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FUEL EFFICIENCY AND EXHAUST EMISSIONS FOR BIODIESEL BLENDS IN AN AGRICULTURAL TRACTOR

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ABSTRACT

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 pipe 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 with diesel in terms of fuel consumption, fuel efficiency and NOx emission. Higher fuel consumption and lower fuel efficiency were observed for B50 and B100 blends which is due to the lower energy content of the biodiesel. NOx emissions were higher with blends with higher biodiesel contents. 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 equipment resulted in lower fuel efficiency, and higher NOx emission on a per hectare basis compared with the tillage implement with a near optimal tractor-implement match.

Keywords: biodiesel, exhaust emission, NOx, fuel efficiency

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. Biodiesel can be used pure (neat) or blended with petroleum diesel and used as a fuel extender.

Vegetable oil has been as a fuel for compression ignition engines for a very long time. Rudolph Diesel, inventor of diesel engine, used peanut oil to fuel a diesel engine during the late 1800s (Nitschke and Wilson 1965; Goering et al. 1982; Schumacher et al. 2001a). Petroleum based diesel fuel has been the fuel of choice for diesel engines for many years due to abundant supply and low fuel prices. World energy shortages in the 1970's contributed to re-evaluation of biodiesel use in Europe in early 1970s and subsequently in the United States in late 1970s and early 1980s. Biodiesel is a renewable energy source and has cleaner burning attributes, and concomitant environmental benefits Hills and Donaldson 2003; Shumacher et al. 2001b).

Researchers have shown that using raw vegetable oils for diesel engines can cause numerous engine-related problems such as plugged filters, deposits on injectors, stuck piston rings and fuel system failure etc. Goodrum et al. 1996; Canakci and Van Gerpen 1999). Goering et al. (1982) also reported that all the raw vegetable oils were much more viscous, and had higher cloud point and pour point temperatures compared with diesel fuel. Jone and Peterson (2003) provided an excellent review of literature on research on raw vegetable oil and its problems. 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 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 diesel fuel (Canakci and Van Gerpen 2001).

EPA (2002) provided a comprehensive analysis of biodiesel use and exhaust emissions from heavy-duty highway engines and its impact on the environment and economy using data from various emissions research reports and test programs. Most of the reports reviewed showed that biodiesel burns cleaner with lower emissions of most pollutants in the exhaust than for petroleum diesel fuels. Statistical regression analysis of data from the various reports showed that as 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. B20 (20% volume biodiesel and 80% volume diesel), one of the most common blends of biodiesel, 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 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), and are having a detrimental effect on global climate warming. For the diesel engines studied, the tailpipe emissions of two potent greenhouse gases, nitrous oxide (N_2O) and methane (CH_4) were both negligible, therefore CO_2 is usually the only GHG 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. CO_2 production in biodiesel combustion is 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.

Diesel engines were designed over many years to operate on petroleum diesel. Many studies show they perform well without engine modifications when biodiesel or biodiesel blends are used as a fuel (Peterson and Reece 1996). Biodiesel has potential as a diesel fuel extender for agricultural machinery.

Most of the research on biodiesel use and exhaust emissions was conducted in laboratories using dynamometers to apply a constant load and speed, or simulate a real operation by applying a predetermined load cycle. Most test engines were heavy-duty highway engines, but little attention was given to off-road engines, especially in real-time in-use conditions (EPA 2002). Although biodiesel is derived from agriculture, and many of studies were conducted by agricultural engineers, there is virtually no documentation on exhaust emissions from either petroleum or biodiesel fuel use in agricultural application (EPA 2002; McLaughlin and Layer 2003).

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 emissions 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, soil texture, and operator habits including traffic and tillage management which contributes to soil compaction, gear and engine speed selection, traveling from and to 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 emissions of HC, CO and PM vary according to engine loads Peterson and Reece 1996).

The objective of this study is to evaluate compare fuel efficiency and exhaust emissions from different biodiesel blends under typical field operations using an instrument 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. This tractor was fitted with instrumentation and an onboard data logging system to facilitate measurement and recording of tractor operational parameters as the tractor is doing normal field work (McLaughlin et al. 1993). It is capable of very accurate real time measurements of engine speed, implement draft and fuel consumption and exhaust gas emissions. The tractor was recently fitted with auxiliary fuel tanks and a set of valves to allow switching among the different premixed biodiesel blends within a few minutes (Fig. 1).

Exhaust gas instrumentation

Instrumentation was installed in a modified tractor exhaust stack for measurement of exhaust temperature, mass flow and 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 down stream from the averaging Pitot tube. Exhaust mass flow rate was calculated using the following equation:

$$Q_m = KD^2 \sqrt{\frac{\Delta P * P}{T}}$$

where, Q_m -- mass flow rate (Standard cubic meters per second)
K -- constant flow coefficient
D -- internal diameter of exhaust pipe (m)
ΔP -- differential pressure created on the averaging Pitot tube (Pa)
P -- atmospheric pressure (Pa)
T -- temperature of exhaust gas, (°K)

The flow coefficient, K, was provided by the averaging Pitot tube manufacturer. It includes factors such as air density at standard temperature and pressure required to make the equation homogeneous.

NOx analyzer

A Zirconia non-sampling NOx sensor and associated signal conditioning equipment (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 zero, 600, 1400 and 2500 ppm nitric oxide (NO) in nitrogen. Exhaust gas NOx concentrations in 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 on the right side of tractor. Four blends were used: 100% diesel (D), 80% diesel with 20% biodiesel (B20), 50% diesel with 50% biodiesel (B50) and 100% biodiesel (B100). Fuels of diesel, B20 and B100 were analyzed by 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 (ADRI), Ottawa, ON, Canada (Lat 45º 19´ N, Long 75º 47´ W) for spring tillage and soybean planting. The site was cash cropped for the past 10 years, and the previous crop in 2003 was corn and sorghum strips. 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 north east 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 was measured prior to tillage operation.

Experimental procedure

Spring tillage was done with a single pass using a 6.0 m wide John Deere mulch finisher at about 6 km/h forward 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 7th gear (105:1 engine to wheel axle speed ratio) 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 so 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 was then run at high idle for about 5-10 minutes to purge the fuel filters with the new blend. A total of four passes, two passes for each of the four biodiesel blends, were made with the 6.0 m wide mulch finisher in each 48 m wide block.

Procedure for planting with the 3.0 m wide grain drill was the same as for the tillage. As the grain drill was only half of the width of the 6.0 m wide tillage implement, a total of four passes were made for each of the four fuels in each 48 m wide block. As the tractor was overpowered for 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) was 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 therefore are 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 processing into biodiesel. The net CO_2 emissions factors used for biodiesel blends in this study were used for biodiesel blends were 15.6, 39.2 and 78.5% reduction for B20, B50 and B100 respectively compared with diesel (National Renewable Energy Laboratory 1998).

Data analysis

Data were extracted from the raw data files and converted to engineering units using custom software developed for the purpose. Depending on the end use, 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 using Equation 1. 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. Area covered 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 diesel, B20 and B100 are given in Table 1. B100 had very low sulfur content compared with diesel. The negligible level of sulfur in biodiesel can reduce emission of sulfur dioxide (SO_2) which is a large contributor to acid rain. This is in general agreement with biodiesel studies from literature (Schumacher et al. 2001a; Dorado et al. 2002; Peterson et al. 1999; Peterson et al. 2000). New regulations for ultra low sulfur (ULS) diesel with maximum 15 ppm sulfur will also reduce SO_2 emissions, but low sulfur 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 diesel fuel (BIOBUS final report, 2003). Since B20 contained 20% of biodiesel, its sulfur content fell between B100 and diesel.

B100 contained 12.8% less energy than the same mass of diesel. The density of B100 is about 5% higher than diesel. Fuel efficiency of engine is sometimes expressed on a volumetric basis (MJ/litre), and sometimes on 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 diesel. Lower energy content was also found by Dorado et al. (2002), and 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. 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. There is a lot of high frequency "chatter" in plots of both draft and fuel consumption. This high frequency component is normal for field operations, and is likely a result of both surface roughness of the field which results in tractor and implement bounce and varying operating depth, and brittle failure of the soil. Experience has shown that sandy soils exhibit much smoother signals. It is easy to see general trends from the low frequency component of the graphs. As expected, fuel consumption tracked draft very well with and higher draft requiring more fuel. The changes of draft and fuel consumption over the 370 m run are likely due to the combination of variations in soil texture, land topography and previous tillage management of the site.

Fuel efficiency was expressed in Mega Joules of drawbar energy per litre of fuel 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 energy per litre of fuel available at the drawbar to do field work. Compared to fuel consumption (Fig. 2), fuel efficiency is relatively independent of draft within the normal operating range for the tillage implement.

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 likely a combination of higher fuel consumption and higher engine temperatures at higher draft values. These results indicate that reducing draft and fuel consumption through best 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 at the study of the City of Houston Diesel Field Demonstration Project by Environment Canada (Howes, 2002) for heavy duty highway engines. 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 time response time of the exhaust temperature (Pascal and Sharp 1984; Pang et al. 1985).

Mean draft

Mean draft under both tillage and drill operations for each of the four biodiesel blends is given in Fig. 6. 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. Even in adjacent passes, some variability in mean draft is expected due normal variability of conditions within the field including soil texture, land topography and previous tillage management system which can result in localized compacted areas. Sometimes, these factors may produce significant differences in draft between adjacent passes. For example, draft for diesel fuel was significantly greater than that for other fuels under tillage, and draft for B50 was significantly greater than others under drill. There was considerable variability in soil texture with a higher sand content in the north east corner of the field and higher clay content in the south west corner which contributes to variability in draft.

Draft for the 3.0 m wide double disk grain drill was only about one sixth 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 over-powered for drill operation, which is a common scenario on smaller family farms. Well maintained grain drills can last 20 to 30 years, while 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 miss match 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 run with a miss match between tractor and existing 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 drill is given in Fig. 7. The tractor required 4% more B100 fuel for both tillage and drill operations. Some increase was expected because the energy content of B100 was lower than diesel (Table 1). Fuel consumption for B20 was the smallest under both tillage and drill, although the energy content for B20 was 2.7% lower than diesel. The difference of fuel consumption between B20 and diesel was not significant ($P > 0.05$). Fuel consumption for B50 followed B100 as the second greatest within the four fuels. Other studies have shown lower fuel consumption with small percentages of biodiesel (Biobus 2003). This reduction in fuel consumption is often attributed to enhanced lubricity achieved with small amounts of biodiesel.

Fuel consumption on a per hectare basis for drill was three fourths of that for tillage, although draft for the drill was only one sixth of that for tillage (Fig. 6). As discussed above, the tractor was over powered for the drill, and made twice as many passes to cover the same land area as for tillage. We used a higher gear and lower engine speed for the drill, but we did not make any attempt to optimize fuel consumption using a gear up throttle down (GUTD) strategy.

Mean fuel efficiency

Mean fuel efficiency for the four biodiesel blends for both tillage and drill is given in Fig. 8. Fuel efficiency expressed in Mega Joules of drawbar energy per litre of fuel is more independent of draft compared with 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 the increasing percentage of biodiesel. Drill had similar trend as tillage operation except for B50, which was significantly higher than other fuels. This may be due to the higher draft in drill operation (Fig. 6).

Under tillage, the fuel efficiency of B100 and B20 was 6.4% and 1.6% respectively lower than for diesel. Fuel test results showed that B100 and B20 had 8.2% and 1.7% lower energy content (by volume) than 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 under drill was approximately one fifth of that under tillage operation. As discussed earlier, fuel efficiency expressed in Mega Joules of drawbar energy per litre of fuel 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 drill could likely be achieved by implementing a gear up throttle down strategy which would improve the engine fuel efficiency. The trend in decreasing fuel efficiency with increasing biodiesel content observed for tillage was not evident for the drill (Fig. 8). This was likely due to experimental error.

Mean NOx emission

The results of mean NOx emission for different biodiesel blends under tillage and drill are given in Fig. 9. Compared with diesel, NOx emission was 6.6% and 13.1% higher for B50 and B100 respectively under tillage operation. NOx was 2.3% higher than diesel for B100 under drill operation. NOx emission for B20 was lower than diesel under both tillage and drill operations, but there differences were not 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 NOx emission increased up to 17% when exhaust gas was sampled without water contact in the exhaust stream, but no difference when exhaust gas was sampled with scrubbing in the exhaust steam for B100 compared with diesel. Some reports in the literature showed that NOx emission for biodiesel blends sometimes decreased compared with 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 diesel (0.89%) (Table 1).

NOx emission on a per hectare basis under drill operation was nearly two thirds of that under tillage, although fuel efficiency under drill was only one fifth of that under tillage. The ratio of NOx emissions for drill to tillage was slightly lower than the ratio of fuel consumption for drill to tillage. The lower engine temperature for drill than tillage may have contributed to a lower ratio of NOx than fuel consumption between drill and tillage.

Mean net CO_2 emission

The CO_2 emission for the four biodiesel blends was 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. 10. 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 drill with higher biodiesel contents.

Suggestions on biodiesel use in agricultural machines

The percentage of biodiesel in this study was intentionally selected as high as 20, 50 and 100% for this extreme case study. Some problems with high percentage of biodiesel have been reported in the literature, especially for older vehicles. Blockage of the of fuel supply system, particularly the fuel filters, is a common problem. We experienced the first problem with filter blockage in 15 years in the instrumented research tractor after we started using biodiesel. Biodiesel is a good solvent, and is generally assumed that biodiesel loosens deposits in the fuel tank and lines, and these get carried through the system in plug the filters. This suggests that biodiesel use, especially for older agricultural machines, should start with low percentage of biodiesel to let the supply system to clean up slowly and to avoid the blockage.

CONCLUSIONS

Fuel consumption and NOx emissions for four biodiesel blends, diesel, B20, B50 and B100 were compared for spring tillage and seeding using field scale equipment. The following is the conclusions of this study.

1. B20 had similar performance with diesel, in terms of fuel consumption, fuel efficiency, NOx emission.
2. Fuel consumption and NOx emissions both increased and fuel efficiency decreased with increasing percentages of biodiesel beyond B20.
3. The tractor is overpowered to the 3.0 m wide grain drill, resulting in lower fuel efficiency than 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 drill and tillage was higher than the ratio of draft between drill 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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Table 1 Fuel properties for diesel, B20 and B100.

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

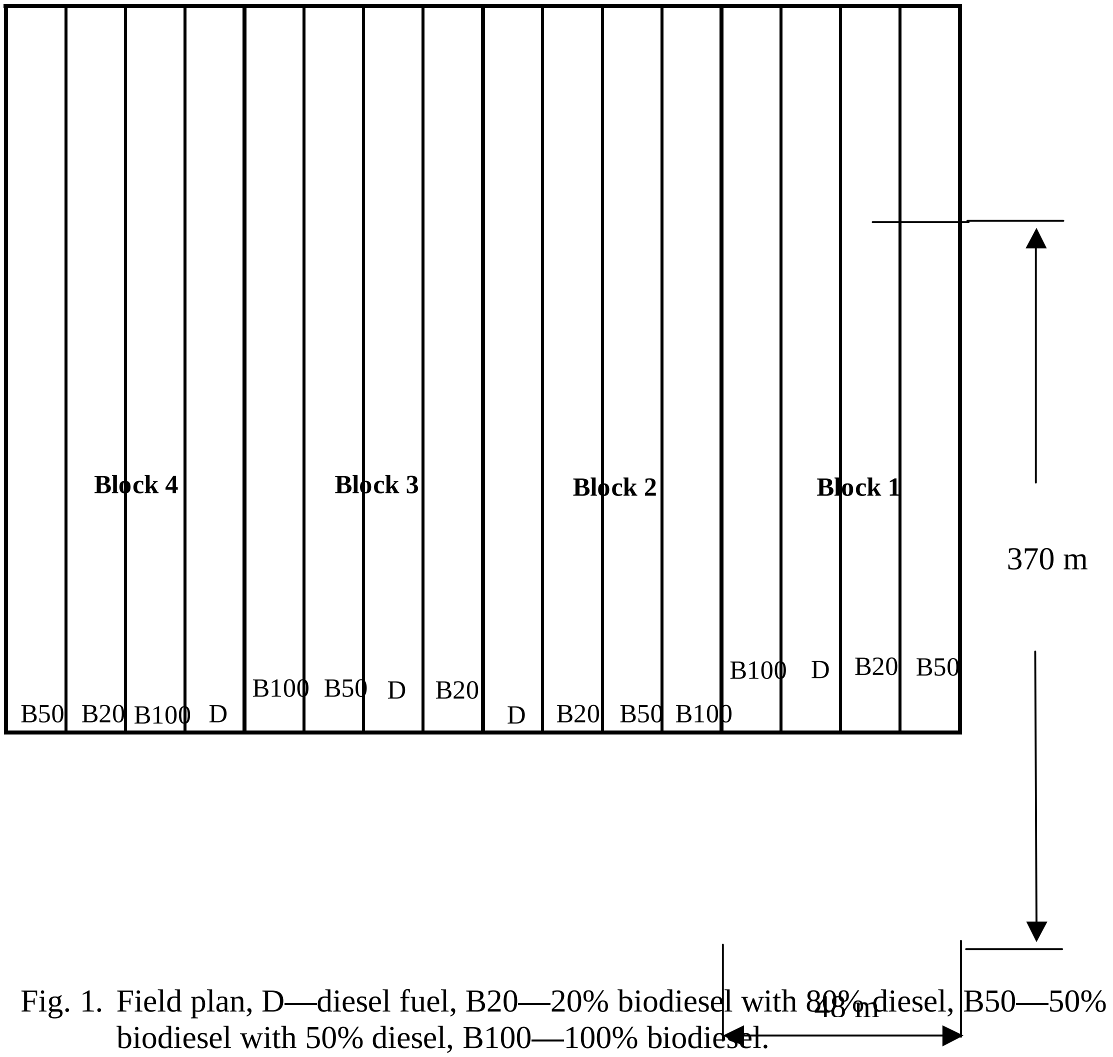

Fig. 1. Field plan, D—diesel fuel, B20—20% biodiesel with 80% diesel, B50—50% biodiesel with 50% diesel, B100—100% biodiesel.

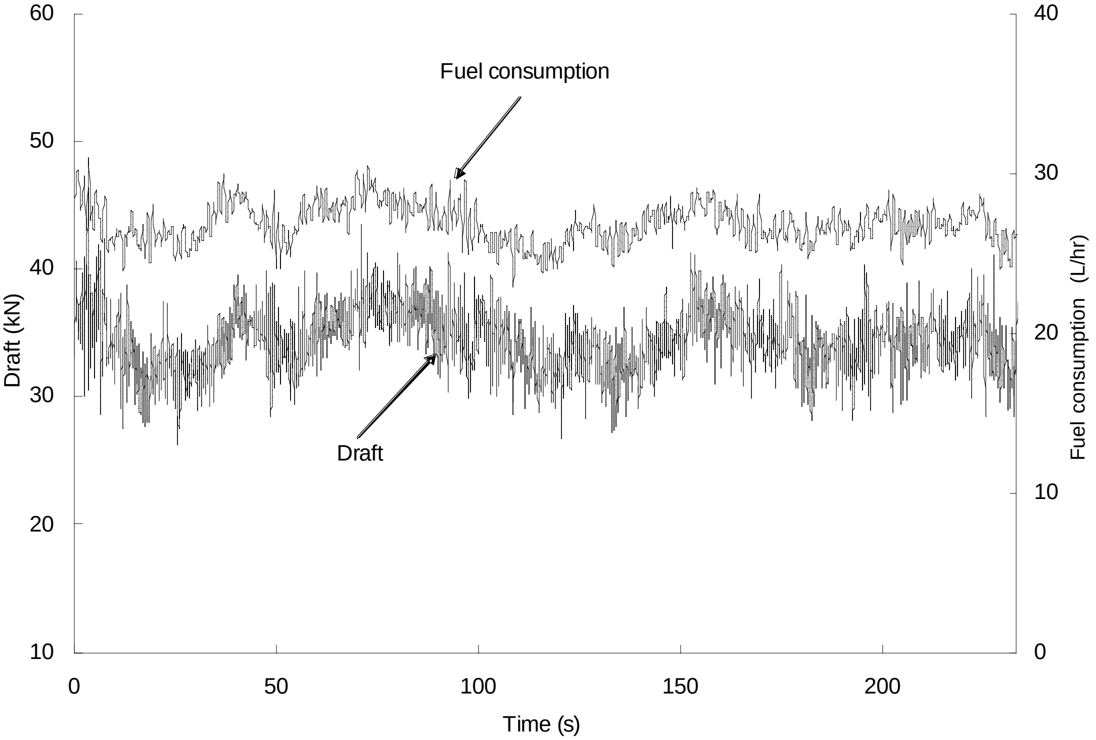

Fig. 2. Real-time measurement of draft (kN) and fuel consumption (L/hr) with B20 under tillage operation

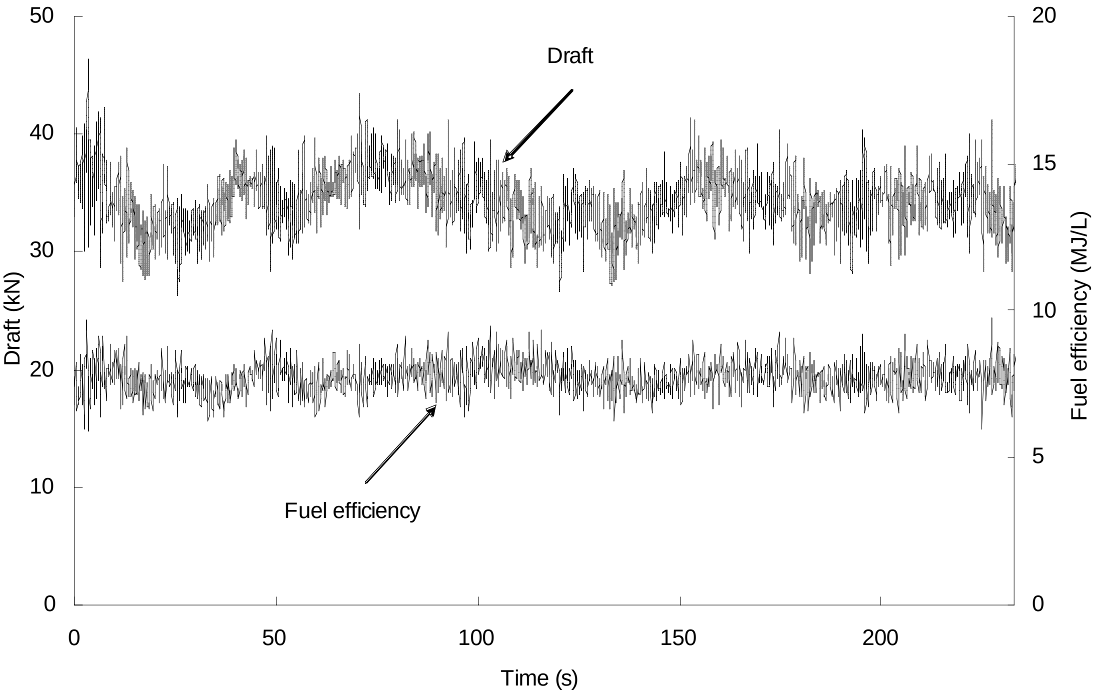

Fig. 3. Real-time measurement of draft (kN) and fuel efficiency (MJ/L) with B20 under tillage operation.

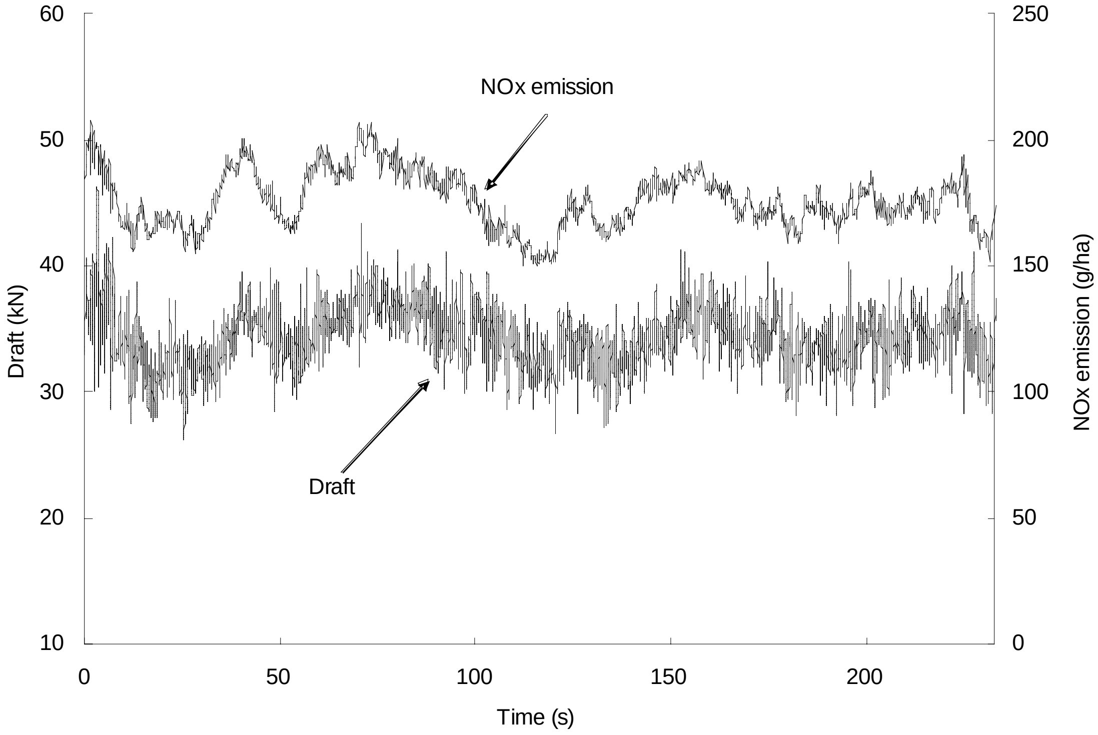

Fig. 4. Real-time measurement of draft (kN) and NOx emission (g/ha) with B20 under tillage operation.

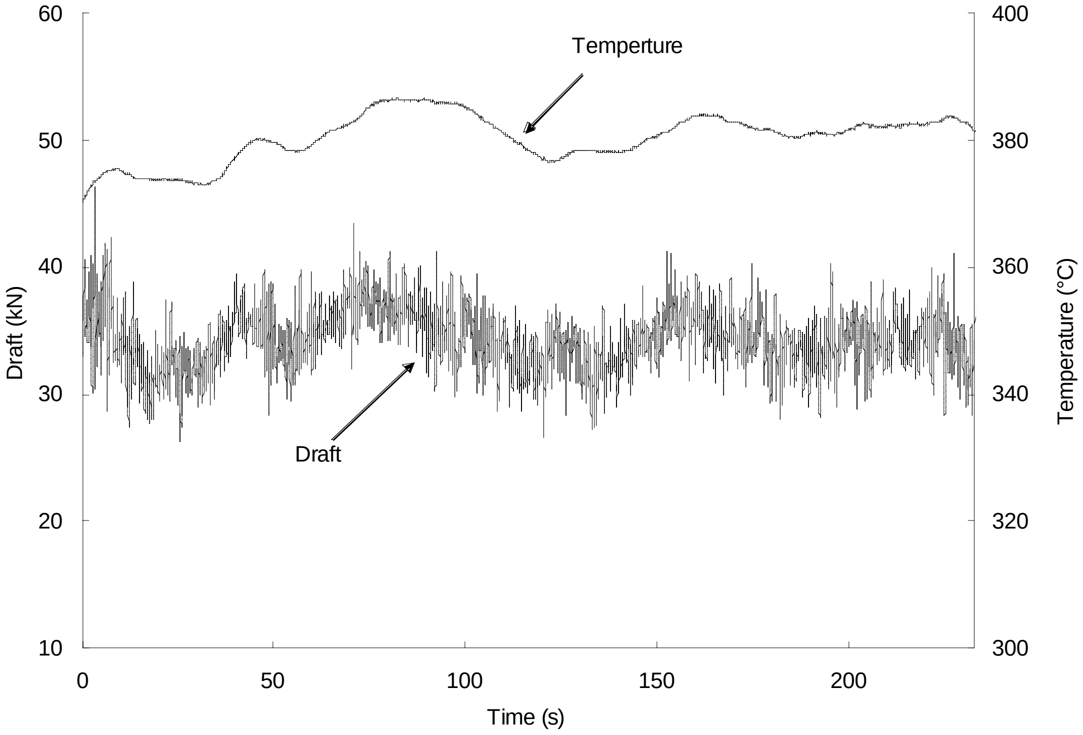

Fig. 5. Real-time measurement of draft (kN) and exhaust temperature (°C) with B20 under tillage operation.

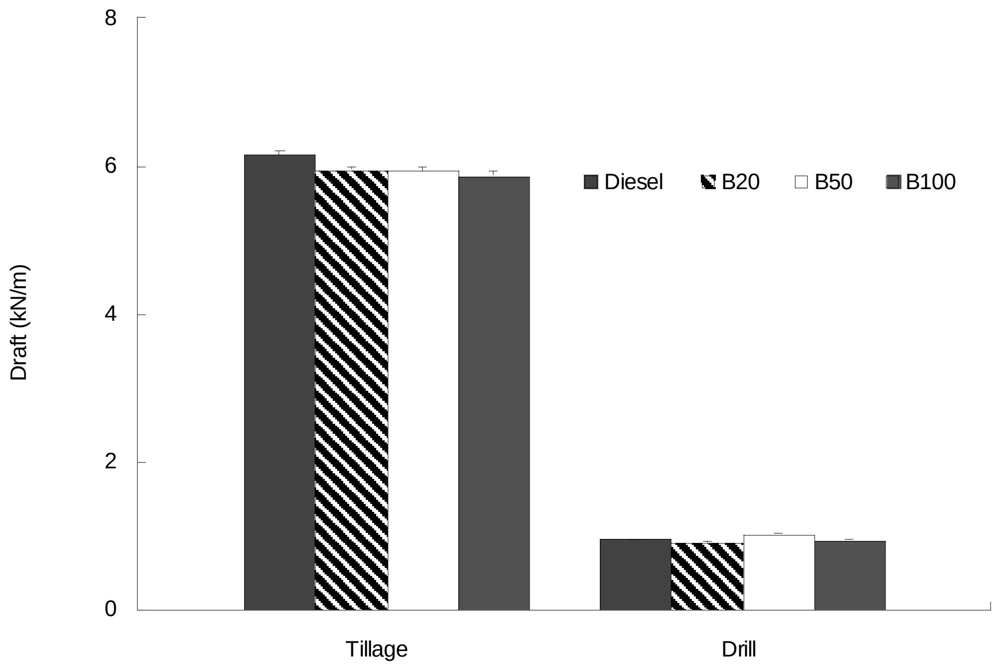

Fig. 6. Mean draft (kN/m) with different biodiesel blends under tillage and drill operations.

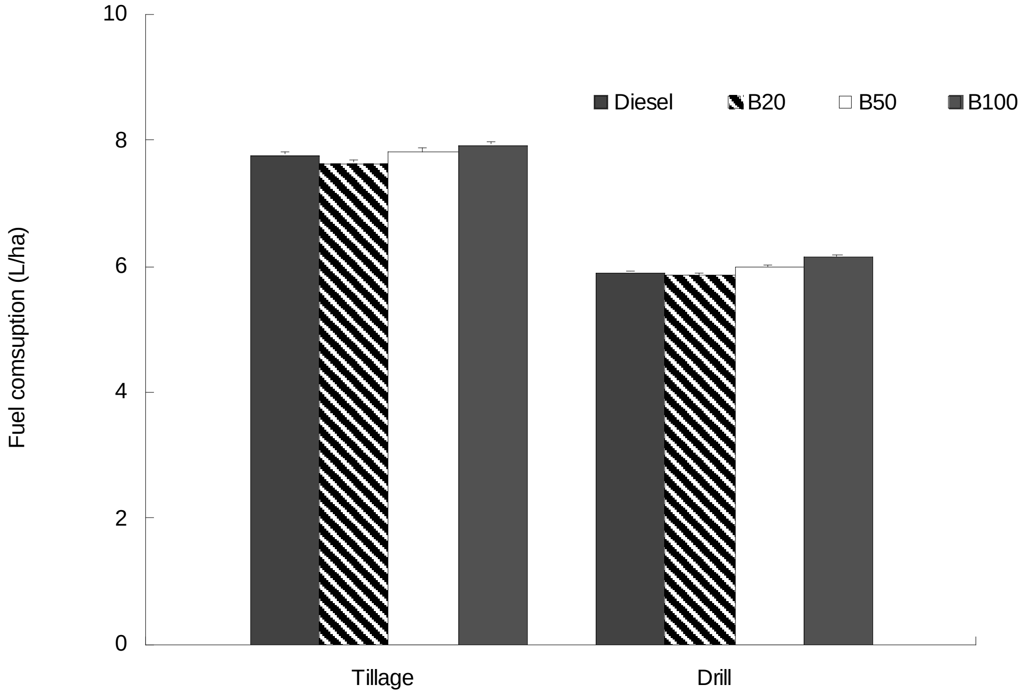

Fig. 7. Mean fuel consumption (L/hr) with different biodiesel blends under tillage and drill operations.

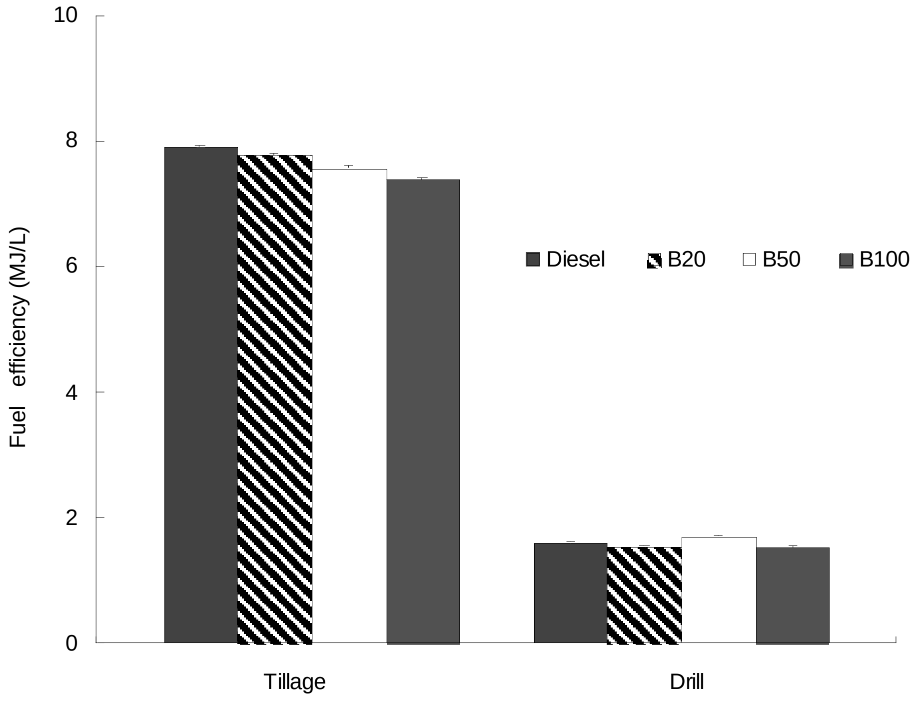

Fig. 8. Mean fuel efficiency (MJ/L) with different biodiesel blends under tillage and drill operations.

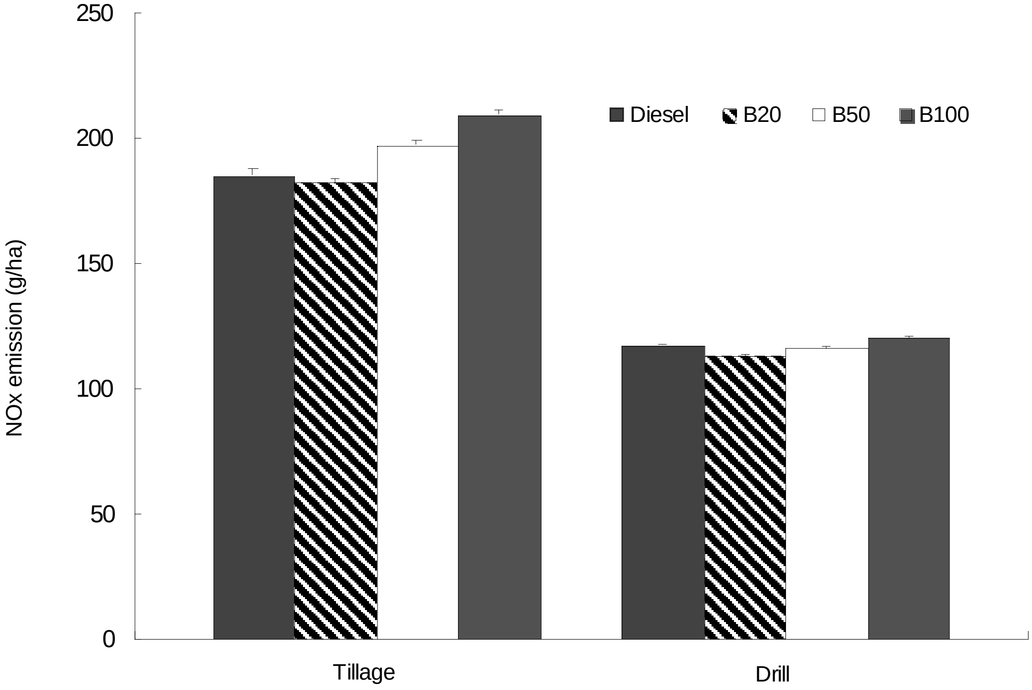

Fig. 9. Mean NOx emission (g/ha) with different biodiesel blends under tillage and drill operations.

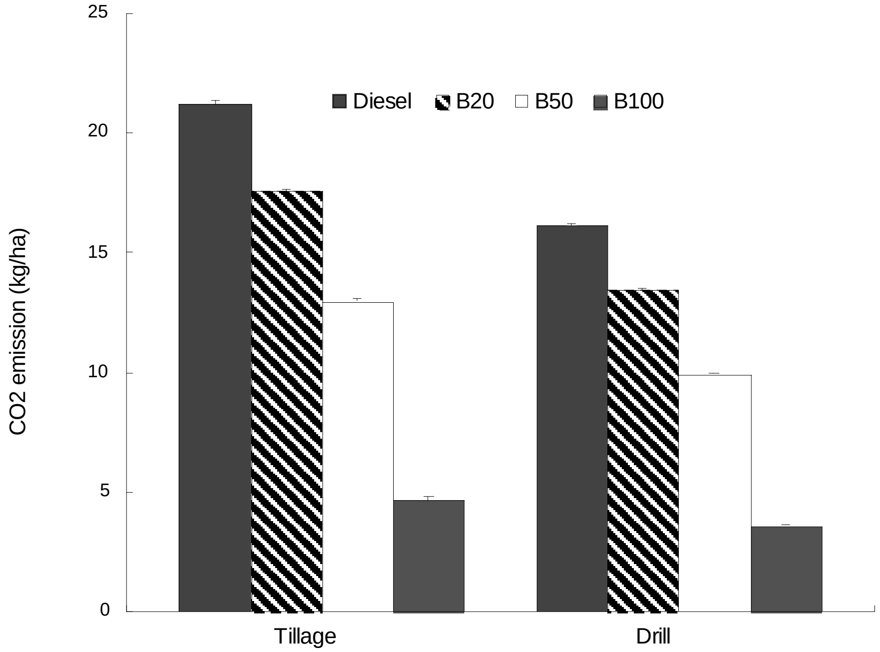

Fig. 10.Mean net CO_2 emission (kg/ha) with different biodiesel blends under tillage and drill operations.