Transportation of maize silage to biogas plants

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Abstract

Maize silage is one of the most used feedstock for the anaerobic digestion plants in Italy. As biomass, it is necessary to choose maize hybrids and sowing times to reach the maturity stage at the planned harvest period. In addition, the contractor has to set up transport chains considering distances and other factors affecting the forward speed in function of the supplied biogas plants.

This work examined different road conditions (length, weather and congestion) that might influence the maize silage transportation under both the energy and economic points of view. Tests were carried out with an agricultural tractor equipped with two trailers (a turntable steering and a dumper) along six itineraries (6.2, 15.3, 22.1, 32.5, 44.4, and 58.2 km) in two different traffic conditions: high congestion (early morning) and low congestion (evening). Tests were also performed in two seasons with different weather conditions: late Summer and early Autumn.

The average forward speed was 27.40 km h^{-1} with a 15% difference between the best (evening and late Summer) and the worst (early morning and early Autumn) condition, with a productivity that varied between 9.50 and 81.98 m^{3}h^{-1} respectively. The performed tests confirmed that the energetic evaluation is always positive also in the longest itinerary (58.2 km), but the actual market value of maize silage (52.00 € t^{-1}) limits the convenience of the transportation distance up to 18 km. In conclusion, the study showed that the maize silage transportation using agricultural tractors not only depends on the travelled distance, but also on the road congestion and the weather conditions.

Introduction

In these last years the importance of the biomass for energetic purposes increased, especially for its economic and energetic convenience (Spinelli *et al.*, 2011). The biogas plants that use agricultural biomasses are very spread in all the geographic areas at small and large scales (Lijo *et al.*, 2015). Livestock slurries, agro industry residues and cereal silages, are the main products used to feed the anaerobic digestion plants and among cereals, the maize is the most used (Negri *et al.*, 2014). In Europe, many biogas plants are located in livestock farms. In areas with high livestock density, the land for the maize cultivation to feed AD plants can be a limiting factor. In this case, the maize silage may be available some distance away and, as a consequence, increasing the transportation costs, rising the feeding costs (Bacenetti *et al.*, 2015).

Many Authors focused their studies on the generic biomass supply chain in different scenarios (spatial distribution of biomass, road network, …) (Hohn *et al.*, 2014). The main components of the transportation issues are: distance, road characteristics and traffic flow, other than biomass densities (Manzone and Calvo, 2017).

The economic, energetic and environmental sustainability may be influenced by the transportation distance (Bacenetti *et al.*, 2016).

The choice of the vehicles may also be a critical issue (Manzone and Calvo, 2017): the biomass transportation using a truck is more flexible and cheaper for longer distances, but agricultural convoys are more suitable to load the biomass directly in field (Manzone and Balsari, 2015; Manzone and Calvo, 2017). The transport operations are nowadays studied in different agricultural crops (and forestry scenarios). Models to optimize biomass transportation were developed (Jenkins and Sutherland, 2014), but they often considered high distances, not suitable for the maize silage transportation, normally carried out within a radius of 10-50 km. Some studies concerned the biogas production from the biomass, the anaerobic digestion management and the environmental sustainability (Dinuccio *et al.*, 2010; Menardo *et al.*, 2015). Few studies focused the transportation, only considering the logistic aspects and not the energy and economic sustainability. This work analysed the transportation of the maize silage using agricultural tractors and trailers that can load the product directly in field. They can also transport the biomass without intermediate unloads and loads (Manzone and Balsari, 2015), that can negatively influence the product quality and losses (Manzone, 2017). Most of biogas plant manager use contractor for maize silage harvest operated in late summer and early autumn: In about 60 days a single forage harvester runs about 600 h over 1800 ha (180-210 t Wet Basis/h) filling the bunker silos of 6 1MW biogas plants. Every biogas plant has to choose hybrids and sowing times to reach the maturity stage at harvest period planned with the contractor. Contractors have to set up transport chains considering distances but also all factors affecting tractors forward speed on the path from field to plant from plant to field, determining the number of trailers required to keep harvester running. Data on bunker silos location, field distances, roads characteristic and con-

gestion, alternative path and weather forecast are crucial to plan the proper harvesting period for each plant and in each one the daily working time necessary to reduce costs and investments. In critical traffic areas this can lead to the choice of night harvest.

The goal statement was to solve some critical issues that can come out in the transportation of the maize silage. This study examined different routes with different road conditions (as regard weather and congestion) during the maize silage transportation under both the energetic and economic points of view. The road design and congestion influence the vehicles forward speed, the working time and the fuel consumption, important parameters of the environmental impact. The transportation costs for the economic sustainability were also analysed.

Two different trailers (a turntable steering and a dumper) towed to a tractor were used in the tests. These trailers are usually present in the cereal farms and are commonly used for the biomass transportation. A unique operator was involved during all tests, avoiding the influence of different drivers' behaviour.

Materials and methods

Vehicle characteristics

Tests were carried out with a 4WD tractor (New Holland 7-220) equipped with agricultural radial tires and two trailers with the same volume (40 m^3): a turntable steering Crosetto, CMR300, and a dumper Crosetto, NL28, both three–axle trailers and equipped with standard tires (425/65 R22.5).

A driver with three years of experience in tractor driving performed all the test.

The power of the tractor was suitable for the transport operation in different operative conditions (field, gravel and paved road), complying with the allowable forward speed in Italy (40 kmh^{-1}).

Itineraries considered in the tests

Tests were carried out on six commonly used itineraries (Table 1) to transport the maize silage to the anaerobic digestion plant sited in Candiolo (Torino, Italy; GPS: E 7.55902, N 44.95578).

The six itineraries did not cross urban areas and beltways were present in all the examined cases. Since the congestion is influenced by route and weather conditions (Murat *et al.*, 2014), all the itineraries had the same characteristics and only the length was different (Table 1).

The longest distance was 58.2 km, because the availability of maize cultivated area for energy use can be a problem in areas with high zoo technical density. Maize was cut and chopped using a

self-propelled forage harvester (John Deere 7400) and then directly loaded into the trailer in field. The biomass unload was performed tipping the trailers in the bunker silos of the biogas plant.

Scenarios

Agricultural convoys are affected by road condition and traffic volume: as a consequence they cannot travel at a constant forward speed and acceleration and deceleration rates become critical parameters influencing fuel consumption and working time.

The tested convoys travelled each itinerary in two different day times, with different traffic volumes: early morning (high congestion) and evening (low congestion). Tests were also performed in two different road conditions: wet and dry. In the Southern Europe, wet roads are normally present during the Autumn (when fog and moisture are present). During the Summer roads are usually dry, because temperatures are higher (until 35°C) and rain events are occasional. The tests were carried out in 2017, in the second half of August (late Summer) and in the second half of October (early Autumn).

Three repetitions were performed for each roundtrip (144 tests): in the forward journey the trailer was laden, in the return it was unladen.

Travel time consumption and productivity

The productive travel time was acquired following the procedure set up by Magagnotti and Spinelli (2012). The net-working time (NWT; normal travel condition: roundabouts, traffic lights, intersections), the complementary working times (CWT; trailers laden and unladen) and the unproductive working times (UWT; delays referred to unpredictable events during the transportation: roadworks and road accidents) were acquired .

In this study waiting times related to the load of the chopped maize in field and to the unload of the biomass in the biogas plant were not considered because they are influenced by the logistic aspects and not by the transport conditions. A digital stopwatch with a centesimal readability (Hanhart® Profile 5) was used to acquire NWts, CWts and UWts.

The average travel speed was calculated dividing the travel distance by the travel time. The productivity was in m^3 h^{-1} and in m^3 km^{-1}.

Energy evaluation

Energy output

In this study, the output of the transport operation was the energy content of the transported biomass. This value was calculated as a function of the biomass density, dry matter content and high heating value. The transported maize silage had an average density of

Table 1. Route characteristics.

Itinerary	From	To	Lenght (km)	Roundabout (n)	Intersection (n)	Traffic light (n)	Railway crossing (n)	Gravel road (m)
A	None	Candiolo	6.2	3	4	1	1	390
B	Virle	Candiolo	15.3	5	5	2	0	488
C	Vigone	Candiolo	22.1	8	6	1	0	680
D	Villafranca	Candiolo	32.5	7	9	3	0	634
E	Marene	Candiolo	44.4	11	9	2	0	340
F	Fossano	Candiolo	58.2	15	10	4	0	510

320 kgm^{-3} (measured during the load operation). The density of the biomass was calculated weighting each trailer by a certified weighbridge (GOMBA® T5, 20 kg of readability): the loaded biomass was previously levelled in the trailer body.

The average moisture content was 67%. It was calculated using three samples (1 kg each), randomly selected from each trailer before unloading. The gravimetric method was used for the moisture evaluation, by a ventilated stove with an internal temperature of 103°C (UNI EN 14774-2, 2010). A precision digital scale (METTLER TOLEDO ® MS12002TS) was used, with an accuracy of 0.01 kg for each measurement.

The three samples were useful also to calculate the maize silage energy content, measuring the dry matter and the high heating value (HHV), as indicated for biomass for energy use (Magagnotti and Spinelli, 2012). The HHV was determined by the European Standard UNI EN 14918 (2010), using an oxygen bomb calorimeter (IKA® C200). The low heating value (LHV) was calculated using Equation 1 (Magagnotti and Spinelli, 2012).

$$LHV = (Sdw \cdot HHV) - (Ww \cdot Ew) \tag{1}$$

where:
LHV = low heating value (MJ);
Sdw = dry maize silage mass (kg);
HHV = high heating value (MJ kg^{-1});
Ww = water weight (kg);
Ew = amount of energy needed to evaporate the water in the biomass (2.5MJ kg^{-1}).

Energy input

The energy consumption related to the biomass transportation was determined considering the direct energy content (fuel and lubricant consumption) and the indirect energy spent for machines manufacturing.

The input and output energy values of the biomass transportation were calculated multiplying fuel and lubricant consumption (and the amount of other different inputs) by specific energy coefficients. The energy content was 37.0 MJ L^{-1} for fuel and 83.7 MJ kg^{-1} for lubricant. An additional energy value inflation of 1.2 MJ kg^{-1} (linked to the product transportation) was assumed for fuel and lubricant. Equation 2 was used to calculate the energy consumption (E$_C$) related to the machine use:

$$E_C = \frac{E_M \cdot E_L \cdot M}{W_T \cdot U_P} \tag{2}$$

where:
E_C = energy consumption related to the machine use (MJ m^{-3});
E_M = energy embedded in the machine (MJ kg^{-1} per year);
E_L = economic life of the machine (years);
M = mass of the machine (kg);
W_T = annual working time (h);
U_P = unit of production (m^3 h^{-1}).

Different energy coefficients were considered in function of the machine type: 9.5 MJ kg^{-1} per year for the tractor and 7.0 MJ kg^{-1} per year for the trailers. Tractor was assumed to have an useful life of 10,000 h, while 3000 h were considered for the trailer . The surveyed annual utilization was 580 hours for the tractor (used also for other agricultural activities) and 190 hours for the trailer. Repair and maintenance used the 55% of the energy content for machine manufacturing (Fluck, 1985) and it was part of the indi-

rect energy. Fuel consumed during the biomass transportation was measured by the *topping-off system* (tank refilling at the end of the travel). The tank was refilled with a measurement accuracy of 0.02 liters (Manzone and Spinelli, 2014). The consumed lubricant was estimated as 2% of fuel consumption (ASAE, 1999).

Energy parameters

The energy balance (EB) was the method to evaluate the energy efficiency of the transport operation for agricultural systems. It was calculated as the ratio between energy output (MJ m^{-3}) and energy input (MJ m^{-3}) [Eq. (3)]. Other energy indices related to transportation were: the energy productivity (EP), the specific energy (SE) and the net energy (NE) [Eqs. (4-6)]. The energy productivity was calculated both per volume (EP$_v$) (4a) and per distance unit (EP$_d$) (4b).

$$EB = \frac{Eom}{Eim} \tag{3}$$

where:
EB: energy balance;
Eom: energy output [*MJ m^{-3}*];
Eim: energy input [*MJ m^{-3}*];

$$EP_v = \frac{So}{Eih} \tag{4a}$$

where:
EP$_v$: energy productivity per volume unit [*m^{3}MJ^{-1}*];
So: maize silage output[*m^{3}h^{-1}*];
Eih: energy input[*MJ^{-1}*].

$$EP_d = \frac{Fs}{Eih} \tag{4b}$$

where:
EP$_d$: energy productivity per distance unit [*kmMJ^{-1}*];
Fs: forward speed [*km h^{-1}*];
Eih: energy input [*MJ^{-1}*].

$$SE = \frac{Eih}{So} \tag{5}$$

where:
SE: specific energy [*MJm^{-3}*];
Eih: energy input [*MJ h^{-1}*];
So: biomass output [*m^{3}h^{-1}*].

$$NE = Eom - Eim \tag{6}$$

where:
NE: net energy [*MJm^{-3}*];
EOm: energy output [*MJ m^{-3}*];
Eim: energy input [*MJ m^{-3}*].

The manpower was calculated only per time unit and it was not considered in the energy evaluation.

Hourly costs

Transportation costs were calculated considering tractor and trailer hourly costs. The machine fixed costs were determined using the procedures as in Sopegno *et al*. (2016). The economic evaluation considered the useful life and annual utilizations of the machines as in the energy evaluation. The purchase cost of the tractor and the trailers was respectively 85,500.00 € and 25,000.00 €. Repair and maintenance costs were directly obtained by the vehicles owner updated to the current year (2019). The cost of the tractor driver was 18.50 € h^{-1} (including insurance and health costs). The fuel and lubricant costs were 0.90 € kg^{-1} and 5.50 € kg^{-1}. In the Northwest Italy, during the study development, the average market price of the maize silage was about 52.00 € t^{-1}, wet basis (80.00 € tDM^{-1}). Considering the fixed costs (harvesting and in field crop purchase) and a 20% of profit, it is possible to assume a maximum cost of 4.70 € t^{-1} (1.47 € m^{-3}) for the biomass transportation. The economic sustainability of the transport operation was determined adopting the net present value (NPV), the difference between the total income and the total costs.

Statistical analysis

Data were processed using IBM-SPSS Advanced Statistic Package, version 24. The ANOVA test was used, with a significance level equal to 0.05. The ANOVA procedures were executed after testing the variance homogeneity. The Tukey's *post-hoc* analysis was the method to compare individual means.

Results

Differences between the two tractor-trailers combinations

The statistical analysis highlighted any significant difference between the two tractor-trailer combinations in all different conditions, both in transportation times and fuel consumption (Table 2).

The two tractor-trailer combinations (the same tractor towing different trailers, gained energetic and economic results not statistically different.

Statistics did not show any difference between the two combinations also in the manoeuvre times because the different structure of the trailers was negligible in our test conditions due to the large dimension of both the field heads and the bunker silos. For these reasons, all the further elaborations were carried out without considering the factor tractor-trailer combination.

Transportation times and productivity

The travel time (variable between 0.49 and 4.21 h) was influenced by the itinerary length (Table 3), congestion and, only in particular situations, by the weather conditions (Figure 1). The itineraries C and F registered higher travel times in late harvest season when a long-lasting fog was present along the route.

The unproductive working times (UWT) were always under the 1% of the total travel time. The average loading time in field was around 11 min, while the unloading time in biogas plant bunker silo was about 4 min - including, in both cases, times for manoeuvres. Loading and unloading times (CWT) less influenced the net transportation times (NWT) closely related to the length of the route (Figure 2): in any case the return travel (unladen) has always been characterized by a shorter travel time. The NWT per kilometre ranged between 4 and 5.9 minutes respectively for longer and shorter itineraries.

The average forward speed (and consequently the NWT) was affected by the different traffic conditions (Table 3) and it increased from 3-4 kmh^{-1} during the evening to 8 kmh^{-1} in the shortest itinerary (Figure 3).

The productivity varied between 9.50 and 81.98 m^3h^{-1}; the highest value was observed with lower congestion, at the beginning of the harvest season in late summer and in the shorter itineraries.

The manpower was in the range of 44.14 and 379.22 second m^{-3} km^{-1} per work unit (UW) (Table 3).

Statistical analysis highlighted a higher variability among the data along the different itineraries, with the exception of travel speed in itineraries B and C as well as in itineraries E and F (Table 4).
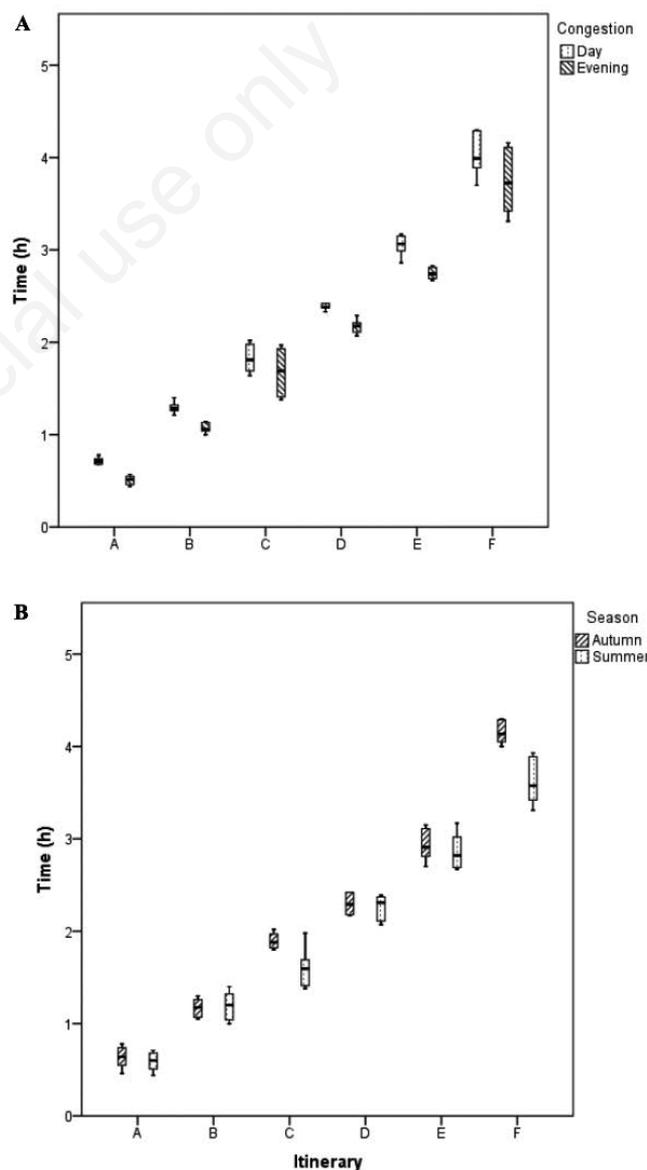
Figure 1. Transportation times along the six itineraries and with different congestion (A) and weather (B) conditions.

Energy consumption

The average HHV of the transported maize silage was 18.6 ± 0.47 MJ·kg⁻¹, while the LHV was 4.6 ± 0.21 MJ·kg⁻¹. These values are in line with other studies carried out in other geographical areas (Pordesimo *et al.,* 2005).

The total energy required varied from 5.99 to 74.52 MJ m⁻³ in function of the itinerary length (Table 5).

The main component of the total energy was the direct energy, that varied exponentially in function of the travelled distance, unlike the linear variation of the indirect energy (Figure 4). In these figures the curve which best fits the direct and indirect aver-

Table 2. GLM output of the transportation times (time) and fuel consumption (consumption) obtained by the two combinations tractor-trailer in the different test conditions (itinerary, season and congestion).

Origin		ss	df	Ms	F	P-value
Corrected model	Time	169.565ᵃ	4	42.391	1221.128	<0.0001
	Consumption	6167.792ᵇ	4	1541.948	1221.872	<0.0001
Intercept	Time	0.090	1	0.090	2.591	0.110
	Consumption	3.224	1	3.224	2.555	0.112
Itinerary	Time	166.673	1	166.673	4801.192	<0.0001
	Consumption	6065.978	1	6065.978	4806.807	<0.0001
Season	Time	0.893	1	0.893	25.725	<0.0001
	Consumption	32.348	1	32.348	25.633	<0.0001
Congestion	Time	1.904	1	1.904	54.858	<0.0001
	Consumption	69.375	1	69.375	54.974	<0.0001
Trailer	Time	0.095	1	0.095	2.739	0.100
	Consumption	0.092	1	0.092	0.073	0.788
Error	Time	4.825	139	0.035		
	Consumption	175.412	139	1.262		
Total	Time	810.355	144			
	Consumption	29494.602	144			
Corrrected total	Time	174.391	143			
	Consumption	6343.204	143			

ᵃR-squared = .972 (R-squared corrected = .972). ᵇR-squared = .972 (R-squared corrected = .972). ss, sum of squares; df, degree of freedom; Ms, mean square; F, F test; P-value, significance.

Table 3. Descriptive statistic of the travelled time (Time), forward speed (Speed), productivity and manpower parameters.

Itinerary	Season	Congestion	Time (s)		Speed (kmh⁻¹)		Productivity (m³h⁻¹)		Manpower (sm⁻³km⁻¹)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
A	Summer	Day	0.69	0.02	18.49	0.51	57.82	1.58	62.29	1.73
		Evening	0.49	0.04	26.21	2.34	81.98	7.32	44.14	3.78
	Autumn	Day	0.74	0.04	17.31	0.83	54.14	2.58	66.59	3.17
		Evening	0.53	0.06	24.58	2.72	76.86	8.49	47.20	4.95
B	Summer	Day	1.33	0.07	23.40	1.14	30.10	1.46	119.77	5.90
		Evening	1.06	0.07	29.53	1.85	38.00	2.38	94.98	6.05
	Autumn	Day	1.26	0.05	24.78	0.87	31.89	1.11	112.99	3.91
		Evening	1.09	0.05	28.66	1.15	36.87	1.48	97.73	3.99
C	Summer	Day	1.77	0.18	25.52	2.49	22.74	2.22	159.37	16.42
		Evening	1.45	0.09	31.16	1.98	27.76	1.76	130.01	8.52
	Autumn	Day	1.88	0.12	23.92	1.50	21.31	1.34	169.36	11.03
		Evening	1.91	0.07	23.50	0.89	20.94	0.79	172.09	6.43
D	Summer	Day	2.36	0.03	27.74	0.35	16.91	0.21	212.94	2.64
		Evening	2.16	0.12	30.53	1.63	18.60	1.00	193.87	10.65
	Autumn	Day	2.40	0.03	27.32	0.33	16.65	0.20	216.26	2.60
		Evening	2.19	0.02	29.97	0.25	18.27	0.15	197.06	1.67
E	Summer	Day	3.02	0.16	29.46	1.55	13.28	0.70	271.60	14.22
		Evening	2.71	0.06	32.71	0.68	14.74	0.30	244.22	5.10
	Autumn	Day	3.08	0.08	28.80	0.77	12.98	0.35	277.50	7.31
		Evening	2.78	0.07	31.93	0.79	14.39	0.36	250.21	6.12
F	Summer	Day	3.84	0.12	30.81	1.02	10.42	0.34	345.86	11.26
		Evening	3.39	0.07	34.86	0.80	11.78	0.27	305.56	6.97
	Autumn	Day	4.21	0.14	28.10	0.96	9.50	0.32	379.22	12.64
		Evening	4.09	0.08	28.93	0.60	9.78	0.21	368.12	7.61

The values in the table are the mean of the three replications. SD, standard deviation.

age values is represented with dot lines, while the curves that represent the minimum and the maximum values are continuous lines. The minimum values refer to the best travel conditions (during the evening at the beginning of harvest season in late Summer): the maximum values resulted in daytime travels in the late harvest season (early Autumn).

The direct energy consumption was function of both itinerary length and road conditions, and values varied between 10% in itinerary D and 120% in itinerary E. The indirect energy data had a variation between 12% in itinerary D and 47% in itinerary A.

The statistical analysis - performed on the direct, indirect and maintenance energy consumption per meter cube of transported biomass - evidenced differences among all the itineraries; likeness were obtained in the two periods of the harvest season and in the different traffic conditions (Table 4).

Energy balance, specific energy, energy productivity and net energy

Energy balance, energy productivity and net energy were

Figure 2. Net-working times (NWT) and complementary working times (CWT) contributions in the different itineraries.
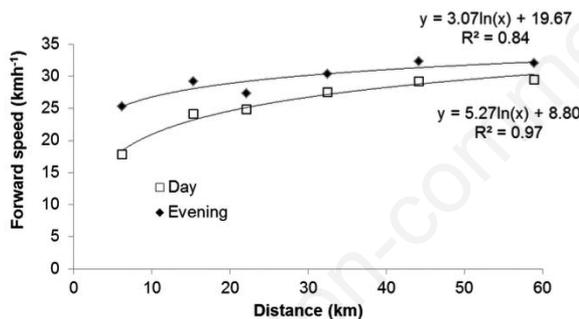
Figure 3. Averaged travel times in different congestion scenarios *versus* the travelled distance (P<0.0001 in both the curves). R² = R squared statistic.
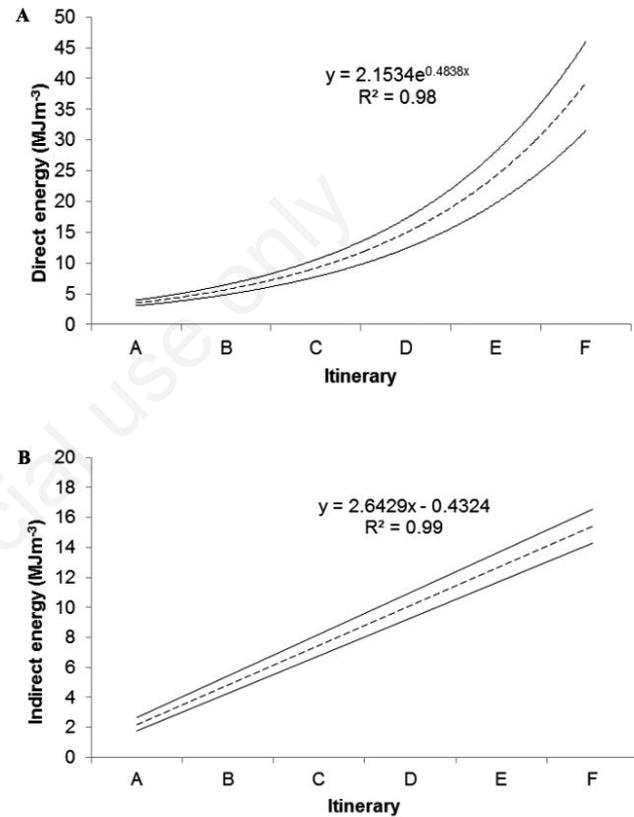
Figure 4. A) Direct energy consumption (MJ m⁻³) and (B) indirect energy consumption (MJm⁻³) in function of the travelled distance (average: dot line, minimum and maximum continuous lines) (P<0.0001). R² = R squared statistic.

Table 4. ANOVA table.

		Time (h)	Speed (kmh⁻¹)	Product. (m³h⁻¹)	Direct energy (MJm⁻³)	Mainten. energy (MJm⁻³)	Indirect energy (MJm⁻³)	Energy balance	Specific energy (MJm⁻³)	Net energy (MJm⁻³)	Energy product. (m³MJ⁻¹)
Itinerary	A	0.61ᵃ	21.65ᵃ	67.70ᵃ	3.43ᵃ	1.41ᵃ	2.57ᵃ	471.83ᵃ	6.26ᵃ	3376.59ᵃ	0.165ᵃ
	B	1.18ᵇ	26.59ᵇ	34.22ᵇ	6.38ᵇ	2.73ᵇ	4.96ᵇ	243.02ᵇ	11.85ᵇ	3369.93ᵇ	0.085ᵇ
	C	1.75ᶜ	26.02ᵇ	23.19ᶜ	9.34ᶜ	4.04ᶜ	7.35ᶜ	165.68ᶜ	17.45ᶜ	3363.26ᶜ	0.058ᶜ
	D	2.28ᵈ	28.89ᶜ	17.61ᵈ	12.07ᵈ	5.26ᵈ	9.56ᵈ	126.20ᵈ	22.61ᵈ	3357.11ᵈ	0.044ᵈ
	E	2.90ᵉ	30.73ᵈ	13.85ᵉ	24.03ᵉ	6.69ᵉ	12.16ᵉ	99.47ᵉ	28.69ᵉ	3349.86ᵉ	0.035ᵉ
	F	3.88ᶠ	30.68ᵈ	10.37ᶠ	43.48ᶠ	8.97ᶠ	16.30ᶠ	74.63ᶠ	38.38ᶠ	3338.32ᶠ	0.026ᶠ
Seas.	Sum.	2.02ᵃ	28.37ᵃ	28.68ᵃ	10.75ᵃ	4.67ᵃ	8.49ᵃ	202.74ᵃ	20.10ᵃ	3360.10ᵃ	0.058ᵃ
	Aut.	2.18ᵃ	26.48ᵇ	26.97ᵇ	11.56a	5.03ᵃ	9.15ᵃ	190.87ᵃ	21.64ᵃ	3358.26ᵃ	0.054ᵃ
Cong.	Day	2.22ᵃ	25.47ᵃ	24.81ᵃ	11.75ᵃ	5.12ᵃ	9.30ᵃ	176.24ᵃ	22.00ᵃ	3357.83ᵃ	0.052ᵃ
	Even.	1.99ᵃ	29.38ᵇ	30.83ᵇ	10.56ᵃ	4.58ᵃ	8.33ᵃ	217.37ᵇ	19.74bᵇ	3360.52ᵃ	0.060ᵇ

ᵃ⁻ᶠDifferent letters indicate significant differences between treatments (α=0.05).

inversely proportional to the itinerary length, while specific energy was directly proportional to it (Table 6).

The energy balance was always positive and decreased in function of the travelled distance (Figure 5). The lowest observed value (68.39) was in the longest itinerary (F) during the late harvest season with high congestion (early morning), while the highest value (567.64) was obtained in the shortest itinerary (A) in early harvest season with low congestion (evening). In this itinerary a high vari-

ability was observed (Figure 5 and Table 6).

Considering the road conditions in the different congestion (early morning and evening), the highest variation of the energy balance was recorded in itinerary A (40%), while the lowest was obtained in itineraries C and F (2%). Considering the harvest season (late Summer and early Autumn), the highest variation was observed in itineraries D and E (2%) and the lowest in the itinerary C (33%).
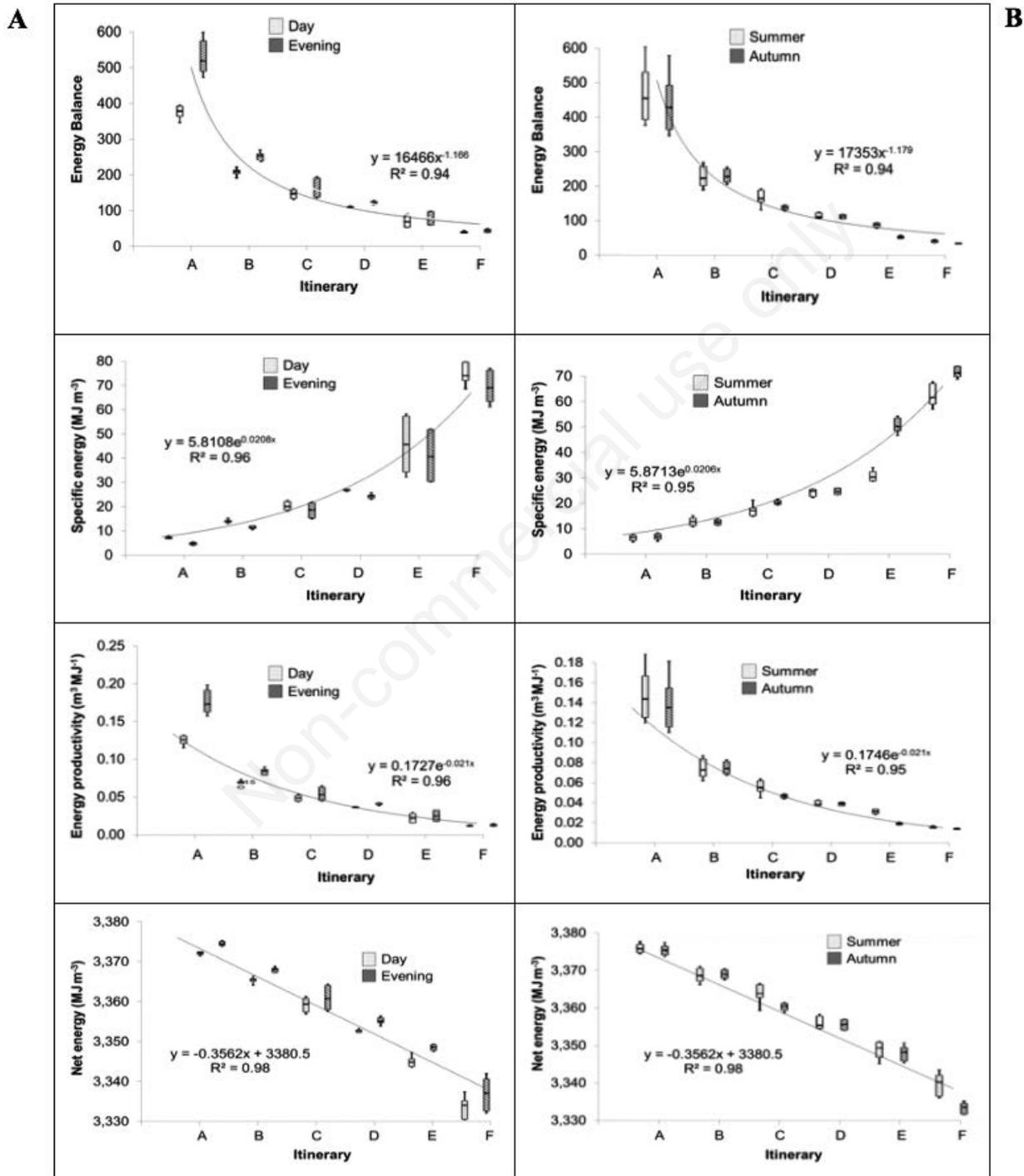
Figure 5. Energy balance, specific energy, energy productivity net energy box plots in function of the itinerary and congestion (A) and itinerary and season (B) (P<0.0001 in all curves). R^2 = R squared statistic.

Table 5. Descriptive analysis of the direct, indirect, maintenance and total energies.

Itinerary	Season	Congestion	Direct energy (MJm^{-3})		Indirect energy (MJm^{-3})		Maintenance energy (MJm^{-3})		Total energy (MJm^{-3})	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
A	Summer	Day	3.85	0.10	2.91	0.08	1.60	0.04	8.35	0.22
		Evening	2.80	0.22	2.06	0.17	1.13	0.10	5.99	0.49
	Autumn	Day	4.09	0.18	3.11	0.15	1.71	0.08	8.91	0.42
		Evening	2.97	0.29	2.20	0.23	1.21	0.13	6.39	0.64
B	Summer	Day	7.15	0.34	5.58	0.27	3.07	0.15	15.81	0.77
		Evening	5.73	0.35	4.43	0.28	2.43	0.15	12.59	0.78
	Autumn	Day	6.77	0.23	5.27	0.18	2.90	0.10	14.93	0.51
		Evening	5.89	0.23	4.55	0.19	2.51	0.10	12.95	0.52
C	Summer	Day	9.44	0.95	7.43	0.77	4.09	0.42	20.96	2.13
		Evening	7.75	0.49	6.06	0.40	3.33	0.22	17.14	1.11
	Autumn	Day	10.02	0.64	7.90	0.52	4.34	0.28	22.25	1.43
		Evening	10.17	0.37	8.02	0.30	4.41	0.17	22.61	0.83
D	Summer	Day	12.53	0.15	9.93	0.12	5.46	0.07	27.92	0.35
		Evening	11.43	0.61	9.04	0.50	4.97	0.27	25.44	1.39
	Autumn	Day	12.72	0.15	10.08	0.13	5.55	0.07	28.35	0.34
		Evening	11.61	0.10	9.19	0.08	5.05	0.04	25.86	0.22
E	Summer	Day	15.91	0.82	12.66	0.66	6.96	0.37	35.54	1.85
		Evening	14.33	0.30	11.39	0.24	6.26	0.13	31.98	0.66
	Autumn	Day	34.62	0.90	12.94	0.34	7.12	0.19	54.67	1.43
		Evening	31.27	0.75	11.66	0.28	6.42	0.16	49.35	1.19
F	Summer	Day	43.01	1.38	16.13	0.52	8.87	0.29	68.01	2.20
		Evening	38.06	0.86	14.25	0.32	7.83	0.18	60.14	1.36
	Autumn	Day	47.11	1.55	17.68	0.59	9.72	0.32	74.52	2.47
		Evening	45.75	0.94	17.16	0.36	9.44	0.20	72.35	1.48

The values in the table are the mean of the three replications. SD, standard deviation.

Table 6. Average energy parameters per congestion, season, and itinerary.

Itinerary	Season	Congestion	Energy balance		Energy productivity (m^{3}MJ^{-1})		Energy productivity (kmMJ^{-1})		Specific energy (MJm^{-3})		Net energy (MJm^{-3})	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
A	Summer	Day	405.59	10.76	0.142	0.004	0.038	0.001	7.04	0.19	3375.65	0.22
		Evening	567.64	48.40	0.198	0.016	0.054	0.005	5.07	0.41	3378.01	0.49
	Autumn	Day	380.49	17.58	0.133	0.006	0.036	0.002	7.52	0.35	3375.09	0.42
		Evening	533.59	56.50	0.186	0.020	0.051	0.006	5.40	0.54	3377.61	0.64
B	Summer	Day	214.32	10.25	0.075	0.004	0.049	0.002	13.31	0.64	3368.19	0.77
		Evening	269.40	16.51	0.095	0.006	0.062	0.004	10.61	0.66	3371.41	0.78
	Autumn	Day	226.79	7.77	0.079	0.003	0.052	0.002	12.57	0.42	3369.07	0.51
		Evening	261.57	10.30	0.092	0.004	0.060	0.003	10.91	0.43	3371.05	0.52
C	Summer	Day	162.54	15.70	0.057	0.005	0.054	0.005	17.63	1.79	3363.04	2.13
		Evening	197.92	12.36	0.070	0.004	0.066	0.004	14.43	0.93	3366.86	1.11
	Autumn	Day	152.47	9.48	0.054	0.003	0.051	0.003	18.72	1.20	3361.75	1.43
		Evening	149.81	5.61	0.053	0.002	0.050	0.002	19.02	0.70	3361.39	0.83
D	Summer	Day	121.23	1.49	0.042	0.001	0.050	0.001	23.47	0.28	3356.08	0.35
		Evening	133.28	7.06	0.047	0.003	0.055	0.003	21.39	1.16	3358.56	1.39
	Autumn	Day	119.39	1.43	0.042	0.001	0.049	0.001	23.83	0.28	3355.65	0.34
		Evening	130.90	1.09	0.046	0.000	0.054	0.001	21.74	0.18	3358.14	0.22
E	Summer	Day	95.40	4.98	0.033	0.002	0.062	0.004	29.86	1.55	3348.46	1.85
		Evening	105.85	2.17	0.037	0.001	0.069	0.001	26.88	0.55	3352.02	0.66
	Autumn	Day	93.26	2.47	0.033	0.001	0.061	0.002	30.50	0.80	3347.70	0.95
		Evening	103.35	2.54	0.036	0.001	0.068	0.002	27.53	0.67	3351.24	0.80
F	Summer	Day	74.95	2.47	0.026	0.001	0.066	0.002	37.96	1.23	3338.82	1.46
		Evening	84.74	1.94	0.030	0.001	0.074	0.002	33.56	0.76	3344.05	0.91
	Autumn	Day	68.39	2.31	0.024	0.001	0.060	0.002	41.59	1.38	3334.49	1.64
		Evening	70.41	1.46	0.025	0.001	0.061	0.002	40.39	0.83	3335.93	0.99

The values in the table are the mean of the three replications. SD, standard deviation.

The highest value of specific energy was observed in the longest itinerary (F, 41.59 MJ m^{-3}), whereas the lowest value was in the shortest (A, 5.07 MJm^{-3}). The specific energy increased as an exponential function of the itinerary length (Figure 5). This energy parameter can also be affected by the weather and traffic conditions (Figure 5). In fact, travelling in different periods of the harvest season may occur a data variation lower than 17% (itinerary F), while performing the travel in different traffic conditions can lead to a variation until 28% (itinerary A) (Table 6).

When the energy productivity is expressed per volume unit (m^3), the observed data followed the trend of a negative exponential function (Figure 5). In this case the values varied from 0.024 to 0.198 (Table 4).

The net energy data were very high, around 3357±21 MJm^{-3} (Table 4). The net energy was inversely proportional to the itinerary length, with a linear trend (Figure 5). For the y-axis a short scale was used, otherwise the graphical representation was reduced to a horizontal line (Figure 5).

As expected, the statistical analysis revealed differences along the travelled itineraries, while similarities were recognized between early and late harvest season, with the exception of the energy productivity expressed per unit of distance. Considering the congestion, likeness were detected only for the net energy parameter (Table 4).

Transportation costs

Transport costs per unit of travelled distance (km) and transported volume (m^3) are reported in table 4. It is possible to appreciate that the variation interval is quite similar for both parameters, decreasing from 3.34 to 1.11 for the costs per kilometre and increasing from 0.86 to 3.97 for the costs per unit volume.

Statistical analysis highlighted likeness in the distance parameter and not in the transported volume (Table 4). The costs per unit of volume were similar in the harvest season (itineraries A, B, D and E) and different in the congestion level (Table 7).

The unit costs per travelled kilometre was a negative power of the distance (Figure 6), and linear increased for transported unit (Figure 6), with a high correlation coefficient (>0.94, p-values 0.072 and 0.089 respectively). The transportation costs are conditioned by the harvest season and traffic flow: for this reason, also indications about minimum and maximum transportation costs are given (Figures 4 and 5).

With a price of maize silage of 52.00 € t^{-1}, data analysis highlighted that the economic advantage exists if the maximum travel distance is lower than 18 km, with a maximum transportation cost of 1.47 € m^{-3} (Figure 7).

Discussion

The productivity (expressed in dry matter transported per-hour) in this experimentation was similar to that calculated in other studies focused on woodchip transportation with agricultural convoys (Manzone and Balsari, 2015; Manzone and Calvo, 2017). Although the maize silage shows a density lower than to the woodchip (about 30%), the amount of biomass transported was similar because in maize transportation is usually to use trailers equipped with specific containers sized to reach the maximum volume allowed by Italian traffic laws (up to 40 m^3). The tests carried out showed that transportation times were influenced more by the congestion (early morning or evening) than by the road conditions (in late Summer or in early Autumn). For this reason, in supply chain

Table 7. ANOVA of the cost parameters per itinerary, season and congestion.

Itinerary	Season	Congestion	Cost per unit			
			(€ km^{-1})		(€ m^{-3})	
			Mean	SD	Mean	SD
A	Summer	Day	3.21[a]	0.05	1.03[a]	0.02
		Evening	2.69[b]	0.11	0.86[b]	0.04
	Autumn	Day	3.34[a]	0.09	1.07[a]	0.03
		Evening	2.78[b]	0.15	0.89[b]	0.04
B	Summer	Day	2.01[c]	0.07	1.56[c]	0.06
		Evening	1.71[d]	0.07	1.33[d]	0.06
	Autumn	Day	1.93[c]	0.05	1.50[c]	0.04
		Evening	1.75[d]	0.05	1.36[d]	0.04
C	Summer	Day	1.72[d]	0.14	1.93[e]	0.16
		Evening	1.48[e]	0.07	1.66[f]	0.08
	Autumn	Day	1.80[f]	0.09	2.02[g]	0.10
		Evening	1.83[f]	0.05	2.05[g]	0.06
D	Summer	Day	1.75[d]	0.02	2.43[h]	0.03
		Evening	1.62[d]	0.07	2.25[i]	0.10
	Autumn	Day	1.77[d]	0.02	2.46[h]	0.03
		Evening	1.64[d]	0.01	2.28[i]	0.02
E	Summer	Day	1.34[g]	0.06	2.97[m]	0.13
		Evening	1.23[h]	0.02	2.72[n]	0.04
	Autumn	Day	1.36[g]	0.03	3.03[m]	0.07
		Evening	1.25[h]	0.03	2.78[n]	0.06
F	Summer	Day	1.24[h]	0.03	3.66[p]	0.11
		Evening	1.11[m]	0.02	3.29[q]	0.06
	Autumn	Day	1.35[g]	0.04	3.97[r]	0.12
		Evening	1.31[g]	0.03	3.87[r]	0.07

The values in the table are the mean of the three replications. SD, standard deviation. [a-r]Different letters indicate significant differences between treatments (α=0.05).

management of biogas plants needs to give higher attention to the potential traffic jams linked to rush hours and road characteristics (urban or extraurban roads, one-lane or multi-lane roads) of the itineraries choose to perform the biomass transportation than the eventual worst weather conditions (rain, fog) present during the transport. Nevertheless, the average forward speed (27.40 km h^{-1}) can suffer of a significant reduction (about 15%) in presence of fog (in early Autumn) and storms (in late Summer) that may cause slowdowns due to poor visibility. Traffic congestion and harvest period (in early Autumn or in late Summer) affected also the productivity (approximately 25%) highlighting the lower values in early Autumn (24.41 m^{3}h^{-1}). In this regard, we wish to recall that the loading times can have a great influence on the total working time, especially in short itineraries where their incidence is higher. In addition, the loading times are unquantifiable, especially during the work planning, because they depend from the logistic aspects of the harvesting operation (waiting times linked to trailers turn over) and regular layout of the field (higher is the irregular layout, higher are the manoeuvres) as observed by Orfanou *et al.* (2013).

Independently by the transport distance and route conditions, the transportation of the maize silage using agricultural convoys was always positive from the energetic point of view, with an energy balance higher than 43. This is a good value, because it is in line with the values obtained for forestry residues (Murphy *et al.,* 2014) and woodchip (Manzone and Calvo, 2017) transportation. Energy balance showed a higher variability in the shortest itinerary, mainly caused by an increased incidence effect of unpredictable road constraints on total travel time, as observed also by other authors in woodchip transportation (Manzone and Calvo, 2017). On the contrary, the bad weather conditions (fog, drizzle, rain) affected mainly longer itineraries. Fuel and lubricant (direct energy) had an incidence near 45% on total energy requirement while the incidence of tractor and trailers embodied energy (indirect energy) was only near 35%; also in this case, the results are in line with those found by other authors for biofuel (Murphy *et al.,* 2014) and woodchip transportation (Manzone and Calvo, 2017). The direct energy resulted inversely proportional to the itineraries length because the incidence of the indirect energy decrease as a function of the vehicles time used (Bijrjesson, 1996). Repair and maintenance highlighted the lowest contribution (average 20%) on the total energy requirement. This aspect is well known in the biomass sector, where similar results are obtained by other machines: planters (Manzone, 2016) and chippers (Manzone, 2015), and loaders (Manzone, 2018). Another key point to support the energetic sustainability of the maize silage transportation using agricultural convoys is the high positive value of the net energy per unit of transported volume: in fact, the input energy required was always lower than 1.5%, compared to the transported material energy content. Considering the economic aspect, the maximum distance to get a profit is only 18 km, as transportation costs are affected by the distance, with an average increase of 0.06 € per travelled kilometre. The maize silage transportation is connected to the harvesting operations: for longer distances (over 15 km), it is difficult to plan a trailer turnover logistic, to allow the continuous operation of the harvester (Velazquez-Marti and Fernandez-Gonzales, 2010). Travelling with good road conditions was advantageous, as found in another study on woodchip transportation (Manzone and Calvo, 2017). The development of a transportation model could also be useful for the biomass transportation, as already done in other contexts (Harmon and Luck, 2016). For longer distances, it could be convenient to use trucks, not only for their higher payload and forward speed (Manzone and Balsari, 2015; Manzone and Calvo, 2017), but also for their lower environmental impact, especially in

roundtrips higher than 25 km (Bacenetti *et al.,* 2015). In this case, it is necessary to transfer the maize silage form the shuttle trailer (used in field) to the truck roadside. If the transportation is instead performed in the farm yard using conventional loaders (requiring the ground discharge of the material), significant biomass losses may occur (Manzone, 2017).
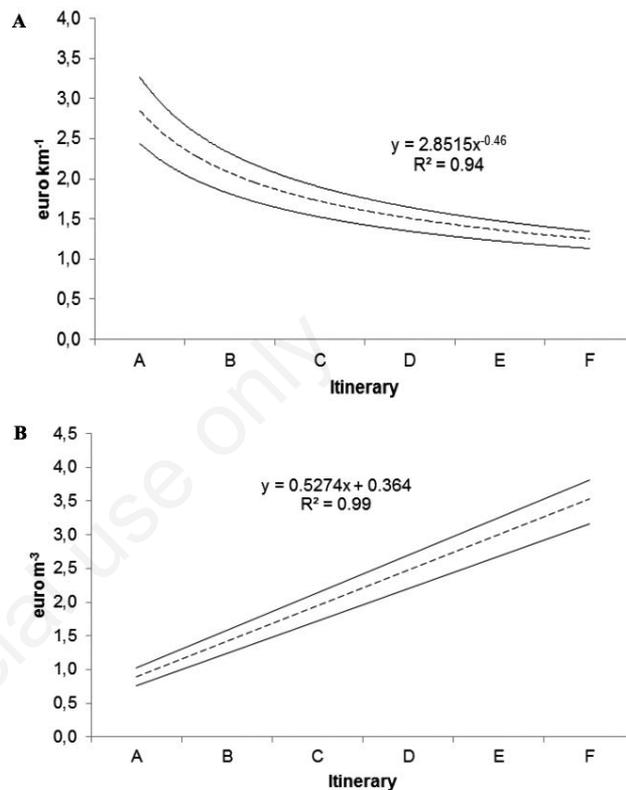
Figure 6. Cost per travelled kilometre and per cubic meter of biomass transported in function of the itinerary (average: dot line; maximum and minimum: continuous lines) (P<0.0001). R^2 = R squared statistic.
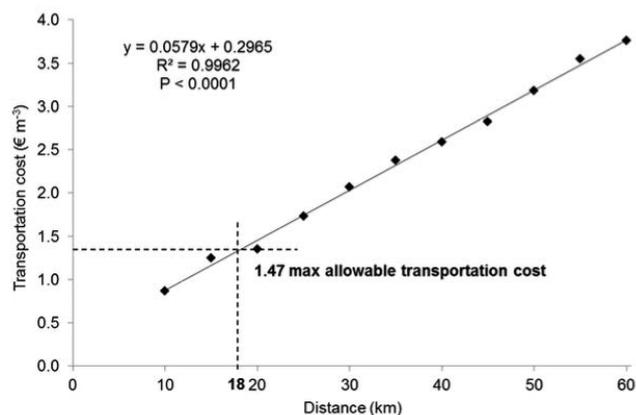
Figure 7. Economic sustainability of biomass transportation in function of the travelled distance. R^2 = R squared statistic.

Conclusions

The study showed that the maize silage transportation using agricultural tractors depends not only on the travelled distance, but also on the road congestion and the weather conditions. Travelling with low congestion is less energetic and economic expensive than transporting the biomass during the high congestion.

The performed tests highlighted that the energy evaluation is always positive also for distances until 60 km; on the contrary, the current market value of maize silage (52.00 € t^{-1}) limits the transportation distance to 18 km.

The farmers may use the described methodology to evaluate slowdowns due to the road and the weather conditions also for the harvesting of the biomass. For example, if he plans the transportation in the evening instead of in the morning, he may know how much the travel times will differ and correctly plan the harvesting.

The tests performed in this experimentation were time consuming and quite expensive, because many itineraries were investigated also in unfavourable weather conditions: for these reasons, the possibility to use a model to foresee the transportation times could be useful.

Highlights

- Agricultural vehicles were considered in used on maize for silage transportation;
- Six itineraries, two climate weather conditions, and two congestions level were considered;
- The energy balance is always positive;
- The energy spent depend by the distance and the climate weather conditions;
- The maize silage transportation is economically sustainable up to 18 km.

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