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Fuel consumption of a sugarcane harvester in different operational settings

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mechanized harvesting
operational performance
harvesting capacity

A B S T R A C T

The interventions performed during the mechanized harvesting are essential to improve the operational performance of sugarcane harvesters and reduce operational costs. The objective of the present study was to evaluate the fuel consumption of a sugarcane harvester in different forward speeds and engine rotations. Harvesting was conducted in a green cane plot, with the variety RB 855156. Flow meters were installed in the harvester's fuel supply system and an electronic device was used for data acquisition. The experiment was carried out in a completely randomized design in a factorial scheme (3 x 2), using three engine rotations and two forward speeds, with six replicates. Harvesting capacity and fuel consumption per hour, per area and per ton of harvested sugarcane were analyzed. The results were subjected to analysis of variance and means were compared by Tukey test. The variations in engine rotation did not affect the performance for harvesting capacity, but influenced fuel consumption. Forward speed influenced both harvesting capacity and fuel consumption.

Palavras-chave:
colheita mecanizada
desempenho operacional
capacidade de colheita

Consumo de combustível de uma colhedora de cana-de-açúcar em diferentes configurações de operação

R E S U M O

As intervenções realizadas durante a colheita mecanizada são fundamentais para a melhoria do desempenho operacional das colhedoras de cana-de-açúcar e redução dos custos desta operação. O objetivo foi avaliar o consumo de combustível de uma colhedora de cana-de-açúcar em diferentes velocidades de trabalho e rotações do motor. A colheita foi realizada em canavial sem queima prévia cuja variedade foi a RB 855156. Foram instalados medidores de fluxo no sistema de alimentação de combustível da colhedora e utilizado equipamento eletrônico para aquisição dos dados. O experimento foi conduzido em delineamento inteiramente casualizado em arranjo fatorial 3 x 2 usando três rotações do motor e duas velocidades de trabalho, com seis repetições. Foram avaliados a capacidade de colheita e o consumo de combustível horário, por área e por tonelada colhida. Os resultados foram submetidos à análise de variância e as médias comparadas pelo teste de Tukey. As variações na rotação do motor não interferiram no desempenho para capacidade de colheita, porém influenciaram significativamente o consumo de combustível da colhedora; já a velocidade influenciou tanto a capacidade de colheita como o consumo de combustível.

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Introduction

The demand for alternative energy sources, the high price and the environmental impact caused by fossil fuels are the main factors that make sugarcane ethanol one of the most competitive fuels in the global market. The reduction in burning and mechanized harvest have contributed to the decrease in the emissions of greenhouse gases by up to 40%, in 20 years of study in São Paulo (Capaz et al., 2013).

The expansion of mechanized harvest depends on technological advances to minimize the presence of impurities and losses, besides improving the efficiency of harvesters (Ma et al., 2014), which can be achieved with the adoption of technologies such as geographic information systems, GPS and remote sensing (Goswami et al., 2012).

Among the steps of the production systems, harvest is one of the most expensive operations, representing about 30% of all the costs (Salassi & Barker, 2008). The increase in field efficiency reduces production costs; however, it requires large management investments (Santos et al., 2014).

Maneuvers represent a small fraction in the production costs, but have high impact on the revenue (Spekken et al., 2015) and the cane wagon is the factor that harms the efficiency of the system, for demanding longer time to perform the maneuvers (Baio, 2012).

The high consumption of the harvesters, which can reach 60 L h^{-1}, has been the greatest aggravating factor of this operation, since it represents about 40% of the total costs (Ripoli & Ripoli, 2009). Therefore, it must be evaluated in various situations, because the known value from 30 to 35 L h^{-1} refers to the mean of one work day (Lanças, 2012).

This study aimed to evaluate the harvesting capacity and fuel consumption in the sugarcane mechanized harvest at different work speeds and engine rotations of the harvester.

Material and Methods

Field determinations were performed at the Nossa Senhora Aparecida Farm, belonging to the Santa Cândida Mill, located in the municipality of Bocaina-SP, Brazil (22º 6' 22" S, 48º 28' 46" W; 532 m).

Harvest was performed without previous burning of the sugarcane field, which had the variety RB 855156 in its second cutting stage, planted at spacing of 1.5 m between rows, with mean yield of 94 t ha^{-1}.

Harvest was performed at two forward speeds, 4.0 km h^{-1} (V1) and 5.5 km h^{-1} (V2), and three engine rotations of the harvester (M1 - 1800 rpm, M2 - 1950 rpm and M3 - 2100 rpm). The entire experiment was harvested using only one harvester, a Case IH A8800 with 8,139 h of use, manufactured in 2012.

The statistical design was completely randomized in a 3 x 2 factorial scheme (three engine rotations and two forward speeds), which resulted in six treatments and six replicates of harvest, totaling 36 experimental plots. The area corresponding to the plots was obtained from the harvest of 300-m-long rows, measured using a GPS (Garmin, GPSmap 60CSx), with accuracy of position of 4 m.

The amount of harvested raw material was measured by weighing the cane wagon that followed the harvester, before and after harvesting the plots, using a scale with interface for direct communication with a computer and weighing platforms with maximum capacity of 20 t.

With the amount of raw material harvested per plot (row), it was possible to obtain the agricultural yield of harvested raw material (t ha^{-1}) in each harvested row or area unit (ha), as well as the effective harvesting capacity (t h^{-1}).

According to Ripoli & Ripoli (2009), the effective harvesting capacity occurs when one considers the amount of material directly released in the transport vehicle without considering the losses in the field and the foreign matter contained in the collected load, and can be calculated through Eq. 1:

$$HCe = \frac{W}{T} \times 3.6 \tag{1}$$

where:

HCe - effective harvesting capacity, t h^{-1};
W - sugarcane mass harvested in the plot, kg;
T - time spent to cover the plot in which the mass W was collected, s; and,
3.6 - conversion factor.

The harvester's fuel consumption was evaluated using two flowmeters (Oval, Model LSF45) with maximum reading capacity of 500 L h^{-1}, one installed in the fuel supply system between the tank and the engine, and the other in the return to the tank.

Data acquisition was performed using a Programmable Logic Controller (PLC) belonging to the Machinery and Agricultural and Forestry Tires Test Center (NEMPA) of the Agronomic Sciences Faculty (FCA-UNESP), Campus of Botucatu-SP, which records one pulse unit every 10 mL of fuel that passed through the flowmeters, allowing the calculation of hourly fuel consumption, based on the difference between the fuel that enters the engine and the fuel that returns to the tank. In each replicate, the PLC was turned on at the beginning of the harvest and turned off at the end, in order to obtain the result of fuel consumption for each harvested row.

Hourly fuel consumption was calculated using Eq. 2:

$$FCh = \frac{\sum (p_E - p_R) \times 3.6}{\Delta t} \tag{2}$$

where:

FCh - hourly fuel consumption, L h^{-1};
$\Sigma(p_E - p_R)$ - difference between the sums of pulses of the flowmeters equivalent to mL of fuel spent, of entry and return of the engine;
Δt - time spent, s; and,
3.6 - conversion factor.

The harvester's speed and planting spacing were used to calculate the effective field capacity (ha h^{-1}). The mean fuel consumption (L h^{-1}) was divided by the field capacity (ha h^{-1}), to calculate fuel consumption per unit of area (L ha^{-1}), and by the harvesting capacity (t h^{-1}), to calculate fuel consumption per unit of mass (L t^{-1}), according to the methodology used by Mathanker et al. (2015).

Fuel consumption per area was calculated according to Eq. 3:

$$FCa = \frac{FCh}{FCe} \quad (3)$$

where:

FCa - fuel consumption per area, L ha^{-1};
FCh - fuel consumption per hour, L h^{-1}; and,
FCe - effective field capacity, ha h^{-1}.

Fuel consumption per harvested ton was calculated according to Eq. 4:

$$FCt = \frac{FCh}{HCe} \quad (4)$$

where:

FCt - fuel consumption per harvested ton of sugarcane, L t^{-1};
FCh - fuel consumption per hour, L h^{-1}; and,
HCe - effective harvesting capacity, t h^{-1}.

Due to the variability of field conditions, effective harvesting capacity data were subjected to analysis of variance and the means were compared by Tukey test at 0.05 probability level, while fuel consumption data were subjected to analysis of variance and the means were compared by Tukey test at 0.01 probability level.

Results and Discussion

The means of effective harvesting capacity for the treatments with engine rotation M1, M2 and M3, considering the forward speed of 4.0 km h^{-1}, did not differ statistically at 0.05 probability level. Among the treatments with speed of 5.5 km h^{-1}, only M3 differed from the others, showing the highest result of effective harvesting capacity, 95.5 t h^{-1} (Table 1).

The main differences of effective harvesting capacity between the treatments with the same forward speed are relative to the agricultural yield (t h^{-1}) observed in their respective plots (replicates), confirming the conclusions of Banchi et al. (2012) and Mathanker et al. (2015), who claim that the machine's harvesting capacity is directly proportional to the yield of the area and that, therefore, at the same speed, variations will occur according to the harvested agricultural yield.

According to Ripoli & Ripoli (2009), yield variations are related to various factors that influence the amount, unit weight, length and architecture of the stalks, such as germination failure, attack of pests and diseases, presence of weeds and even irregular applications of fertilizers and pesticides.

The effective harvesting capacity in the treatments with speed of 5.5 km h^{-1} was superior to and differed from that in the treatments with speed of 4.0 km h^{-1}, at 0.05 probability level. Such difference is expected, because the harvesting capacity has direct relationship with the harvester's speed, i.e., as the speed increases, the harvesting capacity of the machine increases (Ripoli et al., 2001).

Yadav et al. (2002) conducted a study with cultivation spacing of 1.5 m and yield of 103.57 t ha^{-1}, in which the harvesting capacity was equal to 23.9 t h^{-1}, with speed of 4.0 km h^{-1} and efficiency of 39%. In spite of that and considering the effective capacity (100% efficiency), the results are similar to those found in the present study.

Ripoli et al. (1999) claim that the utilization of very low speeds can make the use of the machine unviable in terms of performance, because the increase in speed resulted in higher harvesting capacity without harming quality.

According to Michelazzo & Braunbeck (2008), the amount of collected material can be altered by changing the harvest function settings of the harvesters to cutting of tips and cleaning of straw, allowing partial or total collection; the latter shows greater energetic efficiency and lower cost.

Ma et al. (2015) obtained results lower than those in the present study, with effective capacity around 30 t h^{-1}, working at 5.0 km h^{-1}. However, the authors claim that, at this harvesting rate, the amount of collected billets decreases to 50%, while it varies around 85% at a harvesting rate of up to 20 t h^{-1}. These results are different from those reported by Ramos et al. (2014), who evaluated the quality of mechanized harvest and obtained 85% of presence of billets, regardless of the variation in speed.

The harvesting capacity results in present study were higher than those observed by Rodrigues & Saab (2007), who obtained 45 t h^{-1}, but similar to those reported by many authors, such as Yadav et al. (2002), Belardo (2010) and Mathanker et al. (2015), who found effective capacity between 54 and 93 t h^{-1}, at speeds that ranged from 2.5 to 5.6 km h^{-1}.

According to the obtained values of hourly fuel consumption (L h^{-1}) for the evaluated treatments (Table 2), V2M3 showed the highest result and differed statistically from the others at 0.01 probability level. The treatment with the lowest fuel consumption used the forward speed of 4.0 km h^{-1} (V1) associated with the engine rotation of 1800 rpm (M1).

Table 1. Means of effective harvesting capacity for the treatments (t h^{-1})

Engine rotation	Forward speed		Mean
	V1 - 4.0 km h^{-1}	V2 - 5.5 km h^{-1}	
M1 - 1800 rpm	52.2 Aa	70.8 Ab	61.5 A
M2 - 1950 rpm	52.0 Aa	79.1 Ab	65.5 A
M3 - 2100 rpm	60.5 Aa	95.5 Bb	78.0 B
Mean	54.9 a	81.8 b	

Means followed by different letters, lowercase in the rows and uppercase in the columns, differ at 0.05 probability level by Tukey test

Table 2. Means of hourly fuel consumption for the treatments (L h^{-1})

Engine rotation	Forward speed		Mean
	V1 - 4.0 km h^{-1}	V2 - 5.5 km h^{-1}	
M1 - 1800 rpm	53.0 Aa	57.5 Ab	55.3 A
M2 - 1950 rpm	59.9 Ba	70.4 Bb	65.1 B
M3 - 2100 rpm	66.5 Ca	77.3 Cb	71.9 C
Mean	59.8 a	68.4 b	

Means followed by different letters, lowercase in the rows and uppercase in the columns, differ at 0.01 probability level by Tukey test

The results of hourly fuel consumption in the present study are similar to those reported by Lyra (2012), who obtained 55.8 L h^{-1}, Schmidt Júnior (2011), who obtained 50.3 L h^{-1}, and Belardo (2010), in a test performed at 5.0 km h^{-1}, in which the harvester consumed 63.04 L h^{-1}.

The speed of 5.5 km h^{-1} promoted greater fuel consumption, significantly differing from the speed of 4.0 km h^{-1} at 0.01 probability level. According to Rosa (2013), with the increase in speed, more sugarcane is harvested, requiring more from the machine and making its consumption increase.

In the present study, fuel consumption increased as the engine rotation increased and the results for each rotation are statistically different at 0.01 probability level.

Lyra (2012) concluded that, in low-yield sugarcane field, more than 17 L per worked hour were saved when low engine rotation was used, since the low yield did not require high power for harvest. In addition, this author claims that, regardless of speed, the hourly fuel consumption was lower when the lowest engine rotation was used.

According to Banchi et al. (2012), fuel consumption per hour may give the wrong impression of advantage when it decreases along the season; however, the opposite occurs when the consumption per harvested ton is analyzed.

Table 3 shows the fuel consumption per area (L ha^{-1}) for the evaluated treatments; V1M3 showed the highest consumption, differing from the others at 0.01 probability level, and V2M1 showed the lowest consumption. These results are similar to those of Belardo (2010), who observed consumption from 72 to 85 L ha^{-1}, but higher than those of Lyra (2012), who reported consumption from 53 to 68 L ha^{-1}.

Area fuel consumption decreased always when the speed increased, statistically differing the forward speeds V1 and V2 at 0.01 probability level. Such behavior is related to the time required for the operation to be performed, i.e., the higher the speed, the shorter the time spent for the harvest of one hectare, resulting in lower fuel consumption.

The means of fuel consumption per area at the evaluated engine rotations were statistically different at 0.01 probability level, and the rotation M1 caused the lowest fuel consumption.

Table 4 shows the fuel consumption per harvested ton of sugarcane (L t^{-1}), for the evaluated treatments.

The treatments with speed of 5.5 km h^{-1} showed lower fuel consumption and did not differ at 0.01 probability level, while the treatments with speed of 4.0 km h^{-1} were different from those with speed of 5.5 km h^{-1} and showed the highest fuel consumption per harvested ton of sugarcane.

Fuel consumption is influenced by the harvester's speed; the higher the speed, the greater will also be the hourly fuel consumption and the lower the consumption per harvested ton (Belardo, 2010; Schmidt Júnior, 2011; Lyra, 2012).

Table 3. Means of fuel consumption per area for the treatments (L ha^{-1})

Engine rotation	Forward speed		Mean
	V1 - 4.0 km h^{-1}	V2 - 5.5 km h^{-1}	
M1 - 1800 rpm	82.4 Ab	70.3 Aa	76.3 A
M2 - 1950 rpm	95.3 Aa	84.5 Ba	89.9 B
M3 - 2100 rpm	112.6 Bb	90.5 Ba	101.6 C
Mean	96.7 b	81.8 a	

Means followed by different letters, lowercase in the rows and uppercase in the columns, differ at 0.01 probability level by Tukey test

Table 4. Fuel consumption per harvested ton for the treatments (L t^{-1})

Engine rotation	Forward speed		Mean
	V1 - 4.0 km h^{-1}	V2 - 5.5 km h^{-1}	
M1 - 1800 rpm	1.02 Ab	0.82 Aa	0.92 A
M2 - 1950 rpm	1.16 Ab	0.90 Aa	0.96 A
M3 - 2100 rpm	1.12 Ab	0.82 Aa	1.03 A
Mean	1.10 b	0.85 a	

Means followed by different letters, lowercase in the rows and uppercase in the columns, differ at 0.01 probability level by Tukey test

As already addressed, such behavior is related to the forward speed and the consequent harvesting capacity, since more sugarcane is harvested as the speed increases, requiring more from the machine and making its hourly consumption increase. As a result, since more sugarcane is harvested, the consumption per ton decreases.

The results of the present study were similar to those of Tomazela et al. (2010), who obtained 0.97 L t^{-1} and, although very close, were higher than those obtained by Lyra (2012), 0.71 L t^{-1}, Belardo (2010), 0.70 L t^{-1}, and Schmidt Júnior (2011), 0.75 L t^{-1}.

Rosa (2013) observed that, due to the greater harvesting capacity for the machine harvesting in dual row spacing, the fuel consumption per harvested ton is lower, being virtually half compared with the results of studies using single row spacing. The author claims that the costs per harvested ton at 7.0 km h^{-1} are on average 30% lower than at 5.0 km h^{-1} and that this fact is related to the greater harvesting capacity and lower fuel consumption per harvested ton, leading to the reduction in the costs of the operation.

According to Magalhães et al. (2008), the demand for sugarcane and the economic competition of the products in the market cause the agricultural sector to search more and more machines with higher efficiency and technology, in order to promote lower losses and higher quality of the harvested raw material, maximizing the profitability.

Ma et al. (2014) claim that there must be improvements in the machines in order to reduce plugging, because they increase the idle time by approximately 14%. In addition, the time in paths and maneuvers reduces field efficiency. However, these factors mainly depend on the geometry of the area and on harvesting practices. Therefore, they will probably not be directly impacted by the improvement of the machine.

According to Peloia et al. (2010), studies on mechanization promote improvements in operations and reduce costs, because the utilization of low speeds can make the use of machines unviable, due to the reduction in harvesting capacity (Santos et al., 2015). Therefore, in the comparison between sugarcane harvesters, the fuel consumption per harvested ton and the effective harvesting capacity must be favored when efficiency is the desired parameter.

Conclusions

1. Engine rotation did not interfere with the harvester's performance, allowing the harvest at the highest speed, without influencing its harvesting capacity.

2. The harvester's harvesting capacity was influenced by its speed and was higher as the forward speed increased.

3. Hourly fuel consumption varied with engine rotation and forward speed, always increasing when rotation or speed increased.

4. The higher the harvester's speed, the lower is the fuel consumption per area and per harvested ton of sugarcane.

5. The lowest engine rotation promoted lower fuel consumption.

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