PROPERTIES, PERFORMANCE, AND ECONOMICS OF *RAPHANUS SATIVUS* (OILSEED RADISH) BIODIESEL

by

NICHOLAS CHAMMOUN

(Under the Direction of K.C. Das)

ABSTRACT

Oilseed radish (*Raphanus sativus*) is identified as a potential cool season cover and energy crop for Georgia. Oilseed radish oil is extracted from seed and transesterified to biodiesel. The properties and engine performance of oilseed radish biodiesel are shown to be comparable with No. 2 diesel and other common biodiesel fuels. The economics of a potential oilseed radish crop are examined on a per acre basis accounting for biodiesel value, byproduct meal and glycerin value, and also the agronomic value of nematode control.

INDEX WORDS: biodiesel, oilseed radish, *Raphanus sativus*, Brassica, diesel engine test, nematode

PROPERTIES, PERFORMANCE, AND ECONOMICS OF *RAPHANUS SATIVUS* (OILSEED RADISH) BIODIESEL

by

NICHOLAS CHAMMOUN

B.S.A., The University of Georgia, 2007

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2009

PROPERTIES, PERFORMANCE, AND ECONOMICS OF *RAPHANUS SATIVUS* (OILSEED RADISH) BIODIESEL

by

NICHOLAS CHAMMOUN

Major Professor:	K.C. Das
Committee:	Dan Geller John McKissick Wilson Faircloth Gary Hawkins

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2009

DEDICATION

To my mother, Linda Chammoun, for her encouragement to me, my family, and our community.

ACKNOWLEDGEMENTS

I would like to acknowledge the help of my graduate committee members, especially Dan Geller, Greg Hopkins and his staff at US Biofuels, Dr. John Goodrum, Dr. Mike Azain, Manual Hall, Jeremy Huskey, Troy Rodakowski, and Nathan Melear. A special thanks to my family and to Meagan Remington for the encouragement to finish strong. Thank you all for your assistance in making this thesis possible.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

Page

Chapter 1

Introduction

As the price of crude oil rises, every sector of the United States economy is affected. One sector of the economy that is particularly susceptible to fluctuations in energy prices is agriculture. Approximately 3% of the energy used in the US is used directly for food production (McIntosh et al., 1984). With the increase in farm mechanization fuel consumption on the farm has also increased. Farms produce many different crops, including oilseed crops that are processed into vegetable oils. It has been established in past research that vegetable oils can be used in diesel engines without many modifications (Goodrum, 1996). Further research has shown that continued use of the unprocessed oils can cause undesirable effects on the engine (Schumacher and van Gerpen, 1996). Techniques have been devised to convert long chain vegetable oils into shorter chain methyl esters for use as diesel fuel substitutes, or biodiesel. Since farms produce the world's supply of oilseed crops, and thus vegetable oils, farms should be able to offset their energy consumption by producing biodiesel.

As oil prices have risen rapidly in the past seven years, alternatives for petroleum based fuels have been searched extensively. In diesel fuel substitutes, it has been established that vegetable oil methyl esters (biodiesel) make a suitable diesel fuel substitute. The major crop used for biodiesel production in the United States is soybean. Other crops used include, but are not limited to, peanut, sunflower, and canola. Excluding canola, each of these crops is a warm season crop originally grown for its use as a food crop. The use of these crops for Biodiesel production has caused competition with their food-based markets and thus a price increase in the vegetable oils from these crops (Ma and Hanna, 1999). For Biodiesel to be economical for on-farm production, the vegetable oil feedstock must be inexpensive. (McIntosh et al., 1984) This presents a problem if traditional oilseed crops are to be used for on farm biodiesel production. Furthermore, growing oilseed crops for fuel usage in the warm season, Georgia's main economic growing season, will compete with Georgia's traditional cash crops. If an oilseed crop could be grown in the cool season, it would not compete with traditional economic crops, and farm income could be maintained without compromising fuel production on the farm.

This project was aimed at the evaluation of cool season oilseed crops for potential biodiesel production in Georgia. Fuel quality should be analyzed and fuel performance tests conducted to establish crops for further research on crop rotation and production.

This thesis presents a new crop for biodiesel production in Georgia which has not been previously evaluated for quality and performance as a fuel. This crop would also provide additional economic and agronomic benefits.

Objectives

1. Evaluation of a cool season (fall and winter months) oilseed crop for on-farm biodiesel production in Georgia that also fits into Georgia's economic crop rotation.
2. Extract oil from oilseed, transesterify to biodiesel, and analyze its fuel properties.
3. Evaluate fuel performance of identified oilseed crop in engine testing.
4. Evaluate potential economic feasibility of the oilseed crop.

References

1. Goodrum, J.W. 1996. Review of biodiesel research at University of Georgia. *Liquid Fuels and Industrial Products from Renewable Resources* (1996): 128-135.

2. Ma, F. and M.A. Hanna. 1999. Biodiesel Production: a review. *Bioresource Technology* 70 (1999): 1-15.
3. McIntosh, C.S., S.M. Smith and R.V. Withers. 1984. Energy Balance of on-farm production and extraction of vegetable oil for fuel in the United States' Inland Northwest. *Energy in Agriculture* 3 (1984): 155-166.
4. Schumacher, L.G. and J.H. Van Gerpen. 1996. Research needs resulting from experiences of fueling of diesel engines with Biodiesel. *Liquid Fuels and Industrial Products from Renewable Resources* (1996): 207-216.

Chapter 2

Literature Review

There has not been much literature published on the topic of on-farm production of biodiesel. But there is a growing knowledge base on oilseed crops, their agronomics, economics, and conversion to biodiesel. Using vegetable oils for fuel in diesel engines is as old as the engine itself. In a very well known demonstration, Dr. Rudolph Diesel used peanut oil in his engine in the absence of other fuels.

As petroleum prices have risen, more research has been done in the area of biodiesel from oilseed crops in search of a cheaper alternative to petroleum diesel (Ma and Hanna, 1999). However, increase in demand for biodiesel has lead to the potential for the price of vegetable oil feedstocks to increase by as much as 14% over the period of five years (Raneses et al., 1999). This rise in vegetable oil prices has also increased the price of raw oilseeds leading many farmers to look at growing oilseed crops to sell as biodiesel feedstock. If traditional oilseed crops were grown specifically for commercial biodiesel production in Georgia, they would displace traditional economic crops such as cotton, peanut, tobacco, and vegetables. This displacement would cause a loss of income on the farm (CAED-CAES, 2007). This is because, although vegetable oil prices are rising, crude petroleum oil prices have not reached a level high enough to allow for the more expensive vegetable oils to be converted into biodiesel (Agarwal, 2007). For example, it has been proposed that diesel prices in the US would have to exceed approximately $5.00 per gallon at the pump for biodiesel from peanut oil to reach their break even point (CAED-CAES, 2007). Research is currently being done to reduce the cost of vegetable oil by reducing inputs required to grow oilseed crops (Branch and Fletcher, 2004). Lower prices of vegetable oil feedstock would lead to more biodiesel production.

Crop rotations are used to maintain soil fertility while decreasing the reliance on fertilizers (Yunusa and Rashid, 2007). Cover crops are grown in Georgia's cool season (after major economic crops are harvested, i.e. peanuts and cotton) as a green manure to restore nutrients to the soil, aid in combating soil pathogens for the next economic crop, and to prevent erosion (Larkin and Griffin, 2007). Currently these crops are of economic importance only in the manner that they reduce the costs of fertilizer, pesticides, and erosion control on the farm; the crops are not sold in the market place as cash crops. Some oilseed crops, such as oilseed radish (*Raphanus sativus* ssp. *oleiferus*, in the *Brassica* family), rapeseed, and mustard, can provide many rotational and green manure benefits when grown as cover crops (Bunte et al., 1997). These crops contain comparable levels of seed oil content to the traditional oilseed crops such as soybean and peanut. Oilseed radish contains about 40% oil in its seed (Eckey, 1954). This crop has been grown as a cool season cover crop in the US and has been shown to have favorable effects in aiding in control of plant pathogens (Lazzeri et al., 2004).

Since Biodiesel has been produced on a large scale, certain favorable fuel properties have been established to evaluate potential fuels from new feedstocks (Ali and Hannah, 1995). Some of these properties include temperature and viscosity dependence and boiling point. Cold-flow properties such as cold filter plugging point (CFPP) could be added in the future. Fuel performance properties have also been established when Biodiesel fuels are used in diesel engines (Korus et al., 1985 and Goodrum et al., 1996). These properties include degree of coke deposited on fuel injectors (injector coking). Current Biodiesel made from traditional oilseed crops in Georgia, such as peanut and soybean have been comparable to No.2 diesel fuel in fuel properties and performance (Geller, 1998). Biodiesel made from cool season crops in the *Brassica* family, such as canola, have also been comparable to No.2 diesel fuel as well (Geller et al., 1999).

Analysis

A hurdle in the implementation of biodiesel on a larger scale is the high price of vegetable oil feedstocks obtained from traditional crops (CAED-CAES, 2007). A cheaper feedstock is needed that does not compete with the economic growing season of Georgia. Cover crops provide many agronomic and economic benefits in terms of displacing costs and increasing soil quality (Yunusa and Rashid, 2007). Cool season oilseed cover crops have the potential to provide an alternative vegetable oil feedstock, while maintaining the agronomic and economic benefits of cool season cover crops. One cool season oilseed crop that has been shown to have positive affects on soil quality is oilseed radish (Lazzeri et al., 2004). Using previously established parameters for diesel fuel quality, a comparison between oilseed radish and number two diesel fuel can be made. In addition, an equation based on cold flow versus saturation of a fuel for future screening purposes will be investigated for its functionality. The assumption that oilseed radish oil will successfully convert into biodiesel is made on the basis that oilseed crops within the *Brassica* family, such as canola and rapeseed, have been shown to produce quality biodiesel as a substitute for diesel fuel (Kulkarni et al., 2007).

Hypothesis

The hypothesis is that vegetable oil from oilseed radish will produce biodiesel with comparable fuel properties and performance to that of No.2 petroleum diesel fuel.

References

1. Agarwal, A.K. 2007. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science* 33 (2007): 233-271.
2. Ali, Y. and M.A. Hanna. 1995. Alternative diesel fuels from vegetable oils. *Bioresource Technology* 50: 153-163.
3. Branch, W.D. and S.M. Fletcher. 2004. Evaluation of advanced Georgia peanut breeding lines with reduced-input and without irrigation. *Crop Protection* 23 (2004): 1085-1088.
4. Bunte, R., J. Muller, and W. Friedt. 1997. Genetic variation and response to selection for resistance to root-knot nematodes in oil radish (*Raphanus sativus* ssp. *oleiferus*). *Plant Breeding* 116: 263-267.
5. CAED-CAES. 2007. Economics of Peanuts for Biodiesel Production. Center Report No. CR-07-04. Athens, GA.: Center for Agribusiness and Economic Development, College of Agricultural and Environmental Sciences, University of Georgia.
6. Eckey, E.W. 1954. *Vegetable Oils and Fats.* New York, New York: Reinhold Publishing Corporation.
7. Geller, D.P. 1998. Biologically Modified Plant Seed Oils for Use as Diesel Fuel. MS Thesis. Athens, GA.: University of Georgia, Department of Biological and Agricultural Engineering.
8. Geller, D.P., J.W. Goodrum and S.J. Knapp. 1999. Fuel properties of oil from genetically modified *Cuphea viscosissima. Industrial Crops and Products* 9 (1999): 85-91.

9. Goodrum, J.W., V.C. Patel, and R.W. McClendon. 1996. Diesel injector carbonization by three alternative fuels. *Transactions of the ASAE* 39 (3): 817-821.
10. Korus, R.A., J. Jo, and C.L. Peterson. 1985. A rapid engine test to measure injector fouling in diesel engines using vegetable oil fuels. *Journal of the American Oil Chemists' Society* 62 (11): 1563-1564.
11. Kulkarni, M.G., A.K. Dalai, and N.N. Bakshi. 2007. Transesterification of canola oil in mixed methanol/ethanol system and use of esters as lubricity additive. *Bioresource Technology* 98 (2007): 2027-2033.
12. Larkin, R.P. and T.S. Griffin. 2007. Control of soilborne potato disease using *Brassica* green manures. *Crop Protection* 26 (2007): 1067-1077.
13. Lazzeri, L., M. Errani, O. Leoni, and G. Venturi. 2004. *Eruca sativa* spp. *Oleifera*: a new non-food crop. *Industrial Crops and Products* 20 (2004): 67-73.
14. Ma, F. and M.A. Hanna. 1999. Biodiesel Production: a review. *Bioresource Technology* 70 (1999): 1-15.
15. Raneses, A.R., L.K. Glaser, J.M. Price, and J.A. Duffield. 1999. Potential biodiesel markets and their economic effects on the agricultural sector of the United States. *Industrial Crops and Products* 9 (1999): 151-162.
16. Yunusa, I.A.M. and M.A. Rashid. 2007. Productivity and rotational benefits of grass, medic pastures and faba beans in a rainfall limited environment. *Soil and Tillage Research* 97 (2007): 150-161.

Chapter 3

Fuel Properties and Performance Testing of *Raphanus sativus* (Oilseed Radish) Biodiesel

---

Chammoun, N.A., D. Geller, G. Hawkins, and K.C. Das. To be submitted to: *Industrial Crops and Products*.

Introduction

Fluctuating and unpredictable energy prices throughout the world have encouraged many in the United States to search for alternative energy sources. A reliance on unstable foreign nations for a large portion of US energy has also pushed alternative energy to the forefront as a national security issue. Environmental issues with fossil fuels also help promote clean alternative energy sources. In 2007 Congress proposed the Energy Independence and Security Act (EISA) to address these issues and promote alternative, clean energy sources for the United States. EISA plans to increase biofuel production to 36 billion gallons by the year 2022 (EISA).

As the price of crude oil rises, every sector of the United States economy is affected. One sector of the economy that is particularly susceptible to fluctuations in energy prices is agriculture. Approximately 3% of the energy used in the US is used directly for food production (McIntosh et al., 1984). With the increase in farm mechanization fuel consumption on the farm has also increased. Groups such as 25x'25 have proposed farms as a source of energy to reduce the United States dependency on foreign energy (25x'25). This group's goal is to have twenty percent of the energy in the US supplied by farms, forests, and ranches by the year 2025 (25x'25).

Farms produce many different crops, including oilseed crops that are processed into vegetable oils. It has been established in past research that vegetable oils can be used in diesel engines without many modifications (Goodrum, 1996). Soybean (*Glycine max*) and palm (*Elaeis oleifera* and *Elaeis guineensis Jacq*) are the main sources of vegetable oils in the world. In the US some alternative oilseed crops include peanut (*Arachis hypogaea*), canola (*Brassica napus*), rapeseed (*Brassica napus*), and sunflower (*Helianthus annus*). Further research has shown that continued use of the unprocessed oils can cause undesirable effects on the engine (Schumacher and van Gerpen, 1996). Techniques have been devised to convert long chain vegetable oils into shorter chain methyl esters for use as diesel fuel substitutes, or biodiesel. Since farms produce the world's supply of oilseed crops, and thus vegetable oils, farms should be able to offset their energy consumption by producing biodiesel.

The major crop used for biodiesel production in the United States is soybean. Other crops used include, but are not limited to, peanut, sunflower, and canola. Excluding canola, each of these crops is a warm season crop originally grown for its use as a food crop. The use of these crops for Biodiesel production has caused competition with their food-based markets and thus a price increase in the vegetable oils from these crops (Ma and Hanna, 1999). For Biodiesel to be economical for on-farm production, the vegetable oil feedstock must be inexpensive. (McIntosh et al., 1984) This presents a problem if traditional oilseed crops are to be used for on farm biodiesel production. Furthermore, growing oilseed crops for fuel usage in the warm season, Georgia's main economic growing season, will compete with Georgia's traditional cash crops. If an oilseed crop could be grown in the cool season, it would not compete with traditional economic crops, and farm income could be maintained without compromising fuel production on the farm.

Increase in demand for biodiesel has lead to the potential for the price of vegetable oil feedstocks to increase by as much as 14% over the period of five years (Raneses et al., 1999). This rise in vegetable oil prices has also increased the price of raw oilseeds leading many farmers to look at growing oilseed crops to sell as biodiesel feedstock. If traditional oilseed crops were grown specifically for commercial biodiesel production in Georgia, they would displace traditional economic crops such as cotton, peanut, tobacco, and vegetables. This displacement would cause a loss of income on the farm (CAED-CAES, 2007). This is because, although vegetable oil prices are rising, crude petroleum oil prices have not reached a level high enough to allow for the more expensive vegetable oils to be converted into biodiesel (Agarwal, 2007). For example, it has been proposed that diesel prices in the US would have to exceed approximately $5.00 per gallon at the pump for biodiesel from peanut oil to reach their break even point (CAED-CAES, 2007). Research is currently being done to reduce the cost of vegetable oil by reducing inputs required to grow oilseed crops (Branch and Fletcher, 2004). Lower prices of vegetable oil feedstock would lead to more biodiesel production.

Crop rotations are used to maintain soil fertility while decreasing the reliance on fertilizers (Yunusa and Rashid, 2007). Cover crops are grown in Georgia's cool season (after major economic crops are harvested, i.e. peanuts and cotton) as a green manure to restore nutrients to the soil, aid in combating soil pathogens for the next economic crop, and to prevent erosion (Larkin and Griffin, 2007). Currently these crops are of economic importance only in the manner that they reduce the costs of fertilizer, pesticides, and erosion control on the farm; the crops are not sold in the market place as cash crops. Some oilseed crops, such as oilseed radish (*Raphanus sativus* ssp. *oleiferus*, in the *Brassica* family), rapeseed, and mustard, can provide many rotational and green manure benefits when grown as cover crops (Bunte et al., 1997). These crops contain comparable levels of seed oil content to the traditional oilseed crops such as soybean and peanut. Oilseed radish contains about 40% oil in its seed (Eckey, 1954). This crop has been grown as a cool season cover crop in the US and has been shown to have favorable effects in aiding in control of plant pathogens (Lazzeri et al., 2004).

Since biodiesel has been produced on a large scale, certain favorable fuel properties have been established to evaluate potential fuels from new feedstocks (Ali and Hannah, 1995). Some of these properties include temperature and viscosity dependence and boiling point. Cold-flow properties such as cold filter plugging point (CFPP) could be added in the future. Fuel performance properties have also been established when biodiesel fuels are used in diesel engines (Korus et al., 1985 and Goodrum et al., 1996). These properties include degree of coke deposited on fuel injectors (injector coking). Fuel injector coking is the amount of carbon deposited on the fuel injector during operation of the engine; the carbon is from un-combusted fuel. Current biodiesel made from traditional oilseed crops in Georgia, such as peanut and soybean have been comparable to No.2 diesel fuel in fuel properties and performance (Geller, 1998). Biodiesel made from cool season crops in the *Brassica* family, such as canola, have also been comparable to No.2 diesel fuel as well (Geller et al., 1999).

A hurdle in the implementation of biodiesel on a larger scale is the high price of vegetable oil feedstocks obtained from traditional crops (CAED-CAES, 2007). A cheaper feedstock is needed that does not compete with the economic growing season of Georgia. Cover crops provide many agronomic and economic benefits in terms of displacing costs and increasing soil quality (Yunusa and Rashid, 2007). Cool season oilseed cover crops have the potential to provide an alternative vegetable oil feedstock, while maintaining the agronomic and economic benefits of cool season cover crops. One cool season oilseed crop that has been shown to have positive affects on soil quality is oilseed radish (Lazzeri et al., 2004). Using previously established parameters for diesel fuel quality, a comparison between oilseed radish and No. 2 diesel fuel can be made. In addition, an equation based on cold flow versus saturation of a fuel for future screening purposes will be investigated for its functionality. The assumption that oilseed radish oil will successfully convert into biodiesel is made on the basis that oilseed crops within the *Brassica* family, such as canola and rapeseed, have been shown to produce quality biodiesel as a substitute for diesel fuel (Kulkarni et al., 2007).

Since oilseed radish is in the *Brassica* family, it is believed that oilseed radish biodiesel will behave like that of rapeseed and canola. The fuel properties of oilseed radish biodiesel can be compared with the properties of other biodiesel fuels. Another way of comparing fuel properties to look for trends is by plotting the properties against one another. Cold filter plug point (CFPP) is a cold flow property. The CFPP is the highest temperature at which a fuel fails to pass a standard filtering device. (Mittelbach and Remschmidt, 2004) The CFPP is an operable property to identify cold flow problems. The iodine number of plant oil is a measure of the total unsaturation within a mixture of fatty materials. (Mittelbach and Remschmidt, 2004) The iodine number is determined by a titration. Oils with higher iodine numbers tend to have less desirable characteristics as biodiesel. (Mittelbach and Remschmidt, 2004)

Oilseed radish seed will be acquired, crushed to produce oil, and the oil transesterified into biodiesel; biodiesel properties and performance will be analyzed.

Methodology

Crushing of Oilseed Radish Seed

Four 50 pound bags of seeds were obtained from Johnny's Select Seeds of Winslow, Maine. Seeds were crushed using a model ZY-12C screw type oil press (Shanghai Xuyi Machinery Company, Shanghai, China). Operating conditions were 150 ºC, 60 Hz; the oil was filtered through a metal mesh screen, and thereafter centrifuged in a US Centrifuge model M212 centrifuge. Although heat was supplied, this is considered a cold crush; no solvents were used to extract additional oil.

Preparation of Oilseed Radish Biodiesel

Several protocols for biodiesel reactions were experimented to determine the proper protocol for the conversion of oilseed radish oil into biodiesel. These protocols varied reaction stages (one or two), number of total reactions (one or two), and washing methods. The most desirable protocol, and the one used for this paper, used 9 grams KOH per liter of oil and 200 milliliters methanol per liter of oil. Methanol and KOH were mixed prior to transesterification to produce the methoxide used in the conversion of the oil to biodiesel. The first reaction was a two stage reaction utilizing 85% of the methoxide in the first stage and the remaining 15% of the methoxide in the second stage. In each stage of the reaction the methoxide and oil were mixed at 270 rpm on a heated stir plate for one hour maintaining a temperature range of 50-60ºC. The biodiesel was allowed to settle in a separatory funnel for one hour and all glycerin was removed from the biodiesel. Three washes were done using warm water at 10% of the biodiesel volume; mixing the water and biodiesel for 1.5 minutes at 170 rpm. After each wash the water was separated from the biodiesel. After the third wash the biodiesel was dried (all water removed by heat), and a second, one stage was done, using 9 g KOH per liter and 200 milliliters methanol. After glycerin was decanted, four washes were done at 10% warm water and the fuel was dried on a heated stir plate until all water was evaporated.

Fuel Property Analysis of Oilseed Radish Biodiesel

Fatty acid profile was done using the method of Park and Goins (1994). United States (ASTM) and European (EN) fuel quality analysis was done at the laboratory of US Biofuels in Rome, GA using ASTM and EN methods (Table 3.2).

Engine Performance Testing of Oilseed Radish Biodiesel

The method used for engine testing to evaluate performance was that of Geller (1998). Injector imaging was done using the method of Goodrum et al. (1996). A brief explanation of the engine testing is provided here only for understanding, exact methods were used from Geller (1998). Each engine test or run consists of two single cylinder, direct injection, and identical diesel engines. This provides two numbers per engine test, one for the injector in engine A and one for the injector in engine B. Before and after a fuel of interest is tested, standard number two diesel fuel (ultra-low sulfur on-road diesel fuel, D2) is used as a baseline engine run. This system helps account for decreased efficiency due to wear on the engine over the duration of the study. For example, on D2 engine test is done, then three B100 engine tests, and finally a D2 engine test. The average from the D2 tests is used for the coking index (CI) calculation. The engine test itself consists of a 10 minute warm up on D2 fuel, then six 10 minute intervals with the engine at full throttle and a load placed on the engine. Each 10 minutes the load is increased. After the six loading sessions on full throttle, the engine is decreased in speed, with no load, and is cooled down on D2 fuel. The six 10 minute loading intervals are done on the fuel of interest. For the D2 engine tests, D2 fuel is used for the entire testing period. The cool down and warm-ups are to provide consistent operating conditions for the fuels of interest. After the engine is shut off at the end of the 10 minute cool down, it is allowed to decrease in temperature to a level that the injector can be removed by hand. The fuel injector is then scanned to determine how much coking was deposited over the duration of the engine test. This image is compared to the image of the same injector taken before the engine test when the injector is clean and free of any coking. The average coking deposit is calculated from the 0 and 90 degree scans of the injectors by subtracting the clean injector image from the dirty injector image. A number is assigned to the image based on the number of pixels in the image. A delta pixels is determined from the subtraction of the clean injector from the dirty injector. This delta is used in the statistical calculation to determine differences between the fuels. A coking index is calculated for each fuel and is a measure of how well the fuel performed compared to the diesel fuel performance. The coking index is simply the delta pixels from the fuel of interest divided by the delta pixel from the diesel fuel injectors. If the coking index is larger than one, the fuel did not perform as well as diesel fuel; if it is less than one, the fuel performed better than diesel fuel. It is important to note that the coking index is a quick reference of a fuel's comparable performance to diesel fuel, this number is not based on statistical analysis and therefore it may not be possible to determine if the biodiesel fuel performed better or worse than diesel fuel. Fuel consumption data is recorded and fuel consumption indices are calculated by dividing the biodiesel fuel consumption by the D2 fuel consumption.

Cold Flow Analysis of Oilseed Radish Biodiesel

To compare oilseed radish with other *Brassica* fuels and oilseed fuels, it is necessary to plot the cold flow versus saturation. The properties plotted will be CFPP versus the iodine number and a trend will be determined. For this plot the oilseed radish data is from this study, CFPP data is from Mittelbach and Remschmidt (2004), and iodine values are from Eckey (1954).

Results

Crushing of Oilseed Radish Seed

Crushing methods were not optimized for the small seed of oilseed radish, the press is currently being used for peanut crushing and settings were not adjusted for this crush. The press performed well yielding an average of 28.8% oil from four crushes of 50 pounds each. The first crush did not yield as much as subsequent crushes (Table 3.1), this was attributed to the cold temperature of the press, i.e. the press functions more efficiently as its temperature increases; and the possibility of residual oil required to fill the system.

Table 3.1: Oilseed Radish Oil Yield from Four Cold Crush Replications.

Sample	Percent Oil Yield
1	25.5
2	29.8
3	30.3
4	29.5
Average	28.8

It is believed that if the crush were optimized for the seed size of oilseed radish, more oil could be yielded from the cold crush. Additionally, increased heat of the seed before the crush could also improve yield, or crushing the meal byproduct a second time may produce additional seed from the press. A second stage of oil extraction could be added utilizing solvents to extract the remaining oil in the meal byproduct. A second stage would add time and costs to a commercial operation, but should yield sufficient oil to make it worthy addition. Most commercial crushing operations do utilized a solvent extraction of oil after a cold crush. Since this study was not aimed at oil extraction optimization, it was determined that 28.8% oil yield was adequate to continue to the next step of degumming. Future studies for oilseed radish oil extraction are recommended to increase cold crush yield and quantify how much additional oil can be obtained from a solvent extraction.

Fuel Properties of Oilseed Radish Biodiesel

Two important properties for oilseed radish (Table 3.2) are iodine value and cold filter plugging point (CFPP). For comparison, soybean biodiesel has an iodine value of 131.6 (Eckey, 1954) and a CFPP of -2ºC (Mittelbach and Remschmidt, 2004). Soybean does not meet the limit of 120 iodine value in the table since these are the European limits. Soybean's high iodine value is the main limiting factor in it use as a European biodiesel feedstock. Oilseed radish meets the iodine limit, and thus shows potential as a biodiesel feedstock for the European market. Oilseed radish based biodiesel exhibits a CFPP higher than that for soy based biodiesel. This is important since a high CFPP like that of oilseed radish is a limiting factor in cold weather environments. Soybean's low CFPP allows it to be used in areas with colder climates, whereas oilseed radish should not be used in these areas unless fuel additives are used or the fuel is winterized. Fuel additives can be used to decrease the CFPP of a fuel, but these additives increase the cost of the fuel. Winterization can be done where the fuel is chilled below the CFPP to allow for the gelling compounds of the fuel to fall out of the fuel mixture, and then are easily removed from the fuel, lowering its CFPP.

Table 3.2: Oilseed Radish B100 Fuel Properties.

Parameter	Unit	Test Method	Result	Limit
Total Glycerol	% (m/m)	EN 14105	0.108	≤ 0.24
Free Glycerol	% (m/m)	EN 14105	0.000	≤ 0.02
Monoglyceride Content	% (m/m)	EN 14105	0.301	≤ 0.80
Diglyceride Content	% (m/m)	EN 14105	0.027	≤ 0.20
Triglyceride Content	% (m/m)	EN 14105	0.000	≤ 0.20
Acid Value	mgKOH/g	EN 14104	0.082	≤ 0.50
Sulfur Content	mg/kg	EN ISO 20846	0.79	≤ 10.00
Water Content	mg/kg	EN ISO 12937	68	≤ 500
Iodine Value	g/100g	EN 14111	97	≤ 120
Cold Filter Plugging Point (CFPP)	°C	ASTM 637199	6.0	Report

The fatty acid profile identifies the carbon chain lengths and saturation of fatty acids in the triglycerides. It is important to note the high levels of 22:1, erucic acid, at 31.76% (Table 3.3). This is approaching the levels of rapeseed oil at 45-55% (Eckey, 1954). Rapeseed oil is considered non-edible oil because of the high levels of erucic acid. These levels were decreased by planting breeding and canola was developed. Canola is edible oil and is extensively in this capacity. If the erucic acid levels of oilseed radish were reduced, more uses of oilseed radish could develop while the presence of this oil lends it to unique industrial uses. It is also important to note that the remaining majority of the fatty acid profile is dominated by 18:1 (oleic acid) at 23.87%, 18:2 (linoleic acid) at 13.46%, and 18:3 (linolenic acid) at 10.34%.

Table 3.3: Fatty Acid Profile of Oilseed Radish Oil.

Fatty Acid (n=3)	Percent (%)
16:0	6.13
16:1	0.05
18:0	1.68
18:1	23.87
18:2	13.46
18:3	10.34
20:0	0.68
20:1	8.58
22:0	1.64
22:1	31.76
24:0	0.61
24:1	1.26
Saturated	10.74
Monounsaturated	65.51
Polyunsaturated	23.75

Engine Performance Testing of Oilseed Radish Biodiesel

The coking indices for oilseed radish B100 and B20 both average 1.2 (Table 3.2). This is higher than the index of No. 2 diesel fuel, D2, of one. Usually biodiesel subjected to this engine stress test yield coking indices less than one. Results higher than one indicate this biodiesel may perform slightly less desirable than D2 and other biodiesel suggesting possible pre-mature wear on engine parts. To test for true differences between the biodiesel and D2, statistical analysis was done on the differences (delta) of the dirty and clean injectors. This difference is proportionate to the actual amount of coke deposited during the engine test. These deltas are also the numbers used to calculate the coking indices. The deltas are in six groups, D2A, D2B, B100A, B100B, B20A, and B20B. Two sample F tests were performed to determine if the variances of the six groups were statistically different. Since no differences were detected in the variances of the six groups, an Analysis of Variance (ANOVA) assuming equal variance was performed to detect statistical differences in the mean of the six groups. From the statistical analysis of the difference in areas of the coking on the injectors, there is no statistical difference in means of the six groups. Although the coking index for B20 and B100 oilseed radish biodiesel is higher than one, statistically there was no difference in the amount of coking on the injectors when biodiesel was tested over the baseline of D2. The coking index provides a quick assessment of the fuels performance, but the ANOVA gives actual differences between the groups. Statistical analysis is done on the deltas and not the coking indices because the coking indices do not allow for the variance of the D2 engine tests to be used in the analysis, since it is divided by itself to give a CI of one.

Table 3.4: Coking Indices for Oilseed Radish Biodiesel.

Engine Test	B100 Coking Index	B20 Coking Index
1	1.1	1.3
2	1.3	1.3
3	1.1	0.86
Average	1.2	1.2

The fuel consumption of D2 was observed to be less than that of B100 but not B20 (Table 3.5). A two sample F test was done on the six groups' recorded fuel consumptions, and a difference in variances was detected between the groups. The variances for B20A and B20B were the lowest at 308 and 933 respectively. The variances for B100A and B100B were 4008 and 25833; the variances for D2A and D2B were 33956 and 21683 respectively. The differences in variances were too large to continue the analysis with ANOVA, so the average fuel consumptions are displayed graphically (Figure 3.1).

Table 3.5: Fuel Consumption Indices for Oilseed Radish Biodiesel.

Engine Test	B100 Fuel Consumption Index	B20 Fuel Consumption Index
1	1.0	1.0
2	1.2	1.0
3	1.3	1.0
Average	1.2	1.0

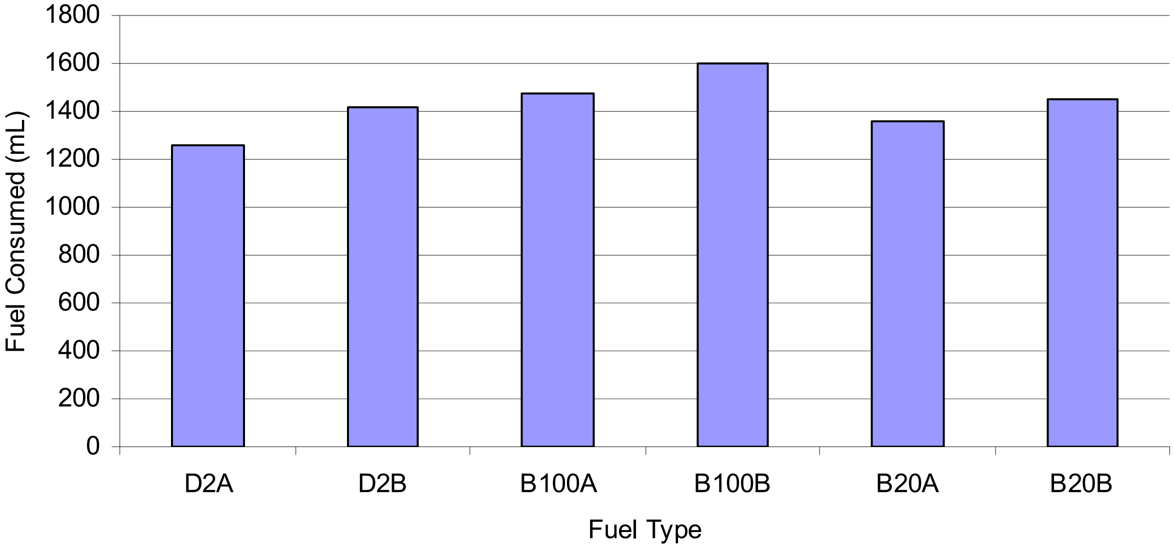

Figure 3.1: Average Fuel Consumption for Engines A and B using D2, B20, and B100 Oilseed Radish Biodiesel.

The average emissions data for each fuel is presented graphically according to engine RPM when running at full throttle (Figures 3.2-3.5). If gas sensors were not operable, no data is presented for that fuel and the number (n) used in averaging is also reported.

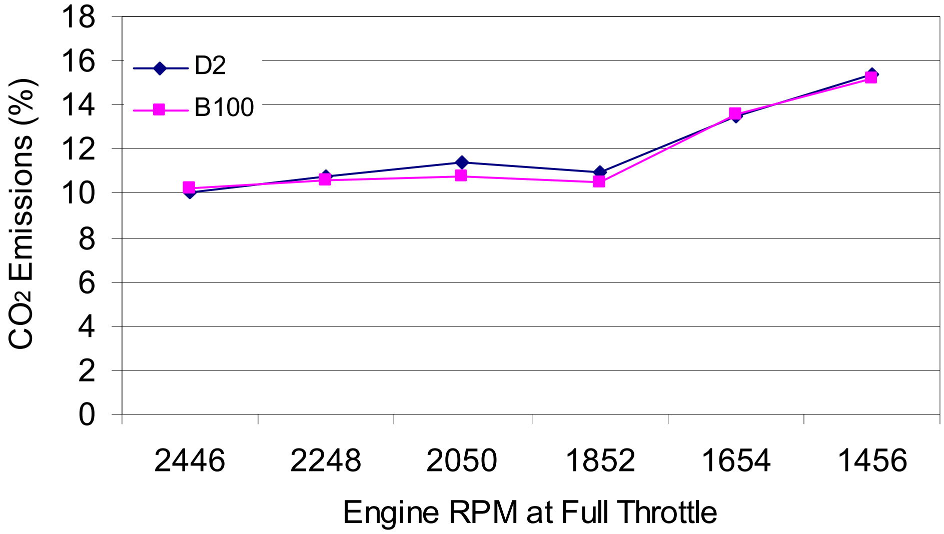

Figure 3.2: CO_2 Emissions of D2 and B100 Oilseed Radish Biodiesel (n=1).

CO_2 emissions (Figure 3.2) were recorded for one test each of D2 and B100, no B20 was recorded. A steady increase is CO_2 is seen as loading on the engine increases. More CO_2 output is the result of more fuel being combusted.

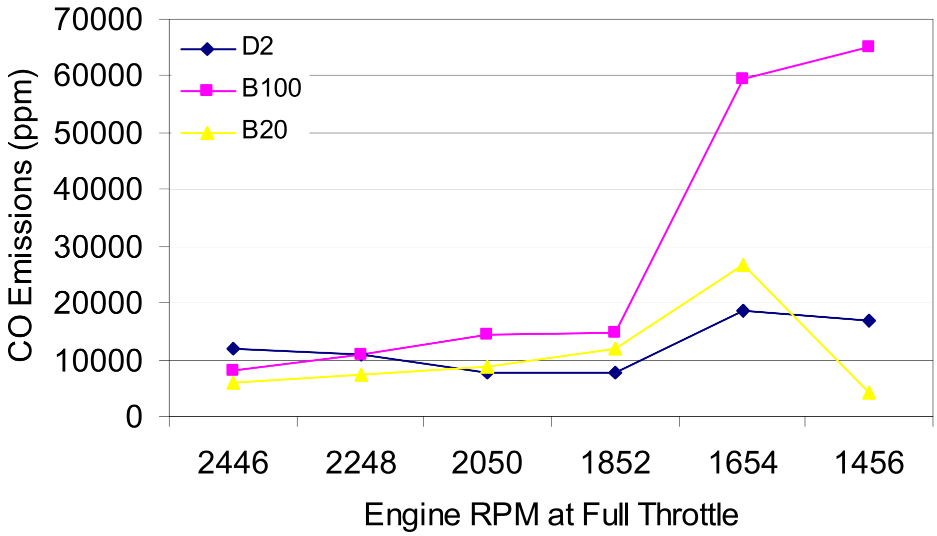

Figure 3.3: CO Emissions of D2, B20, and B100 Oilseed Radish Biodiesel (n=3).

A rapid jump in CO emissions (Figure 3.3) is seen at the heavy engine loadings when more fuel is being consumed. As more fuel is consumed, more carbon is released thus the levels of CO increase. The increased in B100 CO emissions at heavier loadings is more than that of D2 or B20.

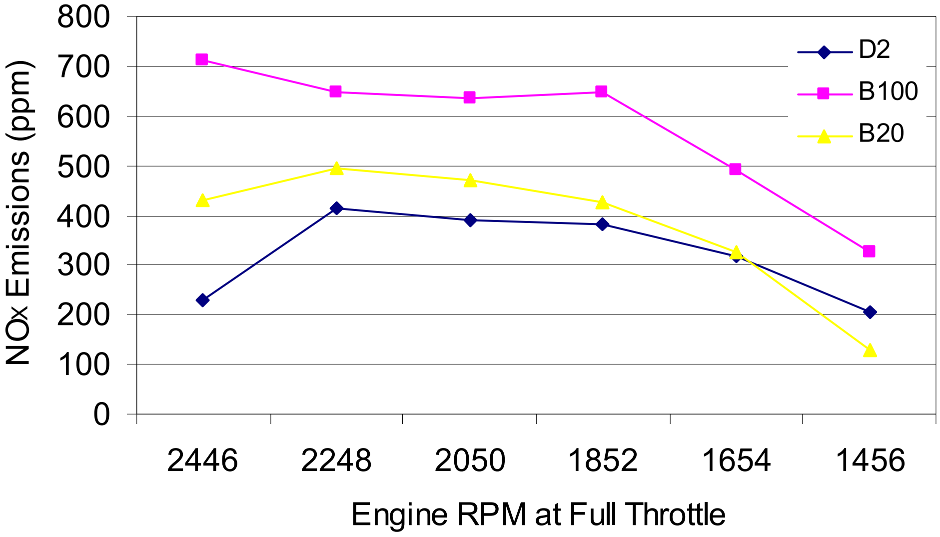

Figure 3.4: NO_x Emissions of D2, B20, and B100 Oilseed Radish Biodiesel (n=3).

NO_x emissions (Figure 3.4) show a marked increase of NO_x in B100 over that of B20 and D2. This is what is typically reported in the literature, that biodiesel NO_x emissions will increase over D2. But, this is the first time we have seen an increase in NO_x in our engine testing. NO emissions and NO_x emissions are essentially identical.

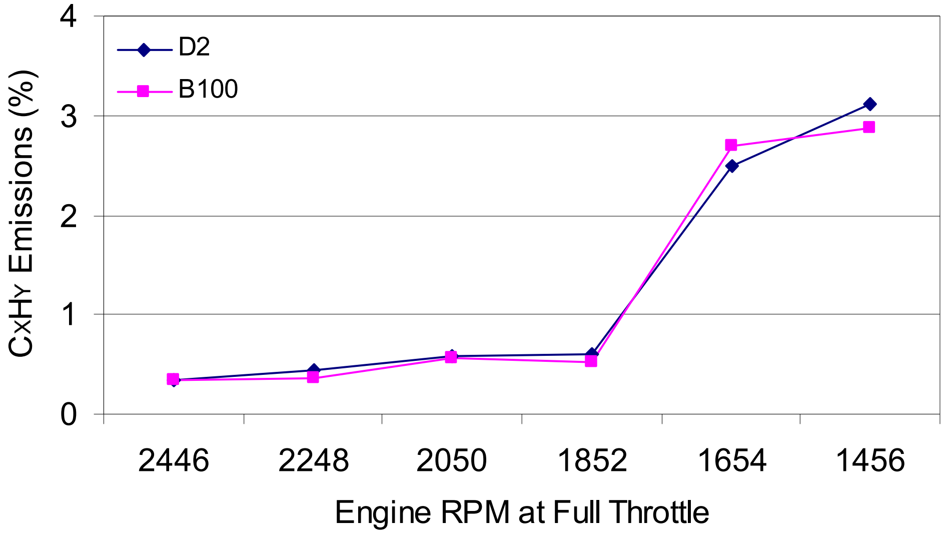

Figure 3.5: C_xH_y Emissions of D2 and B100 Oilseed Radish Biodiesel (n=1).

C_xH_y emissions (Figure 3.5) are reported at one run each for D2 and B100, no data was recorded for B20. C_xH_y emissions report hydrocarbon levels in fuel emissions. This would include any uncombusted fuel contained in the exhaust gases. Levels of hydrocarbons increase drastically at heavy loadings of the engine. This result is due to larger amounts of fuel consumption at the heavier loadings of the engine.

Cold Flow Analysis of Oilseed Radish Biodiesel

From the plots of iodine number versus CFPP, it does not appear that any trend can be observed in the plot. The R-squared values are too low to indicate a significant trend. Although, it is notable that when oilseed radish and crambe are removed from the data set and it is re-plotted, the linear, logarithmic, and 2nd order polynomial trends improved based on the R-squared values. For these plots the oilseed radish data is from this study (Table 3.6), CFPP data is from Mittelbach and Remschmidt (2004), and iodine values are from Eckey (1954).

Table 3.6: Iodine Numbers and CFPP Temperatures for Vegetable Oils and Their Fuels.

Oil/Fuel	Iodine Number	CFPP
Oilseed Radish	97	6
Soybean	131.6	-2
Sunflower	132.5	-3
Camellina	140.5	-1
Tall Oil	129.5	-7
Castor	86	-3
Crambe	100	8.5
Olive	84.5	-6
Poppy Seed	137	-1

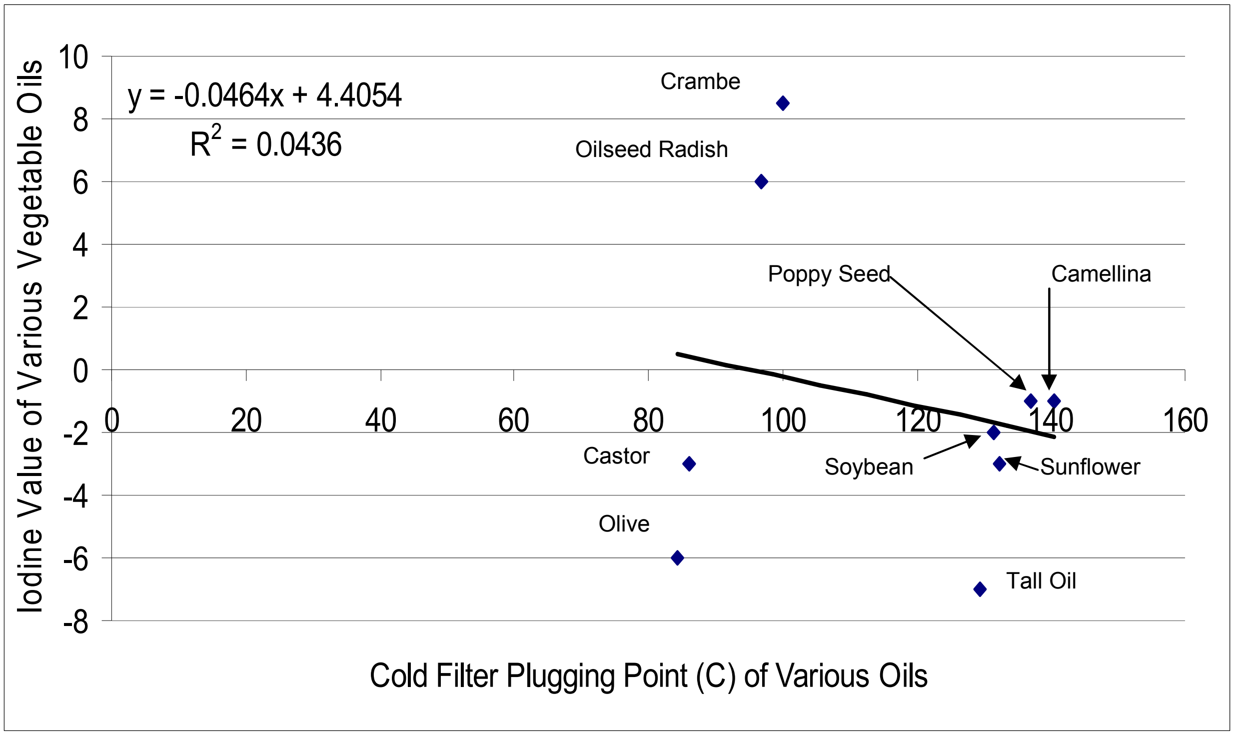

Figure 3.6: Linear Plot of Iodine Number vs. CFPP

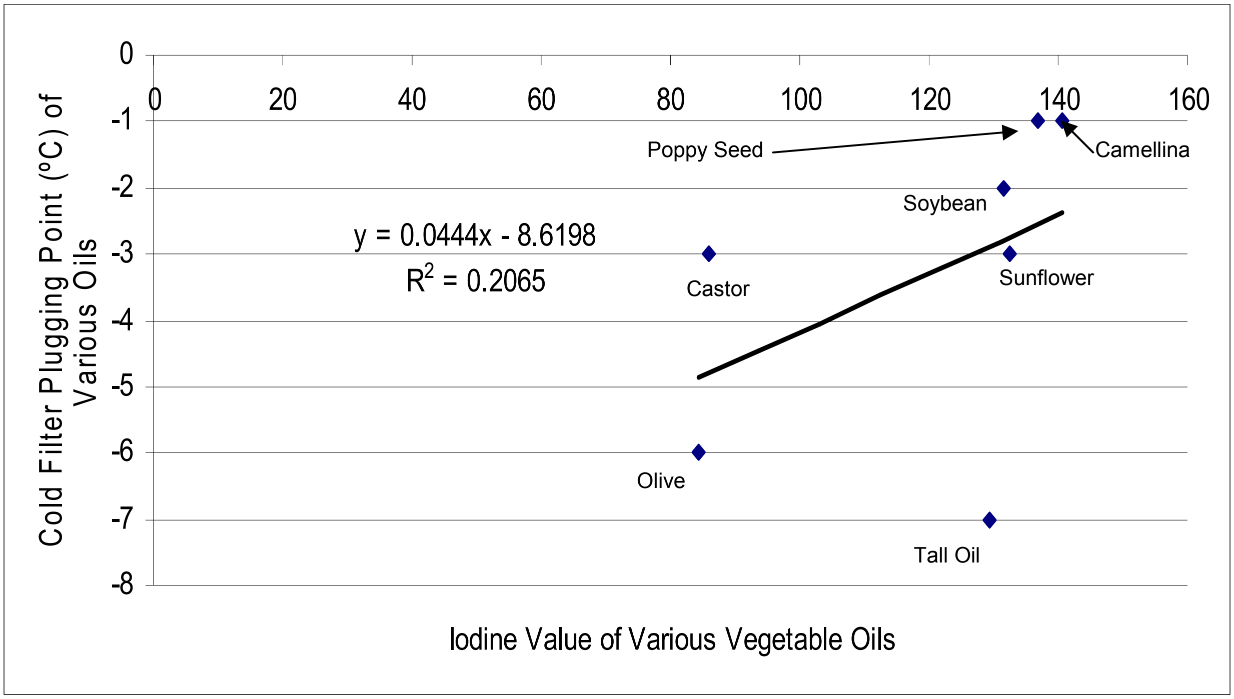

Figure 3.7: Linear Plot of Iodine Number vs. CFPP without Oilseed Radish and Crambe

Conclusions

From the crush results it can be concluded that oilseed radish can adequately be crushed using a screw type press in a one stage cold crush. With an average oil yield of 28.8%, the majority of the oil was extracted using only the cold crush. More oil could be obtained using either a second stage cold crush of the residual meal, or adding a solvent extraction step to the residual meal. It is believed more oil could be extracted from the cold crush if the process were optimized for oilseed radish seed size. Increasing the temperature of the seed would also yield more oil from the cold crush.

Fuel properties results indicate that it is possible to meet ASTM and EU standards for biodiesel using oilseed radish oil as a feedstock. The CFPP number for oilseed radish oil based biodiesel is high and would be a problem if a cold flow specification level was set. Currently

CFPP is required to be reported and no threshold is set. If a threshold level is set, it is likely that oilseed radish cold flow would not ASTM or European standards. It is possible that future research on oilseed radish could lead to varieties that yield better CFPP numbers. Through plant breeding, more desirable cold flow properties could be bred into the crop for its use as a biodiesel feedstock. The high level of erucic acid seen in the fatty acid profile of oilseed radish is similar to that of rapeseed, a European biodiesel feedstock. Human toxicity of erucic acid will keep oilseed radish oil out of the food market, and thus improve its fit as a dedicated energy crop. Just as in cold flow properties, the levels of erucic acid could be decreased through plant breeding. Similar techniques were used to breed canola from rapeseed. Future work in this area could create additional markets for the crop.

Oilseed radish B100 and B20 shared a coking index of 1.2, although B100 would have been expected to have a higher coking potential than B20. Typically biodiesel produces lower coking indices than petroleum diesel; our results were contrary to this behavior. From the statistical analysis of coking deltas, there was not a statistical difference in the means of the deltas between any of the six groups; i.e. statistically each fuel performed on the same level. B100 or B20 from oilseed radish can be used in diesel engines without a statistical decrease in performance of the engine. Based on the fuel consumption indices, B20 performed the same as D2 and B100 performance was slightly less desirable at 1.2. But, since the variances within D2 and B100 were so high, further statistical analysis was determined to be unnecessary and coking indices are used to judge fuel consumption performance. Emissions data were not consistent enough for statistical analysis due to problems with gas sensors in the emissions testing equipment. For this reason the emissions data are presented as averages (if values were present) in graphs as a progression of loading and decreasing engine revolutions per minute (rpm).

A relationship between iodine value and CFPP was determined to be less significant than predicted. When oilseed radish and crambe were removed from the plot, the r-squared value improved five fold. The leads us to believe that even though strong relationship was not established, oilseed radish and crambe lay outside the norm of other oils plotted. Both had high CFPP values, yet relatively low iodine values. The r-squared values lead us to believe that the relationship is more complex than originally believed. More research should be conducted to determine the relationship, if it exists, between cold flow and saturation of vegetable oils. One method would be to attempt the same analysis using pure triglycerides. If a relationship can be determined, a biodiesel from a particular vegetable oil can have a CFPP predicted before the oil is ever converted to biodiesel. This could serve as a rapid analysis for potential cold flow properties of a particular biodiesel feedstock.

There is need for future research into the agronomics of oilseed radish. Field trial should be done to quantify the agronomic benefits this crop has to offer in Georgia. Dr. Wilson Faircloth at the United States Department of Agriculture's National Peanut Research Laboratory in Dawson, Georgia is leading the effort to establish oilseed radish field trials. Dr. Faircloth reports excellent germination and crop growth throughout the cool season. Dr. Faircloth estimates harvest in adequate time to follow with a warm season crop. Although one season is not enough data to make any conclusions on the growth of the plant, it is a starting point in which future studies should be continued to assess the agronomic potential of oilseed radish. Since oilseed radish adds value to a cropping system as a cover crop, more research should be done to quantify these benefits and account for them along with the value of the oil for biodiesel feedstock. We believe that focusing attention on biofuel crops that have additional benefits to cropping systems in the form of improved soil fertility, pest protection, and soil health, is a route that should be pursued in future biofuel research. With the ever-changing dynamic of world fuel prices, additional value in a biofuel crop will increase the crop's ability to withstand large fluctuations in the fuel market. Added agronomic benefits also increase a producer's desire to grow a particular crop. Energy crops with agronomic benefits that can be used in crop rotations, lead to more sustainable farming practices and money savings to producers.

Oilseed radish oil was extracted, biodiesel produced and analyzed, and performance testing completed. The results verify that oilseed radish biodiesel meets ASTM and European standards, and performance testing concludes oilseed radish performs on the same level as petroleum diesel.

References

1. Agarwal, A.K. 2007. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science* 33 (2007): 233-271.
2. Ali, Y. and M.A. Hanna. 1995. Alternative diesel fuels from vegetable oils. *Bioresource Technology* 50: 153-163.
3. Branch, W.D. and S.M. Fletcher. 2004. Evaluation of advanced Georgia peanut breeding lines with reduced-input and without irrigation. *Crop Protection* 23 (2004): 1085-1088.
4. Bunte, R., J. Muller, and W. Friedt. 1997. Genetic variation and response to selection for resistance to root-knot nematodes in oil radish (*Raphanus sativus* ssp. *oleiferus*). *Plant Breeding* 116: 263-267.
5. CAED-CAES. 2007. Economics of Peanuts for Biodiesel Production. Center Report No. CR-07-04. Athens, GA.: Center for Agribusiness and Economic Development, College of Agricultural and Environmental Sciences, University of Georgia.

6. Cavigelli, M.A., T.E. Martin, and D.R. Mutch. 2008. Michigan Cover Crop Species: Oilseed Radish. *Michigan State University Extension.*
7. Eckey, E.W. 1954. *Vegetable Oils and Fats.* New York, New York: Reinhold Publishing Corporation.
8. Eiteman, M.A. and J.W. Goodrum. 1994. Density and Viscosity of low molecular weight triglycerides and their mixture. *Journal of the American Chemists' Society* 71 (11): 1261-1265.
9. Energy Independence and Security Act of 2007 (EISA). 110th Congress of the United States of America. 2007.
10. Geller, D.P. 1998. Biologically Modified Plant Seed Oils for Use as Diesel Fuel. MS Thesis. Athens, GA.: University of Georgia, Department of Biological and Agricultural Engineering.
11. Geller, D.P., J.W. Goodrum and S.J. Knapp. 1999. Fuel properties of oil from genetically modified *Cuphea viscosissima. Industrial Crops and Products* 9 (1999): 85-91.
12. Goodrum, J.W. 1996. Review of biodiesel research at University of Georgia. *Liquid Fuels and Industrial Products from Renewable Resources* (1996): 128-135.
13. Goodrum, J.W., V.C. Patel, and R.W. McClendon. 1996. Diesel injector carbonization by three alternative fuels. *Transactions of the ASAE* 39 (3): 817-821.
14. Hafez, S.L. 1998. Management of Sugar Beet Nematode. *University of Idaho College of Agriculture Cooperative Extension System: Agricultural Experiment Station,* CIS 1071.

15. Korus, R.A., J. Jo, and C.L. Peterson. 1985. A rapid engine test to measure injector fouling in diesel engines using vegetable oil fuels. *Journal of the American Oil Chemists' Society* 62 (11): 1563-1564.

16. Kulkarni, M.G., A.K. Dalai, and N.N. Bakshi. 2007. Transesterification of canola oil in mixed methanol/ethanol system and use of esters as lubricity additive. *Bioresource Technology* 98 (2007): 2027-2033.

17. Larkin, R.P. and T.S. Griffin. 2007. Control of soilborne potato disease using *Brassica* green manures. *Crop Protection* 26 (2007): 1067-1077.

18. Lazzeri, L., M. Errani, O. Leoni, and G. Venturi. 2004. *Eruca sativa* spp. *Oleifera*: a new non-food crop. *Industrial Crops and Products* 20 (2004): 67-73.

19. Ma, F. and M.A. Hanna. 1999. Biodiesel Production: a review. *Bioresource Technology* 70 (1999): 1-15.

20. McIntosh, C.S., S.M. Smith and R.V. Withers. 1984. Energy Balance of on-farm production and extraction of vegetable oil for fuel in the United States' Inland Northwest. *Energy in Agriculture* 3 (1984): 155-166.

21. Noureddini, H., D. Harkey, and V. Medikonduru. 1996. A continuous process for the conversion of vegetable oils into Biodiesel. *Liquid Fuels and Industrial Products from Renewable Resources* (1996): 83-94.

22. Park, P.W. and R.E. Goins. 1994. In situ preparation of fatty acid methyl esters for analysis of fatty acid composition in foods. *Journal of Food Science*, 59:1262-1266.

23. Raneses, A.R., L.K. Glaser, J.M. Price, and J.A. Duffield. 1999. Potential biodiesel markets and their economic effects on the agricultural sector of the United States. *Industrial Crops and Products* 9 (1999): 151-162.

24. Schumacher, L.G. and J.H. Van Gerpen. 1996. Research needs resulting from experiences of fueling of diesel engines with Biodiesel. *Liquid Fuels and Industrial Products from Renewable Resources* (1996): 207-216.
25. Twenty five by Twenty five Group (25x'25). www.25x25.org Date accessed 27 April 2009
26. Yunusa, I.A.M. and M.A. Rashid. 2007. Productivity and rotational benefits of grass, medic pastures and faba beans in a rainfall limited environment. *Soil and Tillage Research* 97 (2007): 150-161.

Chapter 4

The Economics for the Potential of Oilseed Radish (*Raphanus sativus*) as a Cover Crop and Biodiesel Energy Crop in Georgia

---

Chammoun, N.A., J. McKissick, W. Faircloth, D. Geller, and K.C. Das. To be submitted to: The University of Georgia, Center for Agribusiness and Economic Development.

Introduction

In Georgia cover crops are primarily grown in the cool season (fall and winter) when Georgia's primary warm season (spring and summer) crops like cotton and peanuts are not being produced. Cover crops help prevent erosion from wind and water, increase soil organic matter, and aid in retaining nutrients. Cover crops are not primarily grown for sale in the market, thus they are generally grown on a low input basis, i.e. inputs such as fertilizer and pesticides are not used in great quantity in many instances. Some cool season crops, such as wheat and rye, are grown as economic crops in the cool season; yet these crops require a higher input system and some of the (cover crops) benefits are not retained since crop residues are removed from the field.

Oilseed radish (*Raphanus sativus*) is a cover crop that has been used in sugar beet production to aid in soil pest control. (Hafez, 1998) Nematodes are plant pathogens that live in the soil and cause yield losses on a wide range of crops. In a study done by Saad Hafez of The University of Idaho's Cooperative Extension, an average level of 92% in nematode population reduction was observed when oilseed radish was used in rotation with sugar beets. (Hafez, 1998) Assuming oilseed radish could yield similar results on nematode populations in Georgia when used as a cover crop, a reduction of input costs could be achieved when economic crops were grown in the warm season. Six pounds of aldicarb per acre is the recommended rate of insecticide to apply on Georgia cotton when nematode populations are problem in the field. (Baird et al., 1995) Oilseed radish appears to have the potential to save this application of pesticide when used in a rotation with cotton in Georgia. Oilseed radish has also been observed providing additional benefits of soil compaction reduction, soil aeration, weed suppression, and nitrogen trapping. (Ngouajio and Mutch, 2004, Sundermeier, 2008) A reduction in soil nitrogen leaching during the cool season has also been observed. (Justes et al., 1999) With these benefits in mind, oilseed radish is commonly referred to as a green manure crop (Hafez et al.).

The seed of the oilseed radish contains 40% oil by weight. (Eckey, 1954) A high oil value makes this crop a good candidate for biodiesel production also. Assuming a cover crop of oilseed radish could be grown and harvested as seed, leaving other crop residues in the field, could allow for added value in growing the crop in Georgia. In order to provide and estimate of the value of the co-products of oilseed radish we obtained assessments through personal communications from collaborators for three cases, cover crop, meal, and biodiesel. In the first case, viability as a Georgia cover crop was estimated by planting five plots totaling one acre were planted at the USDA National Peanut Research Laboratory in Dawson, GA in late September 2008 after peanut harvest. Excellent germination was achieved and the crop has grown well with minimal inputs. Harvest is planned for May 2009 and yield data will be recorded (personal communication with Wilson Faircloth).

In the second case, value of the meal was estimated by crushing 200 pounds of seed, and the meal analyzed for its potential as poultry feed in Georgia. A feeding trial was done by Dr. Michael Azain of the University of Georgia's Department of Animal and Dairy Science (personal communication with Dr. Michael Azain). Results from the study confirm that oilseed radish has the potential to be used as a partial replacement in poultry feed in Georgia's poultry industry. More detailed and replicated studies will be needed to establish proper diets and levels of oilseed radish meal. Assuming the results from Dr. Azain's study will be replicated, a potential value for oilseed radish meal can be calculated based on the composition of the meal. To aid in the characterization of the meal, the following tests were reported: the fatty acid profile of oilseed radish meal (Table 4.1), the plant tissue analysis (Table 4.2), the proximate analysis (Table 4.3), and the amino acid profile of oilseed radish meal (Table 4.4). The fatty acid profile provides a detailed description of the different carbon molecules that comprise the meal and oil. It is important to note the high level of erucic acid (22:1) similar to rapeseed. Also the fat content in the meal is typically higher than soybean meal (fat content of 1%) because this meal was extracted with only a screw type press, and not using solvents which would be typical in industrial uses

Table 4.1: Fatty Acid Profile of Oilseed Radish Meal.

Fatty Acid (n=3)	Percent (%)
16:0	6.13
16:1	0.05
18:0	1.68
18:1	23.87
18:2	13.46
18:3	10.34
20:0	0.68
20:1	8.58
22:0	1.64
22:1	31.76
24:0	0.61
24:1	1.26
Saturated	10.74
Monounsaturated	65.51
Polyunsaturated	23.75
Fat Content in Meal	18.48

The values in the plant tissue analysis were in the typical range for grain analysis.

Table 4.2: Plant Tissue Analysis of Oilseed Radish Meal.

Element	Average Value (n=5)
Ca	0.33%
K	1.31%
Mg	0.46%
N	5.41%
P	1.27%
S	2.35%
Al	24.32 ppm
B	8.8 ppm
Cd	< 0.4 ppm
Cr	< 1 ppm
Cu	5.72 ppm
Fe	75.65 ppm
Mn	28.28 ppm
Mo	1.72 ppm
Na	44.28 ppm
Ni	< 2 ppm
Pb	< 5 ppm
Zn	44.52 ppm

The proximate were found to vary from soybean meal. For comparison, soybean has 48-49% crude protein, 3.9% crude fiber, and 1% fat.

Table 4.3: Proximate Analysis of Oilseed Radish Meal.

Parameter	Average Value (n=5)
Moisture	7.35 %
Crude Protein	35.04 %
Fat	17.97 %
Crude Fiber	5.42 %
Ash	6.28 %

The amino acid profile is important in comparing oilseed radish to other known meals that are used for feed.

Table 4.4: Amino Acid Profile of Oilseed Radish Meal.

Amino Acid	(average n=2) W/W% g per 100 g sample
Taurine	0.03
Hydroxyproline	0.22
Aspartic Acid	2.13
Threonine	1.35
Serine	1.13
Glutamic Acid	5.43
Proline	1.99
Lanthionine	0.00
Glycine	1.78
Alanine	1.45
Cysteine	0.92
Valine	1.64
Methionine	0.62
Isoleucine	1.25
Leucine	2.23
Tyrosine	0.95
Phenylalanine	1.26
Hydroxylysine	0.04
Ornithine	0.02
Lysine	1.83
Histidine	1.00
Arginine	2.43
Tryptophan	0.39
Total	30.04

In the third case, to produce biodiesel, seeds purchased from Johnny's Select Seeds of Winslow, Maine were crushed to obtain crude oil. Oil yield was 28.8% by weight (Chammoun, 2009); the remainder was in meal. The oil was then centrifuged and degummed. The degummed oil was then successfully converted into biodiesel by transesterification. Growers of oilseed radish in the Willamette Valley of Oregon report yields ranging from 1200 pounds/acre to over 2000 pounds/acre depending on management practices. More intensely managed crops produce more seed yield. A yield of 40% oil by weight (Eckey, 1954), gives a range of 64 to 107 gallons of oil per acre (7.5 pounds per gallon). At the experimental yield of 28.8% oil, the range of oil per acre is 46 to 77 gallons. It is important to note that this oil yield will be in addition to any warm season crop that is grown in rotation with oilseed radish. In a biofuels rotation designed to maximize oil production per acre, a warm season oilseed crop could be grown, i.e. peanut or soybean and then oilseed radish grown in the cool season to supplement the amount of oil produced per acre per year.

Methodology of Economic Analysis

To evaluate economic feasibility all costs and returns must be calculated. Costs and returns are calculated on a per acre basis using a yield of 1200 pounds of oilseed radish seed production per acre. This is the low yield given by growers in the Willamette Valley of Oregon. The costs and returns calculated are not actual costs and returns, but hypothesized costs and returns based on available data. For actual costs and returns, experimental data should be acquired from growth studies. The costs and returns calculated here assume a low input situation, i.e. planting and harvesting the crop only, no other production costs considered.

Hypothesized Costs for Oilseed Radish

Seed costs consisted of $66.93 per acre with an additional cost of $15.00 per acre for planting and $36.25 per acre for harvesting the seed (Escalante, 2008). A minimum input system is used during production; therefore no additional inputs were calculated for crop production. It is assumed that oilseed radish can be planted into the previous crop's residue without any additional soil preparation. At a seed crushing cost of $50.00 per ton (CAED-CAES, 2007), oilseed radish would cost $30.00 per acre; yielding 346 pounds of oil (28.8%) and 854 pounds of meal (71.2%) per acre. At a refining and degumming cost of $0.025 per pound (CAED-CAES, 2007), it would costs $8.64 per acre to refine and degum the oil. With oil to biodiesel yield of 96% and 7.5 pounds of oil per gallon, production would be 42.5 gallons of oil per acre. With biodiesel production costs of $0.70 per gallon of oil, $30.97 per acre would be the production cost for biodiesel. Total hypothesized costs per acre sum to $187.78. These calculations assume no loss in processing oilseed radish into crude oil and biodiesel. Additional costs not included could be fertilizer required to grow the crop in Georgia, pesticides required to limit pest damage, and additional labor costs. Since hypothesized costs are simplified, actual costs may be greater than hypothesized costs.

Hypothesized Returns for Oilseed Radish

Hypothesized returns were calculated from crop and biodiesel byproducts, and from savings of insecticides that would not be applied (to subsequent crops) based on the nematode controlling capabilities of oilseed radish. A 92% reduction in nematode populations was observed in field studies (Hafez, 1998), therefore it is assumed that no additional nematode control would be needed after a crop of oilseed radish was produced. Meal protein value was calculated using the seven year average (2001-2007) Atlanta, Georgia, price for soybean meal (UGA-UT, 2009). There is currently no market for oilseed radish meal. A potential value for oilseed radish meal is calculated using the crop's crude protein value of 35%. Making the assumption that the price of soybean is composed solely of its protein content and that oilseed radish meal can be priced proportionately; a 48% protein soybean meal price of $222.27 per ton

(UGA-UT, 2009) would give a hypothesized oilseed radish meal price of $162.07 per ton. At the yield of 1200 pounds per acre of oilseed radish, $69.24 per acre is the hypothesized value of the meal. With a five year average price of $3.27 for biodiesel (Shumaker), potential biodiesel returns would be $138.87 per acre. A five year average crude glycerin price of $0.07 per pound and a yield of 10.59% glycerin (Shumaker, CAED-CAES, 2007), glycerin value per acre would be $2.46. A hypothesized savings of $18.24 per acre and $15.20 per acre would be saved on insecticide (aldicarb) and insecticide application costs, respectively. An application rate of 6 pounds of aldicarb per acre was used for nematode control based on the recommendation of the University of Georgia Extension Plant Pathologist cotton budget for soil pathogen control (Baird et al., 1995). A total return of $244.00 per acre leaves the overall system with a hypothesized net return of $56.22 per acre. With a net biodiesel value of $107.90 per acre and an oil yield of 346 pounds per acre, an implied oil value of $0.31 per pound can be obtained. The implied value is the price that can be paid to the producer for crude oilseed radish oil so that a breakeven point can be achieved in biodiesel production. This value is not so important since there is currently no market for oilseed radish oil, but it is provided as a means to compare with other vegetable oil prices. Additional returns that were not included, but may add value to the system, could be weed suppression, soil aeration, soil compaction reduction, and nitrogen trapping (Ngouajio and Mutch, 2004, Sundermeier, 2008). In an actual costing situation, these benefits would need to be assigned an economic value and that value assessed. These values are important, but detailed studies are needed to quantify them. Since these benefits are not included, hypothesized returns calculated may be lower than actual returns.

Table 4.5: Hypothesized Costs and Returns for Oilseed Radish at 1200 lbs/acre yield and Low Input Growing System

Hypothesized Costs				
Activity/Product	Unit	Number of Units	Price per Unit ($)	Price per Acre ($)
Seed	Pound	50	133.85	66.93
Planting	Acre	1	15	15
Harvest	Acre	1	36.25	36.25
Seed Crushing	Ton	0.6	50	30
Refining/Degumming	Pound	346	0.025	8.64
Biodiesel Production	Gallon	42.5	0.7	30.97
Total Hypothesized Costs				187.78
Hypothesized Returns				
Meal	Ton	0.427	162.07	69.24
Biodiesel	Gallon	42.5	3.27	138.87
Glycerin	Pound	35.1	0.07	2.46
Aldicarb	Pound	6	3.04	18.24
Aldicarb Application	Acre	1	15.2	15.2
Total Hypothesized Returns				244.00
Total Hypothesized System Value				56.22

Sensitivity Analysis

Sensitivity analyses were done on seed costs, biodiesel price, meal price, total costs, and total returns. It is believed that lower seed costs would be available to growers once markets for oilseed radish were established. By subtracting a total hypothesized cost per acre without seed of $120.86 from total hypothesized returns of $244.00, a minimum breakeven seed cost of $123.14 per acre, or $4.93 per pound of seed, would be needed to return adequate money to pay for all costs. A seed sensitivity graph is obtained from the break even seed cost and the hypothesized seed cost per acre.

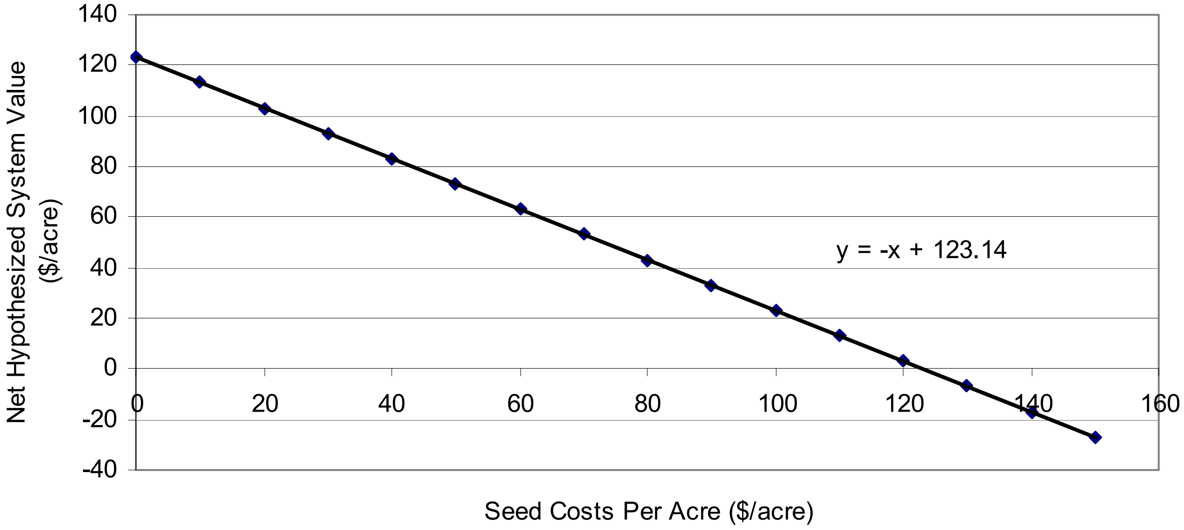

Figure 4.1: Sensitivity of Net Hypothesized System Value to Seed Costs Variation when Planting 25 lbs/acre.

Fuel prices change on a daily basis. For this reason it is necessary to calculate a hypothesized break even price for biodiesel. A hypothesized break even price for biodiesel can be obtained by subtracting hypothesized returns without biodiesel ($105.14) from total hypothesized costs ($187.78) and dividing by biodiesel production per acre (42.5 gallons). The hypothesized break even price for biodiesel would be $1.94 per gallon. This means the biodiesel price could decrease below the $3.27 level (but above $1.94), and net hypothesized returns would remain positive.

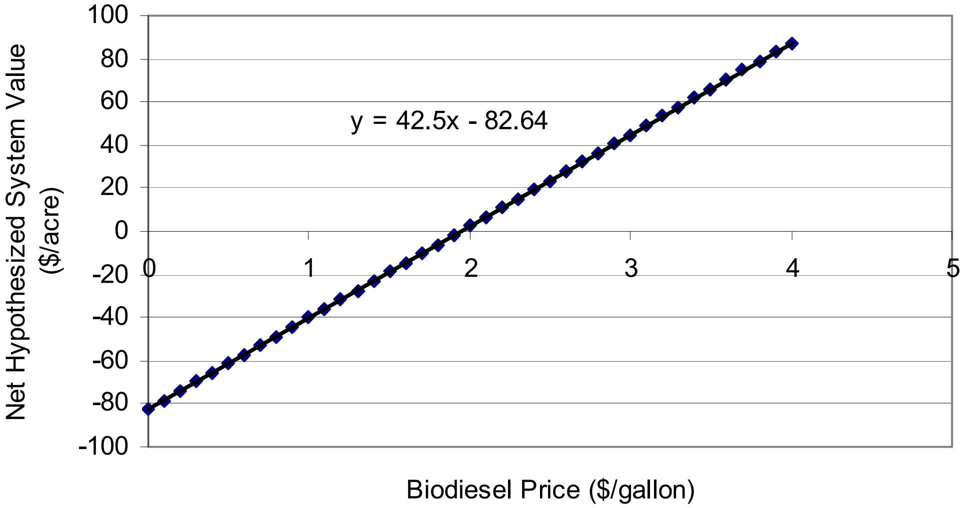

Figure 4.2: Sensitivity of Total Hypothesized System Value to Biodiesel Price Variation

Soybean meal prices change on a daily basis, and it is assumed that the hypothesized meal price for oilseed radish could change regularly as well. Because of this possibility it is important to calculate a hypothesized break even price for oilseed radish meal. The hypothesized break even price for the meal is calculated by subtracting total hypothesized returns without the meal ($174.77) from total hypothesized costs ($187.78) and dividing it by the amount of oilseed radish meal per acre (0.4272 tons). The hypothesized break even meal price for oilseed radish is $30.45 per ton.

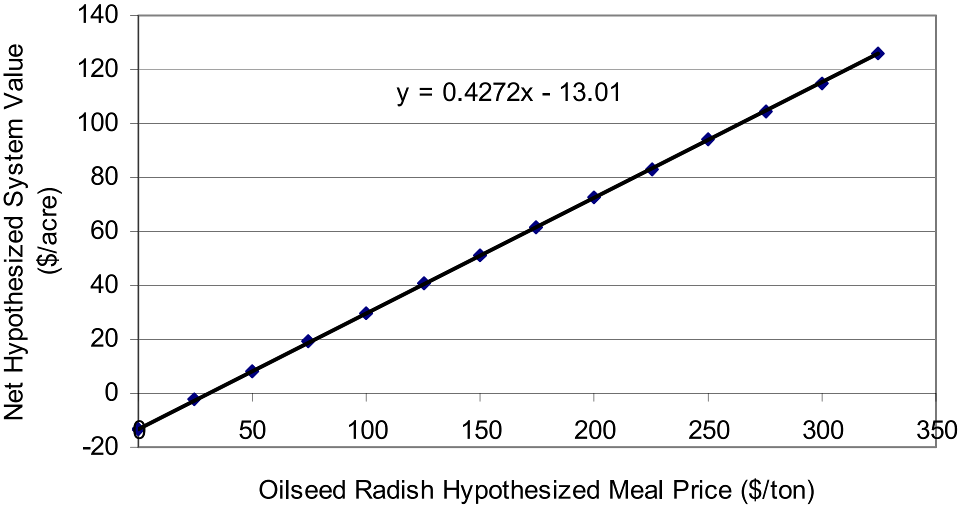

Figure 4.3: Sensitivity of Total Hypothesized System Value to Meal Price Variation

Since many assumptions were made for this analysis it is possible that additional costs would be needed to produce the crop, or that additional returns could be generated from the crop. For this reason, a range of 20% was used to evaluate costs and returns if each were 20% higher or 20% lower. If hypothesized costs were 20% higher, hypothesized returns would be adequate to cover hypothesized costs (Table 4.6). If hypothesized returns were 20% lower, hypothesized costs would not exceed the lowered hypothesized returns (Table 4.7). In fact, hypothesized costs would need to increase by approximately 30% to reach a breakeven point. In the same way, hypothesized returns would need to decrease by 23% to reach a breakeven point.

Table 4.6: (+-) 20% Variation in Hypothesized Costs

Variation (%)	Returns ($)	Costs ($)	Net ($)
-20	244.00	150.22	93.78
-10	244.00	169.00	75.00
0	244.00	187.78	56.22
10	244.00	206.56	37.44
20	244.00	225.34	18.66

Table 4.7: (+-) 20% Variation in Hypothesized Returns

Variation (%)	Returns ($)	Costs ($)	Net ($)
-20	195.20	187.78	7.42
-10	219.60	187.78	31.82
0	244.00	187.78	56.22
10	268.41	187.78	80.63
20	292.81	187.78	105.03

Conclusions

With a hypothesized net return of $56.22 per acre, oilseed radish demonstrates potential to be a viable crop in Georgia, based on the assumptions made. An implied oilseed radish oil value based on biodiesel production of $0.31 per pound was hypothesized, and a hypothesized meal value was determined to be $69.24 per acre. A total hypothesized savings of $33.45 per acre could also be obtained when growing the next economic crop in rotation with oilseed radish if nematode populations were harmful.

A hypothesized break even cost for seed was determined to be $123.14 per acre which is above the hypothesized seed cost of $66.93 per acre. This difference in hypothesized value demonstrates that hypothesized seed costs could increase by approximately 84%, and a break even point still achieved. It is believed that seed costs would actually decrease after one year of growth. Seed could be saved by the producer to supplements seed for next year's crop. It is also believed that once more growers produce oilseed radish as a crop, the seed costs will decrease. The hypothesized break even biodiesel price was calculated to be $1.94 per gallon. The hypothesized break even biodiesel price is approximately 41% below the five year average price of $3.27 per gallon. The hypothesized breakeven price is useful to compare with current fuel prices to judge on the potential for oilseed radish biodiesel to be competitive in the biodiesel market. The hypothesized break even price for oilseed radish meal was calculated to be $30.45

per ton. This is below the hypothesized meal value of $162.07 per ton that is based on protein content. The large gap between the two prices demonstrates that the hypothesized meal price ($162.07 per ton) could decrease by 81% and hypothesized returns would still exceed costs.

Due to the limitations of the hypothesized calculations, a 20% variation in hypothesized costs and returns was calculated. If there was a 20% increase in hypothesized costs, and no increase in returns, hypothesized returns would still be greater than hypothesized costs. If there was a 20% decrease in hypothesized returns, and no decrease in costs, hypothesized returns would still exceed hypothesized costs. This indicates improved potential for oilseed radish to succeed as a crop in Georgia. Even with a decrease in hypothesized system value, oilseed radish remains an attractive crop due to the un-valued benefits the crop can provide. Although values for soil aeration, soil compaction reduction, weed suppression, and nitrogen trapping may not be high, there is still added value in each of these benefits when oilseed radish is used in a crop rotation.

Meal calculations were done based solely on protein content. Oilseed radish meal also had high fat value, giving it a high energy value. The high fat value is due to the cold crush extraction method used, and no additional solvent extraction. The high fat content would increase the value of oilseed radish meal, and therefore increase the total hypothesized value of the system. More detailed studies are needed to allow for a more accurate method of evaluating the potential value of oilseed radish meal. Agronomic benefits should be evaluated with field studies done in Georgia to confirm nematode control levels, weed suppression levels, nitrogen trapping, soil aeration, and soil compaction reduction levels. Quantifying these additional benefits in Georgia soils, would allow for an economic evaluation to be done and a hypothesized value to be assigned, increasing the accuracy of the economic evaluation and adding value to the system.

Hypothesized costs and returns are limited by the assumptions used to calculate them. These assumptions were made in the absence of specific data for oilseed radish in Georgia. Oilseed radish is a new crop to Georgia; therefore no data was available for calculations. Assumptions were made based on data from other parts of the United States. Future studies are needed to gather data on oilseed radish in Georgia. The hypothesized system value shows potential for oilseed radish to succeed as a cover crop and biodiesel energy crop in Georgia. More importantly, crops such as oilseed radish should be considered in future crop rotations for their agronomic benefits and potential energy value. It is believed that energy crops with agronomic benefits will lead to more sustainable biofuel production, increased producer returns, and improved environmental health.

References

1. Agricultural Experiment Station Chemical Laboratories (ESCL). University of Missouri-Columbia. College of Agriculture, Food, and Natural Resources. (http://www.aescl.missouri.edu/AminoAcids.html) Date accessed 27 April 2009
2. Azain, M. The University of Georgia, Department of Animal and Dairy Science. Personal communication on 27 January 2009.
3. Baird, R.E., Davis, R. L., and Mueller, J.D. 1995. Georgia Cotton Nematode and Management Considerations. *The University of Georgia College of Agricultural and Environmental Sciences.* Bulletin July 1995.

(http://plantpath.caes.uga.edu/extension/plants/fieldcrops/CottonNematode.html) Date accessed 27 April 2009

4. CAED-CAES. 2007. Economics of Peanuts for Biodiesel Production. Center Report No. CR-07-04. Athens, GA.: Center for Agribusiness and Economic Development, College of Agricultural and Environmental Sciences, University of Georgia.
5. Cavigelli, M.A., Martin, T.E., and Mutch, D.R. 2008. Michigan Cover Crop Species: Oilseed Radish. *Michigan State University Extension.* (www.covercrops.msu.edu.species/radish.html) Date accessed 27 April 2009
6. Chammoun, N.A. 2009. Properties, Performance, and Economics of *Raphanus sativus* (Oilseed Radish) Biodiesel. MS Thesis. Athens, GA.: The University of Georgia, Department of Biological and Agricultural Engineering.
7. Eckey, E.W. 1954. *Vegetable Oils and Fats.* New York, New York: Reinhold Publishing Corporation.
8. Escalante, C.L. 2008. Custom Farm Machinery Rates in Georgia, 2008. The University of Georgia Cooperative Extension, AGECON-08-003. August 2008.
9. Faircloth, Wilson. The United States Department of Agriculture, National Peanut Research Laboratory, Dawson, Georgia. Personal communication on 3 April 2009.
10. Feed and Environmental Water Lab (FEW). The University of Georgia, Athens, GA 30602. (http://aesl.ces.uga.edu) Date accessed 27 April 2009
11. Hafez, S.L. 1998. Management of Sugar Beet Nematode. *University of Idaho College of Agriculture Cooperative Extension System: Agricultural Experiment Station,* CIS 1071.

12. Hafez, S.L., Thornton, M., Barton, D., Finnigan, B., Harding, G., and Seyedbagheri, M. (www.uidaho.edu/sugarbeet/mntds/oilseed.htm) Date accessed 27 April 2009
13. Justes, E., Bruno, M., and Nicolardot, B. 1999. Comparing the effectiveness of radish cover crop, oilseed rape volunteers and oilseed rape residues incorporation for reducing nitrate leaching. *Nutrient Cycling in Agroecosystems* 55 (1999): 207-220.
14. Ngouajio, M. and Mutch, D.R. 2004. Oilseed Radish: A New Cover Crop for Michigan. *Michigan State University Extension Bulletin* E 2907.
15. Park, P.W. and Goins, R.E. 1994. In situ preparation of fatty acid methyl esters for analysis of fatty acid composition in foods. Journal of Food Science, 59:1262-1266.
16. Shumaker, G. University of Georgia, Center for Agribusiness and Economic Development. Personal communication on 27 April 2009
17. Soil, Plant, and Water Testing Laboratory (SPW). The University of Georgia, Athens, GA 30602. (http://aesl.ces.uga.edu) Date accessed 27 April 2009
18. Sundermeier, A. 2008. Oilseed Radish Cover Crop. *The Ohio State University Extension: Fact Sheet Agriculture and Natural Resources* SAG-5-08.
19. The University of Georgia Cooperative Extension and The University of Tennessee Cooperative Extension (UGA-UT). "Price Risk Management for Purchased Feed Users" Notebook. 2009.

Chapter 5

Conclusions

The cool season crop used for this thesis was oilseed radish (*Raphanus* sativa). Oilseed radish was crushed and the oil was successfully transesterified into biodiesel the performed the same as No. 2 diesel (D2) in engine testing. Previously unknown fuel properties of oilseed radish biodiesel are reported, along with fatty acid and amino acid profiles of the oil. The cold flow analysis yielded little in significant results. The economic analysis shows potential for oilseed radish to produce profit when grown in a Georgia crop rotation to aid in the reduction of nematode populations. The meal from oilseed radish can be successfully fed to chickens up to a 20% level, and a market value for oilseed radish meal is estimated. An implied oil value based on biodiesel production is also assigned to the oil, since no markets currently exist for oilseed radish oil or meal. Overall, this thesis has attempted to investigate the possibility of oilseed radish as a cover crop and energy crop in Georgia. The results from this thesis demonstrate the need for future research on this crop, its fuel, and its byproducts.