Fuel efficiency and exhaust emissions for biodiesel blends in an agricultural tractor

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Li, Y.X., McLaughlin, N.B., Patterson, B.S. and Burtt, S.D. 2006. **Fuel efficiency and exhaust emissions for biodiesel blends in an agricultural tractor**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 2.15 - 2.22. Increased interest in reducing reliance on petroleum, reducing GHG emissions, and improving air quality has led to many investigations on biodiesel as an alternative renewable fuel. Although biodiesel is derived from agricultural production, little is known about the use of biodiesel with farm machinery. The objective of this study was to compare fuel efficiency and exhaust gas emissions among different biodiesel blends for different field operations in agricultural crop production. Field experiments were conducted for spring tillage and soybean planting a 12 hectare field using four different blends of biodiesel derived from soybean oil (B100, B50, B20, and diesel). An instrumented tractor equipped with a set of sensors and a data logger to monitor and record implement draft, fuel consumption, and other tractor operational parameters was used for field work in the experiment. Auxiliary fuel tanks and a system of valves were installed on the tractor to allow switching among premixed blends of biodiesel during the field experiments. An instrumented exhaust stack was installed on the tractor for measurement of exhaust gas temperature, mass flow, and NOx (nitrogen oxides) emissions. Results showed that B20 had very similar performance to diesel in terms of fuel consumption, fuel efficiency, and NOx emission. Due to the lower energy content of the biodiesel, higher fuel consumption and lower fuel efficiency were observed for B50 and B100 blends. NOx emissions were higher with blends with higher biodiesel content. CO_2 emissions estimated from life cycle analysis were substantially lower for blends with higher biodiesel contents. The tractor was overpowered for the three-meter wide grain drill and this mismatch between the tractor and implement resulted in lower fuel efficiency compared with the tillage implement with a near optimal tractor-implement match. **Keywords:** biodiesel, exhaust emission, crop production.

L'intérêt croissant entourant la réduction à la dépendance pétrolière, la réduction des émissions de gaz à effet de serre et l'amélioration de la qualité de l'air a mené à plusieurs projets de recherche sur le biodiesel en tant que combustible alternatif et renouvelable. Même si les biodiesels originent de la production agricole, peu d'information est disponible quant à leur utilisation dans les équipements agricoles. Les objectifs de cette étude étaient de comparer l'efficacité énergétique de même que les émissions de gaz d'échappement de différents mélanges de biodiesels pour différentes opérations culturales. Les essais ont été réalisés sur un champ de 12 hectares pour les opérations de travail du sol secondaire et de semis pour une culture de soya en utilisant quatre mélanges différents de biodiesels dérivés d'huile de soya, B100, B50, B20 et diesel. Un tracteur instrumenté équipé de senseurs et d'un système d'acquisition de données pour la mesure et l'enregistrement de l'effort de tirage de l'équipement ainsi que de la consommation en carburant et d'autres paramètres opérationnels du tracteur a été utilisé pour compléter ces deux opérations. Des réservoirs de carburant auxiliaires et un système de soupapes ont été installés sur le tracteur pour permettre de changer les différents mélanges de carburants durant les expériences au champ. Un tuyau d'échappement instrumenté a été installé sur le tracteur pour mesurer la température des gaz d'échappement, le débit massique ainsi que les émissions de NOx (oxides d'azote). Les résultats ont montré que B20 avait une performance très similaire au diesel au niveau de la consommation de carburant, de l'efficacité énergétique et des émissions de NOx. À cause du niveau d'énergie plus bas du biodiesel, une consommation plus élevée et une efficacité énergétique plus faible ont été observées pour les mélanges B50 et B100. Les émissions de NOx étaient plus élevées avec des mélanges ayant un contenu en biodiésel plus grand. Les émissions de CO_2 estimées par l'analyse de cycle de vie étaient substentiellement plus faibles pour les mélanges avec un contenu en biodiesel plus élevé. Le tracteur était trop puissant pour le semoir de trois mètres de large et ce mauvais agencement entre le tracteur et l'équipement a résulté en une efficacité énergétique plus faible comparativement à l'équipement de travail du sol qui présentait un jumelage tracteur – équipement presqu'optimal. **Mots clés**: biodiesel, émissions de gaz d'échappement, opération culturale

INTRODUCTION

Biodiesel is an alternative fuel for diesel engines made from plant oils, waste restaurant grease, or rendered animal fats. As it is derived from plants, either directly from plant oils or indirectly from animal fats or waste restaurant grease, it is a truly renewable energy source. Use of raw vegetable oils for diesel engines can cause numerous engine-related problems such as plugged fuel filters, deposits on injectors, stuck piston rings, and fuel system failure (Goodrum et al. 1996; Canakci and Van Gerpen 1999). The negative effects of raw vegetable oil can be reduced or eliminated through transesterification, which is a process of using methyl alcohol in the presence of a catalyst to break the oil molecule into methyl esters and glycerol (Peterson and Reece 1996; Canakci and Van Gerpen 2001). The glycerol is then separated and the remaining methyl esters are normally called biodiesel which has a lower viscosity than the original raw vegetable oil and is close to that of petroleum diesel fuel (Canakci and Van Gerpen 2001).

Statistical regression analysis of data from the numerous research reports and test programs showed that as the percent of biodiesel in blends increases, emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) all decrease, but the amount of oxides of nitrogen (NOx) increases (EPA 2002). B20 (20% volume biodiesel and 80% volume petroleum diesel), one of the most common biodiesel blends, decreases emission constituents of HC, CO, and PM by 21.1, 11.0, and 10.1% respectively, and increases NOx by 2.0%. When 100% biodiesel is compared with petroleum diesel, there is a 67% decrease in HC, 48% decrease in CO and PM, and 10% increase in NOx (EPA 2002).

Human activities lead to emissions of greenhouse gases (GHGs) which are a contributing factor to global climate change. For diesel engines studied to date, tailpipe emissions of nitrous oxide (N_2O) and methane (CH_4), which are potent greenhouse gases, were negligible and therefore CO_2 is typically the only GHG emission considered. Burning biodiesel also produces CO_2, but in a full production-to-consumption system, plants recycle CO_2 to grow and produce more vegetable oils required as feedstock for biodiesel production. Therefore, much of the CO_2 production in biodiesel combustion is considered to be offset by CO_2 uptake by plants in the process of photosynthesis (Peterson et al. 2002). Life cycle analysis showed that biodiesel blends reduced net CO_2 in proportion to the percentage of biodiesel used in the blends.

Most research on biodiesel use and exhaust emissions to date has been conducted in laboratories using dynamometers to apply a constant load and speed or to simulate real operation by applying a predetermined load cycle. Most test engines were heavy-duty highway engines, but little or no attention was given to off-road engines, especially in real-time in-situ conditions (EPA 2002). For example, the Environmental Technology Centre, Environment Canada, Ottawa, Ontario investigated the potential exhaust emission reductions through the use of biodiesel in a diesel 1998 Dodge Ram 2500 4X4 pickup truck (Rideout and Howes 1998). The experiment was conducted in the lab to test exhaust emissions with different biodiesel blends in different driving cycles. The results of the tests indicated that the use of biodiesel had little impact on the exhaust emission rates of NOx, while CO and HC were reduced. Recently completed projects with city buses and tour boats in Montreal, Quebec have shown the benefits of biodiesel in public transit and marine applications (BIOBUS 2003; BioMer 2005).

National inventories of exhaust emissions from agricultural machines are normally estimated from total farm fuel sales data or estimated field work for national crop production (Dyer and Desjardins 2003). Both of these approaches require application of standard emission factors that are often derived from laboratory dynamometer tests at constant engine load. Agricultural tractors have a unique duty cycle for each field operation in a crop production system. The duty cycle for field operations varies with the type of field equipment, field conditions including topography and soil texture, and operator habits including traffic patterns and tillage management which contribute to soil compaction, gear and engine speed selection, traveling to and from fields, turning at the end of a field, and idling when making machinery adjustments. The management factor varies considerably among farms and operators. Estimated emissions based on factors derived from a constant engine load cannot account for the variability in field operations because exhaust gas emissions vary according to engine loads (Peterson and Reece 1996).

Although biodiesel is derived from agricultural production and many of the studies on its use have been conducted by agricultural engineers, there is virtually no documentation on exhaust emissions from either petroleum or biodiesel fuel use in agricultural applications (EPA 2002; McLaughlin and Layer 2003). The objective of this study was to evaluate and compare fuel efficiency and exhaust emissions from different biodiesel blends under typical field operations using an instrumented research tractor and field scale implements.

MATERIALS and METHODS

Agricultural tractor and instrumentation

An instrumented research tractor was used to pull field scale tillage and seeding equipment for the experiment. The tractor was fitted with instrumentation and an on-board data logging system to facilitate measurement and recording of tractor operational parameters as the tractor carried out normal field work (McLaughlin et al. 1993). Current instrumentation facilitates very accurate real time measurements of engine speed, implement draft, fuel consumption, and exhaust gas emissions. The tractor was recently fitted with auxiliary fuel tanks and valves to allow switching among the different premixed biodiesel blends.

Exhaust gas instrumentation

Instrumentation was installed in a modified tractor exhaust stack for measurement of exhaust temperature, mass flow, NOx concentration, and air/fuel ratio. An averaging pitot tube (Diamond II Annubar, Rosemont, Inc., Chanhassen, MN) was installed near the top of the exhaust stack to measure mass flow rate. This device has four stagnation ports at strategic positions across the diameter of the stack to obtain an average of the non-uniform velocity profile across the stack diameter. Differential pressure from the averaging pitot tube was measured with a 0-5 kPa industrial differential pressure transmitter (Model 3051, Rosemount, Inc. Chanhassen, MN). The 4-20 ma current from the pressure transmitter was converted to a voltage signal and logged by the tractor data logger. Exhaust gas temperature was measured with a high temperature RTD probe located about 50 mm downstream from the averaging pitot tube. Exhaust mass flow rate was calculated from temperature and differential pressure data using the formula supplied by the manufacturer.

NOx analyzer

A zirconia non-sampling NOx sensor and associated signal conditioning (MEXA-120NOx, Horiba, Engine Measurements Division, Ann Arbor, MI) was used for measurement of NOx concentration in the exhaust gas. The sensor was installed in a port at the lower end of the exhaust stack and protruded into the exhaust stream. The zirconia sensor provides high-speed response (< 0.7 second). The NOx sensor and signal conditioner were calibrated by installing the sensor in a special calibration fixture supplied by the NOx system manufacturer and passing calibration gases with concentrations of 0, 600, 1400, and 2500 ppm nitric oxide (NO) in nitrogen. Exhaust gas NOx concentrations in parts per million (ppm) were first corrected for ambient humidity and then converted to mass flow using the exhaust mass flow data.

Biodiesel blends

Different blends of petroleum and biodiesel derived from soybeans were premixed by volume and stored in separate auxiliary fuel tanks mounted on the tractor. Pure petroleum

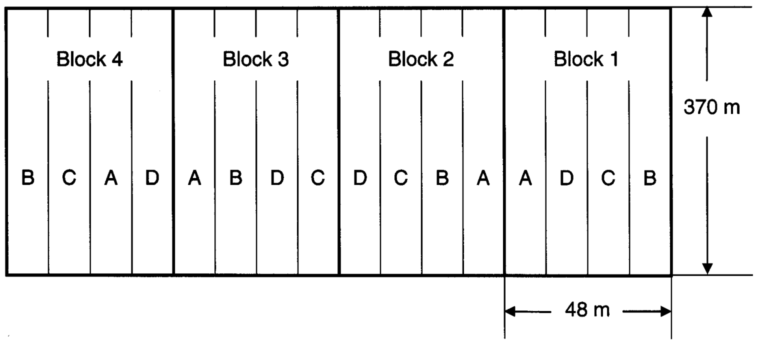

Fig. 1. Field plan for strip plots with four biodiesel blends: A-B100, B-B50, C-B20, D-100% petroleum diesel.

diesel and three biodiesel blends were used: 100% diesel (D), 80% diesel with 20% biodiesel (B20), 50% diesel with 50% biodiesel (B50) and 100% biodiesel (B100). Petroleum diesel, B20, and B100 were analyzed by the Alberta Research Council (Edmonton, AB), a certified fuel test lab.

Site description

The experiments were conducted in a field at the Animal Disease Research Institute, Ottawa, Ontario (45° 19′ N, 75° 47′ W) during spring tillage and soybean planting. The site was planted for cash crops for the past ten years and was planted in strips of corn and sorghum during the year prior to this field study. Fall tillage in November, 2003 was with a disc ripper. Soil texture varied across the field with more clay in the south-west corner, and more sand in the northeast corner. The field was divided into four blocks or replicates, each about 370 m long by 48 m wide. The detailed field experimental plan is given in Fig. 1. Soil moisture in the top 150 mm was measured on the same day as tillage operation using a TDR soil moisture meter.

Experimental procedure

Spring tillage was done with a single pass using a 6.0-m wide John Deere mulch finisher at approximately 6 km/h speed and 150 mm depth. The tractor no-load engine speed was carefully set to 2200 rpm with the tractor sitting on the headland; the engine speed was not adjusted while in the plot area. The tractor was brought up to speed, the implement lowered, and the data logger started while the tractor was moving with the implement in the ground. The tractor's 7th gear (engine to rear axle speed ratio = 105:1) was used for all passes with the tillage implement. Data were logged at a scan rate of 100 Hz for the entire run of approximately 370 m (the field was an irregular shape and therefore the length of the runs varied slightly among the passes). A separate data file of approximately 20,000 records was recorded during the approximately 200 seconds required for each 370-m pass. After one pass in each of the four blocks, the implement was unhitched from the tractor and a "zero" data file was logged with no load on the tractor hitch. These zero files were used to correct draft data for minor instrument drift.

Two adjacent passes were made with the mulch finisher in each block. The fuel source was then switched to another auxiliary tank with a different biodiesel blend by manipulating the selector valves. After switching the fuel source, the fuel lines between the fuel tank and measurement system were purged by running a few litres into a waste bucket. The tractor engine was then run at high idle for about 10 minutes to purge the fuel filters with the new blend. A total of eight passes, two passes for each of the four biodiesel blends, was made with the 6.0-m wide mulch finisher in each 48-m wide block.

The same experimental procedure was followed for seeding with the 3.0-m wide grain drill. However, as the grain drill was only half of the width of the 6.0-m wide tillage implement, a total of 16 passes, four for each of the four fuels, was made in each 48-m wide block. Since the tractor was mismatched between engine power and the small grain drill, a higher gear ratio (9th, 79.4:1 engine to rear axle speed ratio) and lower no-load engine speed (2000 rpm) were used.

CO_2 calculation

CO_2 was not measured in this study, but was calculated based on fuel consumption and life cycle analysis developed by National Renewable Energy Laboratory (1998). Tailpipe emissions of CO_2 from biodiesel are largely biogenic and can therefore be omitted from net CO_2 emissions inventories. However, pre-combustion emissions of CO_2 associated with biodiesel production are significant and have been estimated for different feedstock sources and methods of biodiesel processing. The net CO_2 emission factors used for biodiesel blends in this study were a 15.6, 39.2, and 78.5% reduction in emissions for B20, B50, and B100, respectively, when compared with CO_2 emission from petroleum diesel (National Renewable Energy Laboratory 1998).

Data analysis

Data from draft, engine speed, fuel consumption, etc. were extracted from the raw data files and converted to engineering units using custom software developed for the purpose. Arithmetic averages were calculated for time intervals varying from 0.1 s to an entire pass of approximately 200 s. The extracted draft data were corrected for instrument drift by subtracting apparent draft in the zero files recorded with no load on the tractor hitch.

Exhaust mass flow rate was calculated from the averaging pitot tube differential pressure and exhaust gas temperature. NOx concentration was corrected for ambient temperature and humidity using archived data obtained from an automated weather station at the Central Experimental Farm in Ottawa, about 10 km from the field site. Land area tilled or seeded was calculated from implement width and true distance traveled obtained from GPS position data logged by the tractor data logger. NOx and fuel consumption data were converted to a per hectare basis. All of the data conversions and statistical analysis were done with SAS version 8.

RESULTS and DISCUSSION

Laboratory test results for the petroleum diesel, B20, and B100 are given in Table 1. It can be seen clearly that B100 had very low sulfur content compared with petroleum diesel. The negligible level of sulfur in biodiesel can reduce emissions of sulfur dioxide (SO_2) which is a significant contributor to acid rain. This is in general agreement with biodiesel studies from the literature (Schumacher et al. 2001a; Dorado et al. 2002; Peterson et al. 1999, 2000). New regulations for ultra low sulfur

Table 1. Fuel properties for diesel, B20, and B100.

	Diesel	B20	B100	Method
Carbon (mass %)	86.78	84.50	77.22	ASTM D5291 (ASTM 2002a)
Hydrogen (mass %)	13.16	12.94	11.92	ASTM D5291 (ASTM 2002a)
Oxygen (mass %)	0.89	2.80	11.38	ASTM D5291 (ASTM 2002a)
Cetane number	48.3	55.7	61.6	ASTM D613 (ASTM 2005a)
Density (kg/m^3 at 15°C)	842.6	851.6	887.2	ASTM D4052 (ASTM 2002b)
Energy content (MJ/kg)	45.562	44.332	39.719	ASTM D4809 (ASTM 2005b)
Energy content(MJ/L)	38.391	37.753	35.238	Calculated
Total sulfur (ppm)	397	--	15	ASTM D5453 (ASTM 2005c)
Kinematic viscosity (mm^2/s)	2.419	2.768	4.296	ASTM D445 (ASTM 2004)

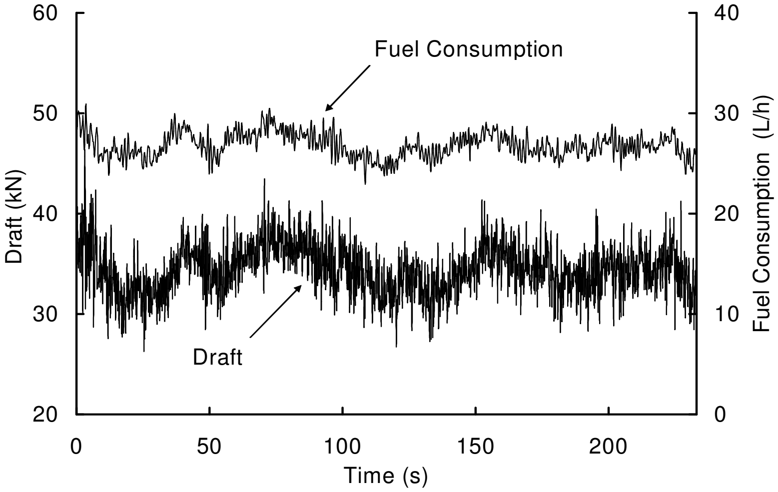

Fig. 2. **Real-time measurement of draft and fuel consumption with B20 under tillage operation.**

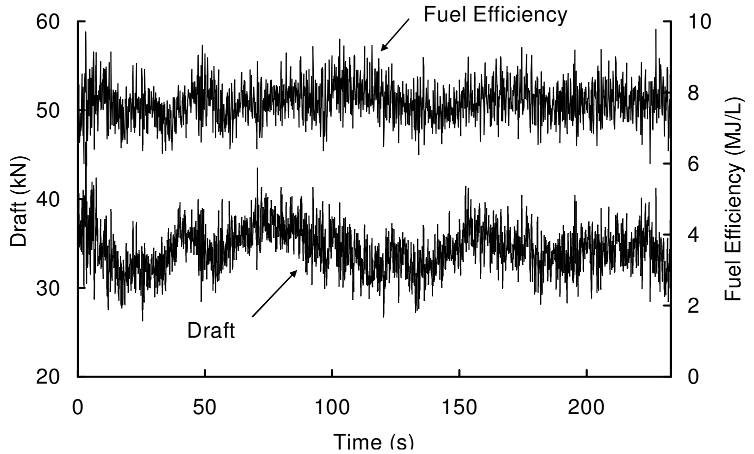

Fig. 3. **Real-time measurement of draft and fuel efficiency with B20 under tillage operation.**

(ULS) diesel with maximum 15 ppm sulfur will also reduce SO_2 emissions, but low sulfur petroleum diesels are "dry" and require additives to improve lubricity. Biodiesel has superb lubricity properties and may have application as an additive to improve lubricity of petroleum diesel fuel (BIOBUS 2003). Sulfur content of B20 was not determined, but since B20 contained 20% biodiesel and 80% petroleum diesel, the sulfur content of the blend could be calculated from that of B100 and petroleum diesel.

B100 contained 12.8% less energy by mass than petroleum diesel and the density of B100 was approximately 5% higher than petroleum diesel (Table 1). Engine fuel efficiency can be expressed on a volumetric basis (MJ/L) or a mass basis (MJ/kg). It is important that the same basis be used for expressing energy content and fuel efficiency When expressed on a volumetric basis, the energy content of B100 was 8.2% less than the same volume of petroleum diesel. Lower energy content was also found by Dorado et al. (2002). This lower energy content could lead to increased fuel consumption.

Real-time measurements

Real-time measurements of draft, fuel consumption, fuel efficiency, and NOx emissions for one pass of the tillage implement with B20 fuel are given in Figs. 2, 3, 4, and 5. The trends depicted in these figures are typical and graphs for other passes with both the tillage implement and grain drill and for other fuels show similar trends. The graphs in Figs. 2, 3, 4, and 5 are based on 0.1 s averages.

The relationship between draft and fuel consumption is given in Fig. 2 and shows significant high frequency "chatter" for both draft and fuel consumption. This high frequency component is normal for field operations and is assumed to result from surface roughness of the field which results in tractor and implement bounce and varying implement operating depth and brittle failure of consolidated soil. Experience has shown that less consolidated sandy soils exhibit much smoother signals. General trends from the low frequency component of the graphs are readily apparent and are due to spatial variability in soil physical parameters. As expected, fuel consumption tracked draft very well, with higher draft requiring more fuel.

Fuel efficiency was expressed in megajoules of drawbar energy per litre of fuel (MJ/L) and plotted against time (Fig. 3). When expressed in this manner, fuel efficiency is the combined engine, transmission, and tractive efficiency of the tractor, and is a measure of the net energy per unit of fuel available at the tractor drawbar to do field work. Compared to fuel consumption, fuel efficiency is relatively independent of draft within the normal operating range for the tillage implement (Figs. 2 and 3).

NOx emissions tracked draft very well, with higher emissions from the engine resulting from greater draft and corresponding higher engine load (Fig. 4). The higher NOx emissions are assumed to result from a combination of higher fuel consumption and higher engine temperatures at higher draft values. These results indicate that reducing draft through best

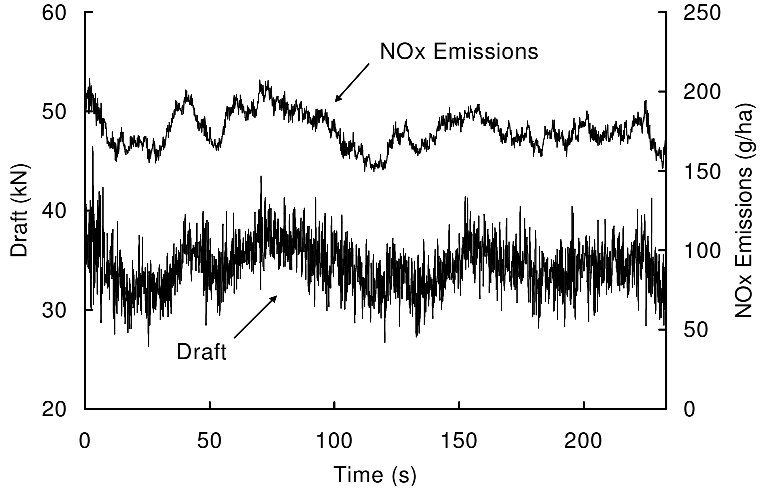

Fig. 4. **Real-time measurement of draft and NOx emission with B20 under tillage operation**

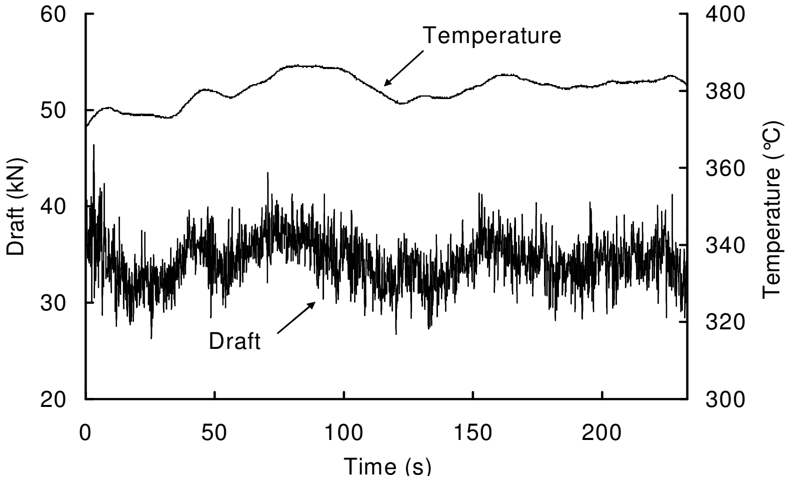

Fig. 5. **Real-time measurement of draft and exhaust temperature with B20 under tillage operation**.

management systems such as reduced tillage or zero tillage could reduce both fuel consumption and NOx emissions in a crop production system.

Exhaust temperature tracked draft very well, but the temperature was initially low and temperature transients lagged transients in draft (Fig. 5). Similar results were found in the study of the City of Houston Diesel Field Demonstration Project by Environment Canada for heavy duty highway engines (Howes 2002). This result was expected because the temperature of the engine was initially low when idling in the headlands, and due to the thermal mass of the engine it takes some time for the exhaust temperature to increase after a sharp increase in draft and engine load. Exhaust temperature has been used as an indirect measure of fuel consumption and engine power, but the method is hampered by the response time of the exhaust temperature (Pascal and Sharp 1984; Pang et al. 1985).

Mean draft

Means for draft under both tillage and grain drill operations for each of the three biodiesel blends and petroleum diesel are given in Tables 2 and 3. The fuel type should not affect the draft since draft is affected only by the implement type (tillage or drill), width, speed, and corresponding soil-implement interactions. However, even in adjacent passes, some variability in mean draft is expected due to normal variability of field conditions such as soil texture, land topography, and historical tillage practices which can result in localized compacted areas. There was considerable variability in soil texture over the field site with a higher sand content in the northeast corner of the field and higher clay content in the southwest corner. The experimental design with the long strip plots and side by side passes for the different biodiesel blends duplicate for each blend the inherent spatial variability in soil texture to the extent possible in field scale agricultural operations (Fig. 1).

Draft for the 3.0-m wide double disk grain drill was approximately one-tenth of that for the 6.0-m wide tillage implement. This was expected since the tillage implement was running much deeper and was twice the width of the grain drill. The tractor was overpowered for grain drill operation, which is a common scenario on smaller family farms. Well maintained grain drills can last 20 to 30 years, while

Table 2. **Mean draft, fuel consumption, fuel efficiency, and NOx emissions for four biodiesel blends in tillage operation.**

Fuel blend	Mean draft (kN)	Fuel consumption (L/ha)	Fuel efficiency (MJ/L)	NOx emissions (g/ha)
Diesel	36.9 b*	7.77 a	7.91 d	185 a
B20	35.7 a	7.65 a	7.78 c	182 a
B50	35.6 a	7.83 b	7.58 b	197 b
B100	35.2 a	7.93 b	7.40 a	209 c

* Means followed by the same letter are not significantly different at the 5% level of probability according to Duncan's Multiple Range Test.

Table 3. **Mean draft, fuel consumption, fuel efficiency, and NOx emissions for four biodiesel blends in drill operation.**

Fuel blend	Mean draft (kN)	Fuel consumption (L/ha)	Fuel efficiency (MJ/L)	NOx emissions (g/ha)
Diesel	2.85 b*	5.91 a	1.61 b	118 b
B20	2.73 a	5.86 a	1.55 a	113 a
B50	3.09 c	5.99 b	1.71 c	116 b
B100	2.82 b	6.15 c	1.53 a	120 c

* Means followed by the same letter are not significantly different at the 5% level of probability according to Duncan's Multiple Range Test.

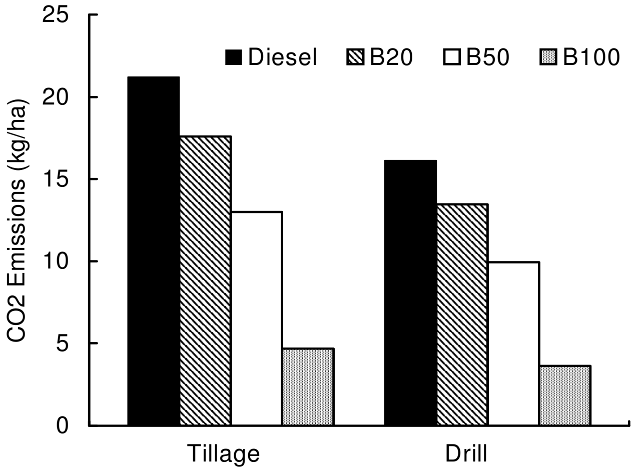

Fig. 6. Mean net CO_2 emission with different biodiesel blends under tillage and drill operations.

the life of a primary tractor is normally about 10 years. The grain drill may have been well matched to the tractor available when it was purchased, but often, farmers purchase larger new tractors when replacing older models resulting in a mismatch with some of the older equipment. As a grain drill is only used a few days in a year, it is often more cost effective to operate with a mismatch between tractor and an existing grain drill than to purchase a new larger grain drill to match the larger tractor.

Mean fuel consumption

Mean fuel consumption for each of the biodiesel blends under both tillage and seeding is given in Tables 2 and 3. The tractor required 4% more B100 fuel for both tillage and seeding operations. Some increase in fuel consumption was expected because the energy content of B100 was lower than petroleum diesel (Table 1). Fuel consumption for B20 was the lowest of all blends under both tillage and seeding operations, although the energy content for B20 was 2.7% lower than petroleum diesel. The difference in fuel consumption between B20 and petroleum diesel was not significant ($P > 0.05$). This reduction in fuel consumption is usually attributed to enhanced lubricity achieved with small amounts of biodiesel. Fuel consumption was highest for B100 followed by B50, and is due to the lower energy contents in the blends with higher biodiesel content.

Fuel consumption on a per hectare basis for seeding was three-fourths of that for tillage, although draft for the grain drill was only one-tenth of that for tillage implement. As discussed previously, the tractor was overpowered for the grain drill and made twice as many passes to cover the same land area as for tillage. A higher gear ratio and lower engine speed combination were used for the drill, but no attempt was made to optimize fuel consumption using a gear up throttle down (GUTD) strategy.

Mean fuel efficiency

Fuel efficiency expressed in megajoules drawbar energy per litre of fuel is more independent of draft than fuel consumption in evaluating the performance of the tractor and fuels, since it takes both load and fuel consumption into account. Under tillage operation, fuel efficiency significantly decreased with increasing percentage of biodiesel. The seeding operation resulted in a similar trend in fuel efficiency to tillage except for B50, which was significantly higher than the other fuels. The higher fuel efficiency for B50 for the grain drill was likely a result of the higher draft for B50.

Under tillage, the fuel efficiency of B100 and B20 was 6.4 and 1.6%, respectively, lower than for petroleum diesel. Fuel test results showed that B100 and B20 had 8.2 and 1.7%, respectively, lower energy content (by volume) than petroleum diesel (Table 1). The measured differences in fuel efficiency among the four fuels are approximately the same as the differences in energy content and are probably within the margin of error in the experiment.

Fuel efficiency while seeding was approximately one-fifth of that under tillage operation. As discussed earlier, fuel efficiency as expressed here is the combination of engine, transmission, and tractive efficiency of the tractor. For low draft, the tractor tractive efficiency is quite low as the tractor rolling resistance is relatively constant, and is a higher percentage of draft. Some improvement in fuel efficiency for the seeding operation could likely be achieved by implementing the GUTD strategy.

Mean NOx emissions

The results of mean NOx emissions for different biodiesel blends while tilling and seeding can be found in Tables 2 and 3. Compared with petroleum diesel, NOx emissions were 6.6 and 13.1% higher for B50 and B100, respectively, under tillage operation. NOx was 2.3% higher than petroleum diesel for B100 while seeding. NOx emissions for B20 were lower than petroleum diesel under both tillage and seeding operations, but the differences were not statistically significant. Schumacher et al. (2001b) reported that NOx increased up to 11.6% for B100 and slightly increased (not significant) for B20 and B35. Nine et al. (2000) reported that for biodiesel, NOx emissions increased up to 17% when exhaust gas was sampled without water contact in the exhaust stream. No difference in NOx concentration was observed when exhaust gas was sampled with scrubbing in the exhaust stream for B100 and petroleum diesel. Some reports in the literature showed that NOx emissions for biodiesel blends sometimes decrease compared with petroleum diesel (Peterson and Reece 1996). The emission of NOx is related to many factors, such as engine condition and post treatment of exhaust gas. The higher NOx emission from biodiesel blends may be related to higher oxygen content in B100 (11.38%) than in petroleum diesel (0.89%, Table 1). The amount of excess air available for combustion can affect NOx formation, but at a given engine load and speed, the amount of excess air should be approximately the same for all of the biodiesel blends.

Mean net CO_2 emissions

The CO_2 emissions for the three biodiesel blends and petroleum diesel were calculated on a per hectare basis using measured fuel consumption data and the net CO_2 emission factors (National Renewable Energy Laboratory 1998). The results are given in Fig. 6. Although there was a small increase in fuel consumption for increasing biodiesel content, there was a substantial reduction in net CO_2 emissions for both tillage and seeding with higher biodiesel contents.

Suggestions on biodiesel use in agricultural machines

Some problems with high percentage biodiesel blends have been reported in the literature, especially for older vehicles (BIOBUS 2003). Blockage of the fuel supply system, particularly the fuel filters, is a common problem, especially at the beginning of using biodiesel blends. Fuel filter blockage was experienced for the first time in 15 years when biodiesel was used in the instrumented research tractor. Biodiesel is a good solvent and it is generally assumed that biodiesel loosens deposits in the fuel tank and lines. These mobilized deposits are then transported through the fuel system and become lodged in the filters. This suggests that biodiesel use, particularly in older tractors, should start with a low percentage of biodiesel and let the fuel system clean up slowly. The fuel filters should be changed more frequently at the beginning to prevent complete blockage as the deposits are loosened and captured by the fuel filters.

CONCLUSIONS

Fuel consumption and NOx emissions for three biodiesel blends, B20, B50, and B100 and petroleum diesel were compared for spring tillage and seeding using field scale equipment.

1. B20 performed comparably with petroleum diesel in terms of fuel consumption, fuel efficiency, and NOx emissions.
2. Fuel consumption and NOx emissions increased and fuel efficiency decreased with increasing percentages of biodiesel beyond B20.
3. The tractor was overpowered with respect to the 3.0-m wide grain drill, resulting in lower fuel efficiency for the seeding operation compared to that for tillage with a 6.0-m wide mulch finisher, which was well matched to the tractor size. The ratio of NOx and CO_2 between seeding and tillage operations was higher than the ratio of draft between seeding and tillage. This indicates that proper tractor-implement match is important for both improving fuel efficiency and reducing exhaust emissions for field operations in crop production.
4. Further research is needed on potential reduction in NOx achievable via gear up throttle down strategies for field operations with light loads which usually occur when the tractor and implement are not well matched.

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