, safflower farming and harvest;
(2) feedstock transportation from farms to processing plants;
(3) oil extraction and biodiesel conversion; and
(4) biodiesel distribution from plants to refueling stations.

The report assumes a hexane extraction method to extract oil from safflower seeds, and transesterification is used to convert oil into biodiesel. Oil extraction and transesterification result in the production of two important coproducts, meal and crude glycerin, respectively, and a mass-based allocation method is used to account for the energy associated with co-products. This method is commonly used because it is easy to apply and provides reasonable results (Vigon et al. 1993). Next, the influence of individual parameters on the overall study results is determined through several sensitivity analyses. The four selected parameters are yield, fertilizer usage, irrigation levels, and transportation distances. Each set of parameters is tested individually, while the others are held at their base case values. In response to governmental policies which aim to reduce GHG emissions, profit-maximizing famers will shift toward biofuel crops cultivation when profits from biofuel crops exceed profits from production of food crops. For example, in response to instruments that make energy sources with low GHG emissions increasingly profitable, such as biofuels, farmers will profit from this increase in relative price of biofuel crops. The final step in this analysis is to analyze farmers' production decisions corresponding to different carbon policies. In order to do that, a production function of safflower and GHG emissions are developed, as well as a related profit function to evaluate possible incentives to change behaviors.

METHODS AND PROCEDURES

This section describes the methods and data used to construct the four stages of the biodiesel life-cycle: feedstock cultivation, feedstock transportation, oil extraction with biodiesel conversion, and product distribution.

Feedstock Cultivation. According to Lai (2004), production, formulation, storage, distribution of carbon-based inputs, and application with tractorized equipment lead to combustion of fossil fuel and use of energy from alternate sources, which also emits CO_2 and other GHGs into the atmosphere. Table 1 below lists the energy required (on a per-acre basis) for safflower seed production. The energy used for planting the seed and other farm activities, such as land preparation, fertilizer and pesticide application, irrigating, and harvesting is included in total farm fuels and electricity estimates. The fuel required for hauling the safflower after harvest is also included in the fuel estimates. The farm input data for safflower production were obtained through crop trials conducted at Texas Tech University (Oswalt, 2008), which were the most recent data available at the time of this study. In addition, all energy inputs were converted to British thermal units (Btu) using low-energy heating values.

Table 1. Annual energy requirements for agricultural inputs before allocating coproduct credits.

Inputs	Usage	Energy Required (Btu/gal)
Urea	50.00 (Lbs/acre)	878.12
Diesel	3.84 (Gal/acre)	7,250.15
Electricity	130.84 (kWh/acre)	6,508.75
Herbicides	1.50 (Lbs/acre)	2,504.81
Total		17,141.83

Crop systems emit N_2O directly, produced through nitrification and denitrification in the cropped soil, and also indirectly, when N is lost from the cropped soil as some form other than N_2O (that is, NO_x, NH_3, or NO_3) and later converted to N_2O off the farm (Adler et al.,2007). Thus, estimation of direct and indirect N_2O emissions from safflower farming requires two important parameters: the amount of nitrogen from fertilizer application and the amount of nitrogen in the aboveground biomass left in the field after harvest and in the belowground biomass (i.e., roots).

According to IPCC (2006) estimates, aboveground biomass for safflower is 91% of the yield (on a dry-matter basis). Aboveground biomass has a nitrogen content of 0.8%. Belowground biomass is about 19% of aboveground biomass, with a nitrogen content of 0.8%. The total amount of nitrogen in safflower biomass that is left in fields per acre of safflower harvested is calculated as shown in the following equation[1]:

$$2000 \text{ lbs/acre} * 85\% \text{ (dry matter content of safflower)} * (91\% * 0.8\% + 19\% * 0.8\%) = 14.96 \text{ lb N/acre}. \quad (1)$$

IPCC (2006) sets the default value at 1% of N applied to soils for direct N_2O emissions from soil. On the other hand, to estimate indirect N_2O emissions, two additional emission factors are required: one associated with volatilized and re-deposited N, and the second associated with N lost through leaching or runoff. According to the IPCC (2006) estimate, the fractions of N that are lost through volatilization is 10%, with a range of 3-30%. The emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces is 1%, with a range of 0.2-5%. The fraction of N losses by leaching and runoff is estimated to be 30%, with a range of 10-80%. The other emission factor of leached and runoff nitrogen to N in N_2O emissions is 0.75%, with a range of

0.05–2.5%. Thus, the total direct and indirect N_2O emissions (in carbon equivalent) from managed soils are calculated as follow[2]:

*14.96 lb N/acre * (1% + 10% * 1% +30% * 0.75%) * 44/28 = 0.31 lbs/acre.* (2)

Adding urea to soils during fertilization leads to a loss of CO_2 that was fixed in the industrial production process, and it is estimated by[3]:

*50 lbs/acre * 0.20 * 44/12 =36.67 lbs/acre* (3)

where 0.20 represents an overall emission factor for urea (IPCC, 2006).

Feedstock Transportation. To estimate energy requirements and GHG emissions from the transport of safflower seeds from the fields on the Southern High Plains of Texas to biodiesel conversion facilities, we assume the average energy used for transporting is 1.13 MJ per kg of safflower seeds (Sheehan et al. 1998). The estimation was based on the total distance of 320 miles, which includes the distance for trucking safflower seeds from the field to the nearest biodiesel conversion facilities located in Dallas, TX, and the distance to get the biodiesel to its final destination.

Biodiesel Production. The production of biodiesel from safflower seeds occurs in two stages: seeds are first treated to remove the oil, and then the oil is converted into biodiesel. The first stage, the removal of the oil from the safflower seeds, is often called crushing, and the most common method used to convert the oil into biodiesel is a process known as transesterification.

Oil Extraction. Safflower seeds contain 28% oil by weight. Two main methods used for extraction of the safflower seed oil are identified as mechanical extraction and solvent extraction, and the latter is more commonly used. The standard solvent extraction process uses n-hexane that is produced from petroleum. Most of the n-hexane used in oil extraction is recovered and recycled, with some inevitable loss (Huo et al. 2008). After extraction, the oil is filtered through a filter press and is then ready for the conversion to bio-diesel.

Table 2 presents the inputs required for the extraction of safflower seed oil using a continuous solvent extraction process. Due to a lack of availability of data on safflower seed-specific extraction processes, this study uses proxy data for the continuous solvent extraction of oil from multiple bio-feedstocks using hexane as the solvent (Whitaker and Heath 2009). It is assumed that the oil is extracted via solvent extraction with an efficiency of 95%.

Table 2. Fossil energy requirements for safflower seed oil extraction before allocating coproduct credits, per ton of input.

Inputs	Equivalent Energy Required	Units
Electricity	50	kWh
Hexane	8	lbs
Steam	560	lbs
Water	2876	gal

Transesterification. Transesterification is the process used to make biodiesel fuel, which is the reaction of a fat or oil with an alcohol to form esters and glycerol in the presence of a catalyst. Methanol and ethanol are used most frequently among all alcohols that can be used in the transesterification process, especially methanol because of its low cost and its physical and chemical advantages (Ma and Hanna, 1999). After biodiesel is derived, the remaining material is then distilled to recover the methanol and most of the water which are reused to avoid waste and reduce input costs. The glycerin is also refined to be used in the production of various other products (Pradhan et al. 2009).

Natural gas and electricity are required as energy inputs during the transesterification process, and the data used in this study is based on a comprehensive survey by the National Biodiesel Board (NBB) of its 230 member companies from biodiesel production in the U.S. (National Biodiesel Board, 2009), since no published data was found for the methanol-based biodiesel transesterification safflower seed oil. The data provided by the survey represent the most accurate depiction of the energy used to produce biodiesel, and are intended to replace all data currently in use for the modeling of the life-cycle GHG and energy impacts of biodiesel production in the U.S. The survey returned one data set that represents the industry average for transesterification of all biodiesel feedstocks used in the survey results, the inputs required during extraction, the recovery of the excess methanol, and treatment of the glycerin are listed in Table 3.

Table 3. Base case data inputs for methanol-based biosiesel transesterification via safflower seed oil, per ton of biodiesel.

Inputs	Equivalent Energy Required	Units
Safflower Seed Oil	2120	lbs
Electricity	57	kWh
Natural Gas	1.12	MJ
Methanol	196	lbs
Sodium Methylate	50	lbs
Sodium Hydroxide	1.98	lbs
Potassium Hydroxide	0.14	lbs
Hydrochloric Acid	56	lbs
Sulfuric Acid	0.28	lbs
Citric Acid	0.74	lbs
Glycerin Output	248	lbs

Calculating Co-product Credits for Biodiesel. The energy used to produce the meal portion and the crude glycerin that is produced during the transesterification stage must be excluded from the life-cycle assessment. Sheehan et al. (1998) used a mass-based allocation method in their study to allocate total energy used to only the production of soybean biodiesel. We choose this method because it is easy to apply and provides reasonable results, which simply allocates energy to the various co-products by their relative weights. Thus, the energy used to produce biodiesel can be calculated in the following way: Energy input allocation for biodiesel = $E_1f_1 + E_2f_2 + E_3$ *(4)* where E_1 is energy input for agriculture, safflower seeds transport and crushing; f_1 is the mass fraction of safflower seeds oil used to produce biodiesel; E_2 is the energy used during transesterification; f_2 is mass fraction of the transesterified oil used to produce biodiesel; and E_3 is energy input for biodiesel transport.

According to personal contact information, 28% of the total energy used for safflower agriculture, transport, and crushing is allocated to the oil used to make biodiesel, and 72%is allocated to the meal. Following transesterification, 90.6%of the total energy used to convert safflower seed oil into biodiesel is allocated to biodiesel and 9.4%is allocated to glycerin. In addition, the coproduct energy value of glycerin must be deducted from safflower agriculture, crushing, and transport, so that f_1 in equation (1) = 0.254 = (0.28 * 0.906), and f_2 = 0.906. All the energy used to transport biodiesel is allocated to biodiesel.

RESULTS

The results for safflower seed-derived biodiesel are compared to the baseline fuel, conventional petroleum diesel, based on three metrics: net changes in life-cycle GHG emissions, net energy value (NEV), and the net energy ratio (NER).

Net Energy Value and Net Energy Ratio. Two widely used types of energy efficiency are reported here. NEV is the difference between the energy output of the final biodiesel product and the fossil energy required to produce the biodiesel. A positive NEV indicates that this biofuel has a positive energy balance. NER is defined as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel, which identifies the degree to which a given fuel is or is not renewable. The base case energy requirements for safflower seed-derived biodiesel are presented in Table 4. After allocating energy by co-products, the total energy required to produce a gallon of biodiesel is 18,410 Btu. The NEV is about 99,886 Btu per gallon. The estimated NER is 6.4.

Table 4. Base case energy use for biodiesel and adjusted by energy efficiency factors.

Life-Cycle Inventory	Fossil Energy Use (Btu/gal of Biodiesel)	
	Total	Biodiesel Fraction
Feedstock Cultivation	17,142	4,800
Safflower Seeds Transport and Biodiesel Distribution	8,507	2,382
Safflower Seeds Oil Extraction	26,534	7,430
Biodiesel Conversion	4,192	3,798
Total Energy Input for Biodiesel Adjusted for Co-products		18,410
Biodiesel Total Energy Content		118,296
Net Energy Value (Btu Out – Btu In)		99,886
Net Energy Ratio (Btu Out/Btu In)		6.4

From a policy perspective, these are important considerations. Policy makers want to understand the extent to which a fuel increases the renewability of the energy supply. The estimated NEV and NER indicate that the safflower seed biodiesel production process generates more energy than it requires, and, in that sense, is sustainable. Another implication of the NER is the question of the effects on climate change of safflower seed biodiesel production. Specifically, it implies that higher fossil energy ratios imply lower net CO_2 emissions (Sheehan et al. 1998).

GHG Emissions. Table 5 presents CO_2-equivalents of GHGs (including CO_2, CH_4 and N_2O) emitted during the irrigated production of safflower seed-derived biodiesel. In addition, considering that safflower has the potential to be planted on non-irrigated cropland (14 inches of growing season rainfall are assumed), where irrigation infrastructure is typically not available, it is meaningful to examine the CO_2-equivalents of GHGs emitted when no irrigation is applied. The results are displayed in Table 6.

Table 5. CO_2 -equivalents of GHG emissions for biodiesel derived from irrigated safflower and adjusted by energy efficiency factors.

Activities	CO_2 Emissions *(kg CO_2 /mmBTU)*
Feedstock Cultivation	6.66
Safflower Seeds Transport and Biodiesel Distribution	1.12
Oil Extraction and Biodiesel Conversion	13.87
Total	21.65

Table 6. CO_2 -equivalents of GHG emissions for biodiesel when irrigation is not required.

Activities	CO_2 Emissions *(kg CO_2 /mmBTU)*
Feedstock Cultivation	3.42
Safflower Seeds Transport and Biodiesel Distribution	1.12
Oil Extraction and Biodiesel Conversion	13.87
Total	18.41

To clearly show the GHG reduction benefit of safflower biodiesel, Table 7 presents the changes in GHG emissions of the biodiesel relative to petroleum diesel, and shows that safflower seed-derived biodiesel production and use reduces net life-cycle greenhouse gas emissions by approximately 78% in the U.S. compared with conventional diesel. As indicated by the results, base case LCA calculations indicate that biodiesel produced from safflower seeds will lead to reduction of greenhouse gas and petroleum consumption compared with petroleum diesel. As outlined in the Energy Independence and Security Act of 2007, safflower seed biodiesel qualifies as an “advanced biofuel” and as a “biomass-based diesel,” and would qualify to meet fuel standards in those categories in the United States. In addition, a recent life-cycle GHG emissions was conducted for soybean biodiesel (Pradhan et al. 2012). This study reported that soybean biodiesel reduced GHG emissions by 81.2% compared to petroleum diesel, which is slightly higher than the 78% GHG reduction of safflower-based biodiesel. Thus, it is considered that winter safflower is still a promising energy crop especially in places lack of water irrigation.

Table 7. Life-cycle GHG emissions for safflower-based biodiesel and petroleum diesel.

Fuel	CO_2 Emissions (kg CO_2/mmBTU)	Percent Change from Diesel
Diesel	97	----
Safflower-based Biodiesel	21.65	-78%

The data on life-cycle GHG emissions for diesel were obtained from U.S. (2010).

Sensitivity analyses. Several sensitivity analyses were conducted to determine the influence of individual parameters on the overall study results. The base case scenario focuses on existing agricultural technology and transportation distance of winter safflower within a short-term time horizon. However, sensitivity analysis allows to consider the potential for near-term improvements. The four selected input parameters are crop yield (that is, pounds of safflower seed per acre), fertilizer usage, irrigation levels, and transportation distances. Each parameter is tested individually while others are held at their base case values. The results identify which input parameters have the greatest impact on the net life-cycle GHG emissions.

According to Whitaker and Heath (2009), the normalized local sensitivity coefficient (known as elasticity) can be interpreted as the fractional change in model output resulting from a percentage change in model input. Equation 5 represents the calculation of the normalized local sensitivity coefficient (dimensionless):

$$(\partial C_j / C_j) / (\partial \lambda_i / \lambda_i) = (\lambda_i / C_j) * (\partial C_j / \partial \lambda_i) \qquad (5)$$

where, C is the set of model output or total GHG emissions per gallon of biodiesel determined as described above, j representing a specific output, and λ is the set of model input parameters, with i representing a specific input parameter. The influence of an individual parameter on model results is indicated by the absolute magnitude of the coefficient. Coefficients with absolute magnitudes of greater than one indicate that a percentage change in the input parameters will lead to a greater percentage change in the model output. Coefficients less than one indicate parameters with a relatively insignificant impact on overall model results. The results of normalized local sensitivity coefficients displayed in Table 8 identify yield as the parameter with the greatest influence on life-cycle GHG emissions, followed by irrigation level. However, absolute values of all these coefficients are less than one, indicating that model outputs are less sensitive to these parameters. Safflower yield has a negative normalized local sensitivity coefficient which indicates a negative relationship between yield and life-cycle GHG emissions. If safflower yield per acre increases from the base case value, life-cycle GHG emissions of safflower-based biodiesel will decrease. In contrast, an increase in irrigation level will lead to an increase in life-cycle GHG emissions as indicated by the positive local sensitivity coefficient. Results of normalized local sensitivity coefficients indicate that fertilizer and transport distance have relatively minimal impacts on GHG emissions with coefficients of less than 0.1.

Table 8. Normalized local sensitivity coefficients for life-cycle GHG emissions for safflower-based biodiesel.

Parameter	Sensitivity Scenario		Normalized Local Sensitivity Coefficient
Yield	High seed yield	Set to high end of estimated range.	-0.2
Irrigation	Less irrigation	Set to low end of estimated range.	0.15
Fertilizer	Low fertilizer level	Set to low end of estimated range.	0.03
Transport	Reduced distance	Reduced distance of travel by 100 miles.	0.05

Producer Profit Analysis. Under the American Clean Energy and Security Act (ACES) that passed the U.S. House of Representatives recently, it is possible to create a cap and trade system for greenhouse gas emissions and new markets for agriculture to be created. Under ACES, capped entities (that is, greenhouse gas emitters) could purchase offsets to meet compliance obligations in lieu of reducing emissions themselves; in total, domestic and international offsets would be allowed up to a total of 2 billion metric tons of GHG emissions annually (Larsen 2009). This creates opportunities for farmers to participate in a new market and generate increased revenue as the legislation looks to the agricultural community to serve as offset providers. Consequently, biofuel crops cultivation is considered as one of the possible manners for providing offsets and also increasing profits. The purpose of the last part of this study is to analyze the costs and revenue from safflower production, as well as farmers' planting decisions under a cap and trade market to provide useful implications. In order to do that, a production function of safflower is estimated, where production is a function of fertilizer and water; production functions of GHG emissions from fertilizer application and irrigation process are also developed. Finally, a related profit function is developed to evaluate possible incentives to change behaviors.

The data used to estimate safflower production function are from Engel and Bergman (1997), which is comprised of 45 observations of safflower yield, fertilizer and water. Although safflower yield is determined by numerous factors, the analysis focuses on two crucial input factors: fertilizer and irrigation water. A cubic functional form (Equation 6) was used to better describe the increasing and decreasing returns to scale as exhibited in the data:

$$Y = \alpha_0 + \alpha_1 w + \alpha_2 f + \alpha_3 w^2 + \alpha_4 f^2 + \alpha_5 w^3 + \alpha_6 f^3 + \alpha_7 wf + \alpha_8 w^2 f + \alpha_9 wf^2 \tag{6}$$

where, Y denotes safflower yield (lbs/acre), f the total amount of nitrogen available to the crop (lbs/acre), and w total water available (inches/acre). Three interaction terms were included to capture the relationship between two input factors, but were ruled out by a joint significance test. The results of the production function estimation are presented in Table 9. The adjusted R-squared value of 0.83 indicates the estimated production function properly captured the underlying relationship between the two input factors, and t-values of coefficients are also acceptable at 10% significant level.

Table 9. Estimated parameter values of the safflower production function.

	intercept	w	f	w^2	f^2	w^3	f^3
Coefficients	4405	-1090	-8.68	86.43	0.12	-1.91	$-4.56*10^{-4}$
Standard Errors		636.65	6.78	46.76	0.10	1.10	$4.12*10^{-4}$
Adjusted R^2							0.83

Finally, the profit function of safflower is simply the difference between the revenue from production and total costs plus a carbon credit that farmers receive by reducing GHG emissions during their production of the fuel feedstock. Specifically, it is expressed as follows:

$$\pi = p * Y - (p_w * w + p_f * f + \text{fixed costs}) + p_c * (c_p - c\,(w, f)) \qquad (7)$$

where π denotes profit, p safflower price, Y denotes safflower yield per acre, p_w irrigation water price per inch, w irrigation water applied per acre, p_f fertilizer price per pound, f nitrogen fertilizer applied per pound. p_c is the per-unit carbon credit which farmers receive for reduced GHG emissions as compared to an equivalent unit of petroleum diesel[4]. c_p is carbon output of an equivalent amount of petroleum diesel, and $c(w, f)$ is carbon output caused by irrigation and fertilizer application which is estimated and expressed in the following equation[5]:

$$c(w, f) = 4.61 * w + 0.338 * f \qquad (8)$$

Note that the change in carbon output calculated in equation 8 does not take into account the secondary effects of a change in fertilizer or irrigation – the change in yield that would change the resulting GHG emissions per unit of fuel value. We use the simplified equation 8 as an approximation to the functional relationship between input use intensity and carbon output. The yield effects of a change in irrigation or fertilizer application would tend to mitigate the change in carbon output for most values of water or fertilizer.

It is obvious from the profit equation that carbon enters simply as an additional cost of using water and fertilizer. So that the cost of water application can be expressed as:

$$cost_w = (p_w + p_c * 4.61) * w \qquad (9)$$

Similarly, the cost of fertilizer application is:

$$cost_f = (p_f + p_c * 0.338) * f \qquad (10)$$

Equation 10 shows an increase in the carbon price should affect the farmer's input demand in the same way as an increase in input price. That is to say, if the carbon price increases, farmers will decrease water and fertilizer usage to decrease GHG emissions to increase profits. This suggests that, instead of a simple increase in price (through increased demand) for the feedstock, the ability to carry the GHG policy instrument over to feedstock producers through a mechanism could have a positive effect on GHG emissions abatement as well as conservation of other scarce resources, such as water.

To determine the magnitude of the possible effect of a carbon credit carried through to the farmer, a simple profit simulation and grid search is run to determine farmer responses to a positive value of p_c in equation 7. The nature of the production functional form makes developing factor demand equations difficult, since part of the first-order condition for profit maximization is a quadratic function of input variables, which, when solved, result in input demand functions that are undefined for a range of variable values. Instead, profit (equation 7) for a wide array of input values is calculated and the input use that maximizes profit is also identified. At baseline prices (and a zero value for p_c), positive farmer profits can be obtained for any safflower seed price greater than \$0.06 per pound[6]. This suggests that safflower seed oil is profitable from about a \$0.25 per pound market price (assuming 30% oil content of safflower seed and \$75/ton crushing costs), which is lower than the comparable prices for soybean oil (assuming a \$0.189/lb seed price and 19% oil content). Market prices for crude safflower oil are currently much higher than this, however, as refined safflower oil is typically sold as a specialty or gourmet cooking oil.

When the carbon credit value increases, that is, when p_c increases from zero, it is found that farmer input choice is relatively unresponsive to changes in carbon credit prices. The producer reduces water use at a rate of about 0.1 acre-in per \$0.12/kg CO_2 carbon credit. Currently, carbon credits in a carbon market are expected to range between \$15 and \$30 per metric ton CO_2, or \$0.015 and \$0.03 per kg. These prices are not high enough to induce safflower farmers to reduce input use.

CONCLUSION AND DISCUSSION

Base case analysis results indicate that biodiesel produced from winter safflower achieves a reduction in net life-cycle GHG emissions of 78% compared with conventional petroleum diesel. With a positive NEV of 99,886 Btu per gallon and NER of significantly greater than one, the safflower-derived biodiesel system yields more useful energy than is required during production, processing, and transport. These results suggest that the safflower-based biodiesel system under consideration could potentially achieve the identified sustainability goals of reducing net GHG emissions, displacing conventional petroleum diesel consumption, with a large net energy ratio. In addition, yield and irrigation level were identified as parameters to which life-cycle GHG emissions are most sensitive.

Finally, the profit function analysis reveals that winter safflower is a profitable feedstock for biodiesel production to grow on the Texas High Plains. However, even carefully designed carbon policy is not likely to induce feedstock producers to further decrease GHG emissions during production. Overall, the benefits of winter safflower biofuel to the nation of providing cleaner burning fuels that improve both regional and global air quality while improving soil and water quality are obvious. Combined with the improvements in farm economy, which can be expected with the production of energy on farms and increased income for local farmers, winter sunflower crop is expected to become increasing competitive in the future on the Texas High Plains.

Note that this study does not consider potential land use changes. Increased CO_2 emissions from potential land use changes are an important factor, but it is not included in the current analysis since reliable data on potential land use changes induced by safflower seed-based biodiesel production are not available. However, safflower is grown on semi-arid or marginal land. It is anticipated that there will be a neutral to positive net carbon sequestration as the areas are changed to hosting large-scale safflower plants.

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APPENDIX

Table A1. Enterprise budget summaries for dryland and irrigated winter safflower production.

Costs and Revenues	Dryland Safflower	Irrigated Safflower
Variable Cost ($/acre)	61.63	151.76
Total Ownership Costs ($/acre)	93.70	93.70
Land Rent ($/acre)	40.00	40.00
Total Costs ($/acre)	195.33	285.46
Yield(lb/acre)	678.40	1745.05
Seed Price($/lb)	0.20	0.20
Cost($/lb)	0.29	0.16
Total Revenue($/acre)	135.68	349.01
Net Revenue($/acre)	-59.65	63.55
Revenue Net of Variable Costs($/acre)	74.05	197.25

Source: Oswalt, S.; Texas Tech University.

ENDNOTES

[1] Safflower yield is 2000 lb/acre as estimated.

[2] 44/28 represents the conversion of nitrogen emissions to N_2O emissions.

[3] 44/12 represents the conversion of carbon emissions to CO_2 emissions.

[4] Currently, carbon credits are expected to be paid to biofuel producers. Here p_c is a hypothetical portion of the total offset that could be paid to farmers to induce additional carbon savings.

[5] This equation is estimated by summing the GHG emissions of these two activities together, and the coefficients are estimated by EPA.

[6] Assuming prices of water and fertilizer are $4.50/acre-in, $500/ton respectively, and that fixed costs are $80/acre.