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Article

Soil Tillage Systems and Wheat Yield in Climate Change Scenarios

Pieranna Servadio [1,*], Simone Bergonzoli [1] and Claudio Beni [2]

[1] Council for Agricultural Research and Economics, Agricultural Engineering Research Unit (CREA-ING), Via della Pascolare 16, 00015 Monterotondo, Italy; simone.bergonzoli@crea.gov.it

[2] Council for Agricultural Research and Economics, Research Centre for Soil-Plant System (CREA-RPS), Via della Navicella 2-4, 00184 Roma, Italy; claudio.beni@crea.gov.it

* Correspondence: pieranna.servadio@crea.gov.it; Tel.: +39-06-9067-5223

Abstract: In this study the effects of three different main preparatory tillage operations: ploughing at 0.4 m (P40) and 0.20 m (P20) depth and harrowing at 0.20 m depth (MT) were investigated. The tillage operations were carried out at two different time, as the soil water content increased in the time from rainfall: [low, 58% (LH) and high, 80% (HH) of field capacity]. Results obtained from the soil monitoring carried out before and after tillage showed high values of soil strength in terms of Penetration resistance and shear strength particularly in deeper soil layers at lower water content. During tillage, fossil-fuel energy requirements both for P40 LH and P20 LH were 25 and 35% higher with respect to the HH treatments and tractor slip was very high (P40 LH = 32.4%) with respect to the P40 HH treatment (16%). Therefore soil water content had significantly influenced tractor performance during soil ploughing, particularly at 0.40 m depth while MT was not influenced at all. The highly significant linear relations between grain yield and soil penetration resistance highlights how soil strength may be good indicator of its productivity. Obtained results during these field tests allow us to conclude that MT and P20 treatments more suitable for this type of soil in climate change scenarios.

Keywords: soil tillage; tractors; soil water content; physical soil properties; GPS; energy requirement; CO_2 emission

1. Introduction

The number of days available for field operations is frequently central, either directly or indirectly, to farm planning decisions. The number, and distribution, of working days influences the type and acreage of crops grown, and the corresponding labour and machinery requirements. The condition of land for field operations can been classified in terms of trafficability and workability. Trafficability is concerned with the ability of soil to provide adequate traction for vehicles, and withstand traffic without excess compaction or structural damage. If land is considered trafficable, then it is deemed suitable for non-soil-engaging operations (e.g. fertilizer application and crop protection). Workability is concerned with soil-engaging operations and can be considered to be a combination of trafficability and the ability of soil to be manipulated in a desired way without causing significant damage or compaction. The most influential factor in determining the suitability of land for field operations is the soil moisture status. When a soil is trafficked or worked in an unsuitable condition, damage to the soil's structure and the consequent effect on crop production can persist for many years [1]. In mechanised agriculture, high axle loads are cause of major concern regarding the risk of soil compaction, especially if wheeling and tillage are conducted at high soil moisture content [2, 3]. Tillage is a fundamental factor influencing soil quality, crop performance and the sustainability of cropping systems [4] because it represents the most influential manipulation or alteration of soil physical properties due to repetitive application, its depth range extending up to tens of centimeter, and because it influences the type of residue management applied.

Soil penetration resistance measurements have been effectively used in many studies as a tool for characterizing soil strength after tillage [5,6]. However, soil penetration resistance as well as other

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soil properties is affected by the soil spatial variability [7] and has been shown to strongly depend on soil water content [8-10]. Therefore the spatial and temporal variability of soil compaction should be affected by soil moisture. [11] Found that soil moisture content during tillage affected the size distribution of aggregates produced and that aggregates formed at low moisture content had three to four times more resistance to crushing than those formed at greater moisture contents. The type of tillage implement also affects the soil structure produced. Tillage implements vary in terms of both width and depth and in terms of the intensity in soil overturn administered by the implement design (disc versus ploughing, etc.). Furthermore, interactions between natural factors (e.g., soil type, climate and weather) and crop selection determine the intensity, depth, frequency, and timing of tillage [12] which highlights the need for understanding the tillage effects on soil properties, tractor performance and crop yield [13,14]. Tillage systems are location specific, so the degree of their success depends on soil, climate, and management practices [15,16].

In recent years, the weather conditions in Central Italy have been unstable. In summer time soil was very dry and strong, in autumn and in spring time soil was too wet and the rainfall has generally been delayed until November-December. Hence, farmers did not accomplish the seedbed preparation at the proper time. As a result, the drilling of cereals such as wheat and barley has been so delayed that there has been a decrease in yield. Therefore the objectives of this study were to assess which tillage techniques could be considered as adaptation to climate change scenarios (CCS). For this, the effects of three different main preparatory tillage operations of wheat: ploughing at 0.4 m and 0.2 m depth and harrowing at 0.2 m depth were compared and quantified. Each of them was tested at two different times, as the soil water content increase in the time from rainfall: [low, 58% (LH) and high, 80% (HH) of field capacity. The quality of the different tillage operations was assessed through wheat yield, clods size, soil water infiltration, structural stability, cone index and shear strength.

2. Materials and Methods

The study was conducted in Central Italy on a hilly plateau (57 m.a.s.l.), (42°05′57.84″ N, 12°38′09.59″ E) on a silt loam soil. Three tillage systems: harrowing 0.20 m depth coded MT; ploughing, superficial (0.2 m depth) coded P20 and deeper (0.4 m depth) coded P40, have been compared. All treatments were carried out at two different times (21 October and 15 November 2010), as the soil water content increased in the time from rainfall as showed in Figure 1: low (18%, treatments LH), corresponding to 58% of field capacity and high (25%, treatments HH), corresponding to 80% of field capacity (Table. 1).

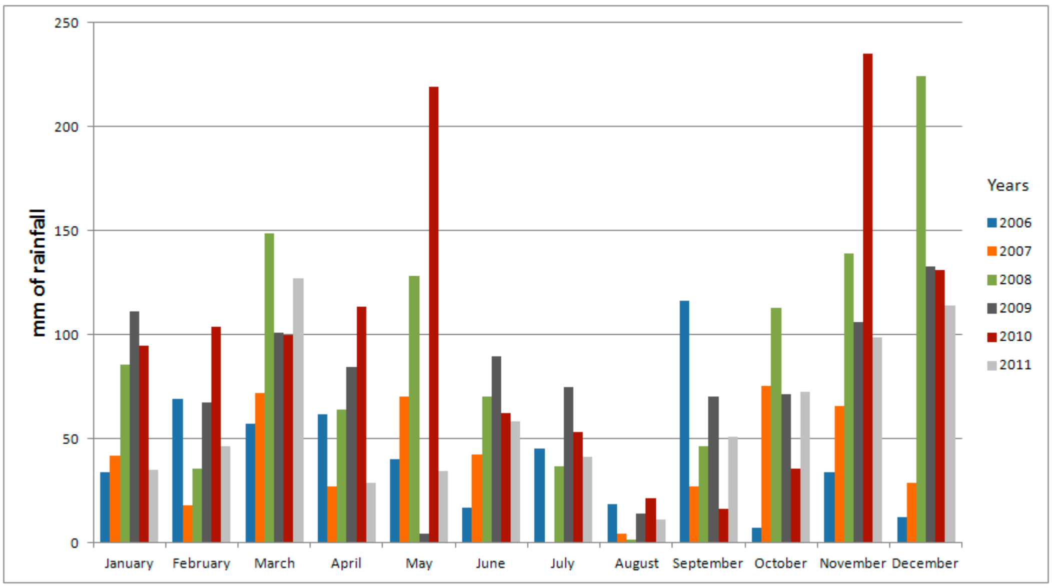

Fig. 1. Monthly rainfall data of the experimental site during the tests (2010-2011). Data since 2006 indicate the climatic average.

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Table 1. Soil conditions during field tests (0-0.20 m depth).

Particle size distribution (%):	Sand (2000 - 50 mm)	24.7
	Silt (50 - 2 mm)	52.5
	Clay (< 2 mm)	22.7
Texture		Silty loam
pH		6.4
Organic matter (%)		2.4
Field capacity (%)		31
Moisture content (%) measured during:		
Soil sampling tests carried out on 20.10.2010		18
Soil tillage carried out on 21.10.2010	(LH)	18
Soil tillage carried out on 15.11.2010	(HH)	25
Soil sampling tests carried out on 15.02.2011		22

The main factor was the soil tillage (MT, P20 and P40) while the secondary factor was soil water content (LH and HH). The treatments coded: P40 LH, P40 HH, P20 LH, P20 HH, MT LH, MT HH were arranged according to the split plot design (six treatments per three replications) for a total of eighteen plots each of 200 m^2, in three blocks. After the ploughing, no additional seed bed preparation was necessary because the meteorological events favoured the clods disgregation. All plots were seeded (28 November 2010) with wheat (*Triticum durum* variety Duilio 0.21 t ha^{-1}). Plots were fertilized with: 1) NP (11-30) fertilizer (0.1 t ha^{-1}) the day before the sowing time; 2) urea 46% at 27 February 2011 (0.1 t ha^{-1}); 3) urea 46% at 9 April 2011 (0.1 t ha^{-1}). Harvesting of wheat was carried out on 30 June 2011. At the end relations between measured soil strength and wheat yield were developed.

2.1. Soil Sampling tests

To assess soil mechanical conditions, the following soil properties: water content (WC), penetration resistance (CI) and shear strength (SS) were monitored at two different times. One georeferenced sampling tests before starting the trials (20 October 2010) and another after the tillage (15 February 2011), as shown in Table 1. Penetration resistance was measured using a Eijkelkamp penetrologger with a 60° cone and base area of 100 mm^2, driven into the soil at a constant rate (5 cm s^{-1}). In each plot, 4 penetrometer readings were taken in increments of 1 cm to a depth of 0.40 m. Soil shear strength was measured using a field inspection vane tester from 0 to 260 kPa (Eijkelkamp). In each plot 6 shear strength readings were taken in increments of 0.05 m to a depth of 0.20 m. Soil water content at the time of field tests was measured from 0 to 0.20 m depth by taking 6 samples of soil in each plot that were weighed and dried until they reached a constant weight. The Richards water extraction apparatus was used to determine soil field capacity (FC).

2.2. Soil tillage

To assess which tillage techniques could be considered as adaptation to climate change scenarios (CCS) in central Italy, soil tillage was carried out at two different time: in October at low water content (58% FC) and in November at high water content (80% FC). Some field conditions during the tests are shown in Table 1 while Figure 1 shows monthly rainfall data of the experimental during 2006-2011 years. Due to the work width and mass of the trailed disk harrow, harrowing was carried out using a mean power metal tracked tractor (62 kW engine power, 4100 kg mass front ballasted) while ploughing with mounted one furrow plow was carried out using a mean power wheeled tractor (62 kW engine power, 3400 kg mass front ballasted). The performance of tractors carrying out tillage operations were evaluated through: forward speed, slip, global energy employed, effective work capacity, real work width and work depth, fossil-fuel energy requirements (GJ/ha) and carbon dioxide emissions (kg C/ha). In addition field data collected has allowed appraisal of the global energetic efficiency of the tractors that depends on the area (ha) covered as a function of the time and

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from the ability of the tractor to convert the energy of combustion into useful power. As a result, three field oriented performance indicators consisting in time efficiency (h/ha), area specific consumption (kg ha^{-1}) and slip (%) were applied [19, 16].

In order to evaluate the quality of the tillage operations, the followings parameters were measured by taking in each plot 6 samples: clod size distribution, water infiltration rate into the soil, structural stability of soil aggregates. Clod size distribution was determined by taking samples of tilled soil, sifting them through sieves with holes of 200, 100, 50, 25 and 10 mm of diameter and then separating into size classes [13, 14]; structural stability of soil aggregates on the 0.25 mm fraction through the method of [22]; water infiltration rate by the double ring infiltrometer [20], according to the Simplified Falling Head (SFH) technique suggested by [21] with a 32 cm inner diameter and 57 cm outer diameter cylinder inserted 5 cm into the soil. The wheat harvesting was carried out by hand into the sampling areas consisting in 1 m^2 (for 6 replications), sampling areas were chosen through a subjective method suggested by [23].

2.3. Statistically methods

The statistical significant differences between treatments was determined by means of the student's test and at the same depth of sample for the soil variables. Mean results are flanked on the same line by letters. Each mean, which share a letter, does not differ significantly, level of significance ≤0.01 [24].

3. Results

3.1. Soil sampling tests

Due to the low water content (58% FC), soil was very strong during the sampling tests carried out before tillage on 20 October 2010. In fact, as shown in Tables 2 and 3 the values of penetration resistance (CI in the deeper layer up to 4 MPa) and of shear strength (SS up to 189 kPa) were very elevated. Due, both to the effect of soil tillage and to the higher water content (80% FC) these values decreased significantly (Δ>50%) in the sampling tests carried out after tillage on 15 February 2011.

Table 2. Mean values of soil layers from 0 to 0.40 m depth of penetration resistance carried out before (B) and after (A) tillage and its increment ratio Δ.

Treatments	Depth (m)	Mean Penetration Resistance[a] (MPa) (20.10.2010) (B)	Mean Penetration Resistance[a] (MPa) (15.02.2011) (A)	$\Delta = \frac{B-A}{B}$
MT LH	0.0-0.20	2.77 a	1.34 b	0.52
	0.21-0.40	4.36 b	1.91 a	0.56
P20 LH	0.0-0.20	2.53 c	0.91 e	0.64
	0.21-0.40	3.99 e	1.55 f	0.61
P40 LH	0.0-0.20	2.19 d	0.92 e	0.58
	0.21-0.40	3.89 e	1.30 f	0.66
MT HH	0.0-0.20	2.48 a	1.32 b	0.47
	0.21-0.40	4.41 b	1.91 a	0.57
P20 HH	0.0-0.20	2.42 ac	1.26 a	0.48
	0.21-0.40	3.75 d	1.83 b	0.51
P40 HH	0.0-0.20	2.78 a	0.96 e	0.65
	0.21-0.40	3.96 de	1.31 f	0.67

[a] Average of 240 values.

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Table 3. Mean values from 0 to 0.20 m depth of shear strength carried out before (B) and after (A) tillage and its increment ratio Δ

Treatments	Depth (m)	Mean shear strength [a] (kPa) (20.10.2010) (B)	Mean shear strength [a] (kPa) (15.02.2011) (A)	$\Delta = \frac{B-A}{B}$
MT LH	0.0-0.20	172.83 a,b	83.83 a	0.51
P20 LH	0.0-0.20	155.67 a	42.33 b	0.72
P40 LH	0.0-0.20	188.67 b	56.50 bc	0.70
MT HH	0.0-0.20	154.50 a	72.75 ab	0.52
P20 HH	0.0-0.20	165.33 a	45.42 b	0.72
P40 H	0.0-0.20	177.50 a	37.67 b	0.78

[a] Average of 72 values.

3.2. Soil tillage

Due to the high soil strength in term of CI and SS obtained in the tests carried out at low water content, the tractor performance during ploughing was not so good if compared with that of other studies carried out, for istance, on silty clay soil (water content at 0.25 of the field capacity) with 217 kW powered wheeled tractors [16]. In fact, the three field oriented performance indicators consisting in time efficiency (h/ha), area specific consumption (kg ha^{-1}) and slip (%) applied, showed:

1) in the tests carried out at low water content LH (58% FC), the results of the time efficiency were very low (8 and 6.3 h ha^{-1}) for 0.40 and 0.20 m respectively (Table 4). Accordingly, the results of area specific consumption for 0.40 and 0.20 m respectively were 120 and 91 kg ha^{-1}, fossil-fuel energy requirements (4.67 and 3.54 GJ ha^{-1}) and CO_2 emission (101 and 77 kg C ha^{-1}) were very high. Besides, tractor slip were very high (32.4 %), particularly during ploughing at 0.40 m depth.

Table 4. Performance of tracked and wheeled tractors during soil tillage carried out at low soil water content LH (58% FC).

	P40 LH	P20 LH	MT LH
Forward speed (m s^{-1})	0.73	0.93	0.93
Measured work width (m)	0.5	0.5	2.5
Effective work capacity (ha h^{-1})	0.13	0.17	0.84
Time efficiency (h ha^{-1})	8.09	6.28	1.19
Slip (%)	32.4	14.3	5.0
Hourly Fuel consumption (kg h^{-1})	15	14.5	12.5
Area specific consumption (kg ha^{-1})	120	91	15
Global energy employed (kWh ha^{-1})	310	235	183
Energy (GJ ha^{-1})	4.67	3.54	0.58
CO_2 emission (kg C ha^{-1})	101	77	13

2) in the tests carried out in November 2010, at higher water content HH (80% FC,) increased in the time from rainfall as Figure 1 shows, the results were significantly best: the time efficiency were (6 and 4 h ha^{-1}) for 0.40 and 0.20 m respectively (Table 5). Accordingly, the results for 0.40 and 0.20 m depth were: area specific consumption 91 and 60 kg ha^{-1}, fossil-fuel energy requirements 3.54 and 2.33 GJ ha^{-1} and CO_2 emission 77 and 51 kg C ha^{-1} respectively. Tractor slip (16 and 17%) can be considered as good for a wheeled tractor during ploughing. Tractor slip is an index of traction performance and to obtain the maximum of the traction efficiency, the slip must be from 15 to 20% on dry soil and from 15 to 25% on wet soil [9].

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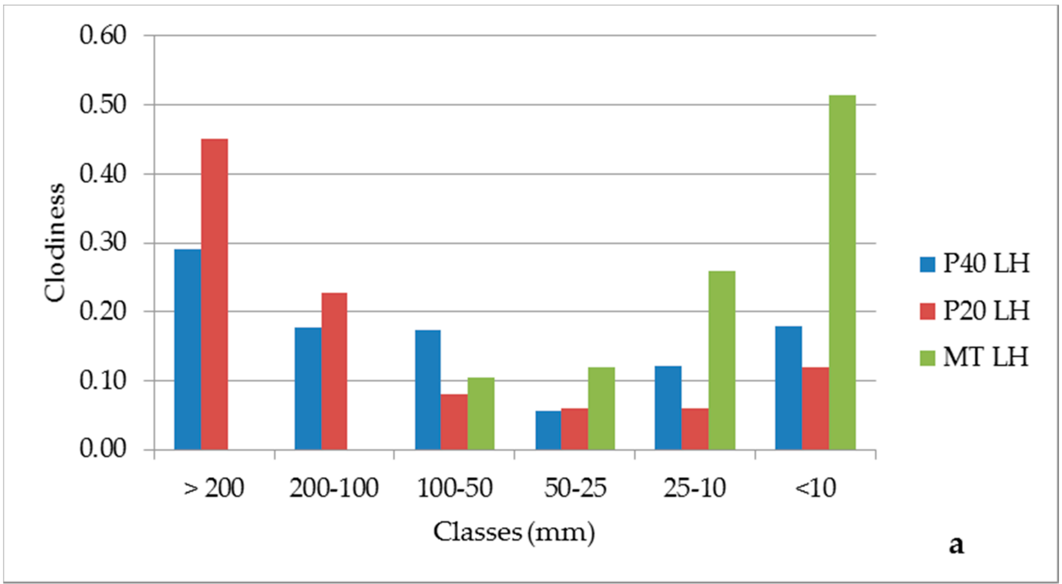
Table 5. Performance of tracked and wheeled tractors during soil tillage carried out at high soil water content HH (80% FC).

	P40 HH	P20 HH	MT HH
Forward speed (m s^{-1})	0.90	1.34	0.94
Measured work width (m)	0.5	0.5	2.5
Effective work capacity (ha h^{-1})	0.16	0.24	0.85
Time efficiency (h ha $^{-1}$)	6.25	4.17	1.18
Slip (%)	15.8	17.0	5.1
Hourly Fuel consumption (kg h^{-1})	14.5	14.5	12.5
Area specific consumption (kg ha^{-1})	91	60	15
Global energy employed (kWh ha^{-1})	250	166	182
Energy (GJ ha^{-1})	3.54	2.33	0.58
CO_2 emission (kg C ha^{-1})	77	51	13

3) Between the two different field conditions (low and high water content), performance of the tracked tractor during harrowing were of the same magnitude for the MT treatment: time efficiency was 1.2 h ha^{-1}. Accordingly, the results of area specific consumption was 15 kg ha^{-1}, fossil-fuel energy requirements was 0.58 GJ ha^{-1} and CO_2 emission was 13 kg C ha^{-1}.

As it regards the quality of the developed tillage, results of clods size distribution showed a good quality of the work in particular for the treatments P20 HH and MT HH where a high percentage of the size of clods less than 50 mm and the absence of clods upper 200 mm were found (Fig. 2b). The others treatments showed: i) higher percentage of clods larger than 200 mm (50%) for P40 HH and (30%) for P40 LH, ii) almost the same trend in LH and HH condition for MT treatments and iii) opposite trend in the LH and HH conditions for P20 treatments where LH has recorded more than 40% of clods larger than 200 mm and approximately 10% of clods smaller than 10% (Figure 2a).



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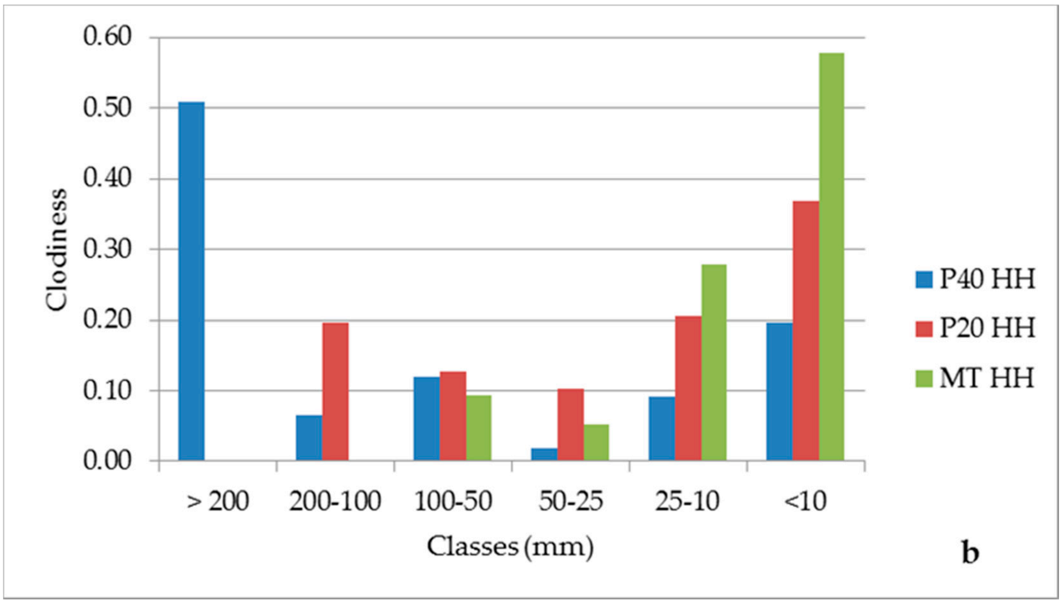

Figure 2. Clods size distribution of different treatments: a) for LH (58% FC) and b) for HH (80% FC).

About the water infiltration rate on soil, results depicted in Figure 3 showed that, due to the hard field conditions of the silty loam soil, only the 3 following treatments have got results: P40 LH and P20 LH (2 replications), P20 HH (1 replication). In particular: highest values of infiltration rate (above 2500 mm h^{-1}) for P20 LH, similar values (between 500 and 1000 mm h^{-1}) for the treatments P40 LH and P20 HH and last, value equal to 0 for MT treatment were obtained.

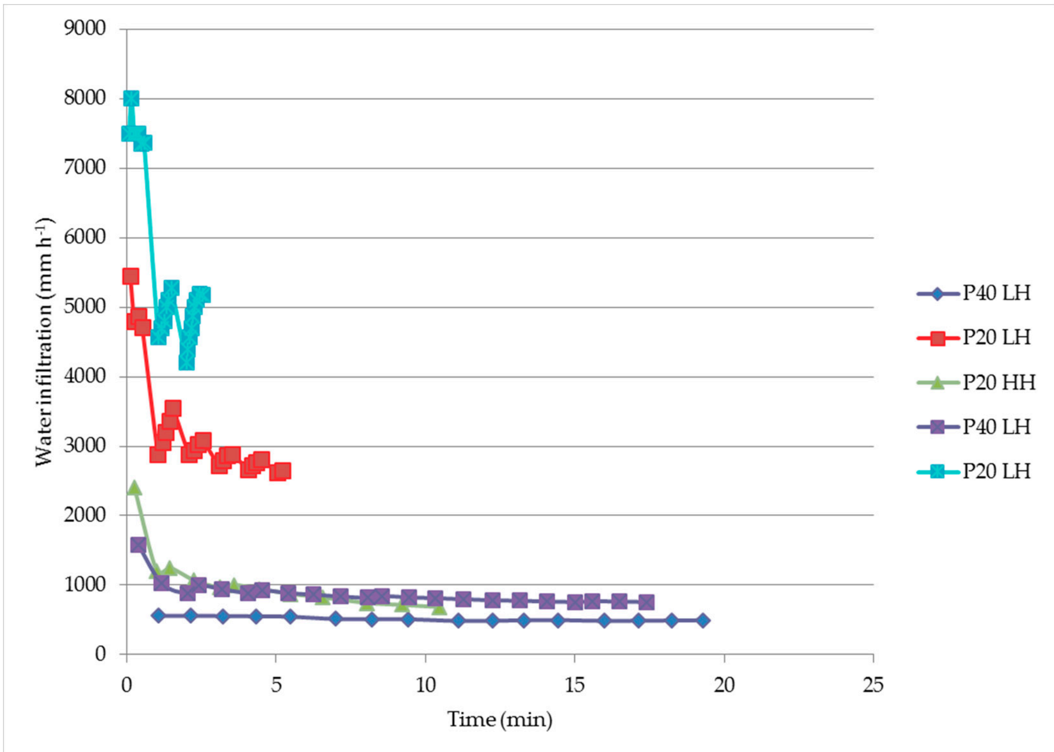

Figure 3. Soil water infiltration rate.

Findings of structural stability of soil aggregates showed that treatment P40 had the highest structural stability value within LH treatments (68.7%). Treatments P20 and MT showed quite similar values, 66% and 65.3% respectively (Figure 4a). Results of tests conducted on HH treatments have shown

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that the best effect on structural stability was created by the treatment MT (70%), while ploughed plots showed values of 65,3% and 64% for what concern P20 and P40 respectively (Figure 4b).

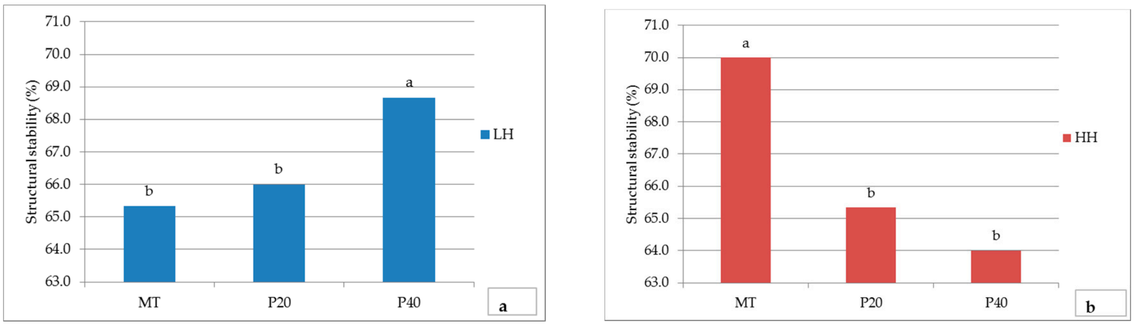

Figure 4. Structural stability of soil aggregates related: a) to low humidity treatments LH (58% FC) and b) to high humidity treatments HH (80% FC). Average of 18 values.

According with structural stability of soil aggregates, the results of wheat yield (Figure 5) showed that grain yield under LH condition was higher for P40 treatment (2.1 t ha^{-1}) and for P20 (2.05 t ha^{-1}) it followed MT with 1.7 t ha^{-1}. The trend of grain yield under HH was similar to that of LH condition: higher for P40 (1.9 t ha^{-1}) and for P20 (1.5 t ha^{-1}) it followed MT with 1.3 (t ha^{-1}). Figure 5 shows the values of differences of grain yield respect to the treatment P40 (treatment P40 was chosen as control because represents the traditional tillage of this crop). Concerning condition LH, P20 produced the same amount of P40 while MT produced 23% less; regarding HH condition, P20 and MT produced 26% and 46% less than P40. Grain yield of each treatment LH was higher than the respective treatment HH and treatment P40 produced the highest, MT the lowest and P20 the mean value of grain yield either for HH that for LH conditions.

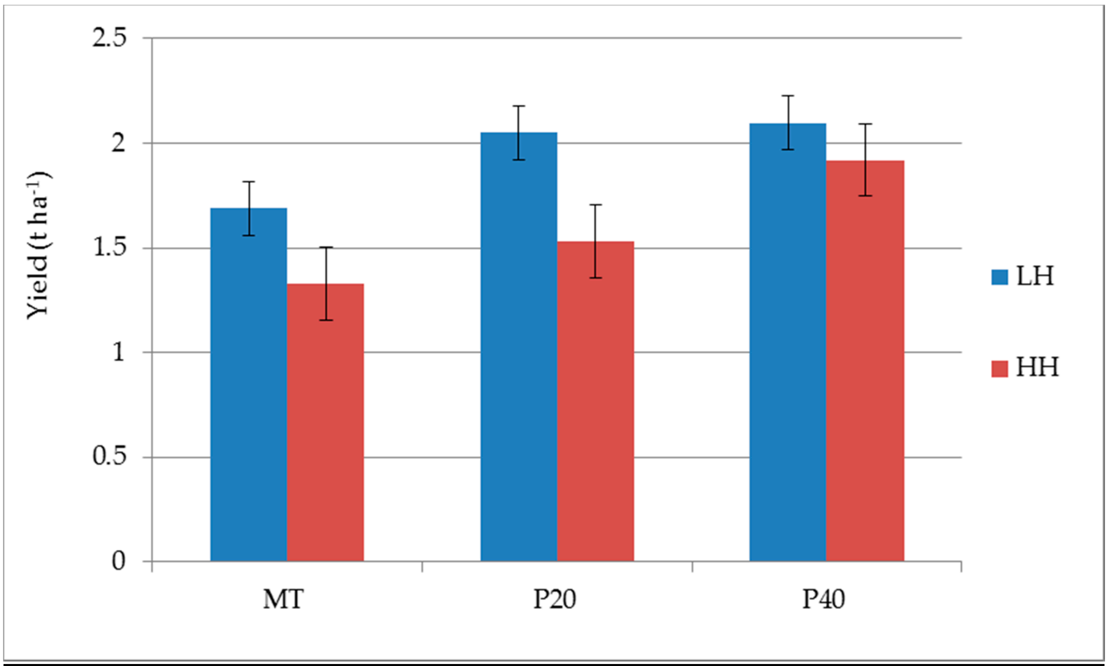

Figure 5. Results of wheat harvesting (Error bars represent the standard deviation. Average of 18 values.)

Highly significant linear relationships between soil penetration resistance and yield for three treatments for each soil water content (Fig. 6) were found.

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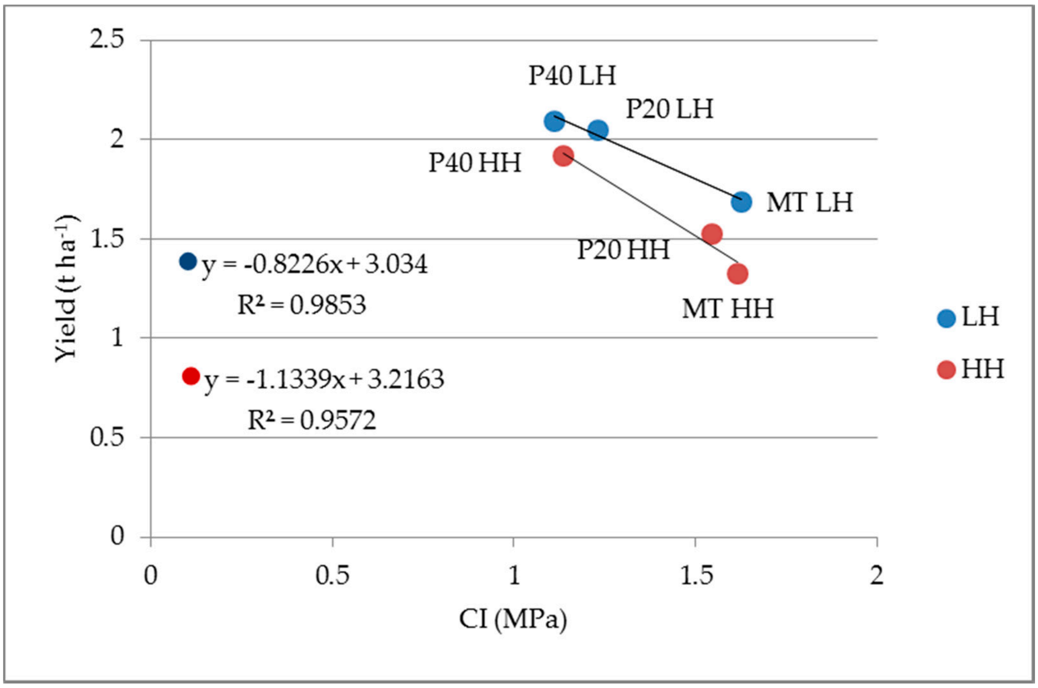

Figure 6. Relation between grain yield and soil penetration resistance for Low (LH) and High (HH) soil water content (P≤0.01).

4. Discussion

In view of recent international agreements, which set an ambitious goal of limiting the increase in global temperature of 1.5 ° C, the actions that each country will undertake will be crucial for the success of such an agreement, and it will be necessary to intervene in the most energy-intensive sectors and / or polluting human activity. Agro-food industries, both in agriculture that livestock, is, in global terms, a source of CO_2 emissions is not negligible, in the proportions of the economy of each country. In the Italian context, the regional development plans have made funds aimed to innovation and the energy efficiency of farms, offering the possibility to achieve greater environmental sustainability.

According with [4] tillage is a fundamental factor influencing soil quality. In Central Italy, the mouldboard deep ploughing is widely used but it has several disadvantages compared with shallower tillage [16], such as greater energy requirement as shown in Tab. 4 and 5, surface roughness as shown in Fig. 2, often, the degree of crushing of the soil, required further operation to seedbed preparation.

The results obtained in this research showed that soil water content had significantly influenced the soil strength in term of penetration resistance and shear strength and consequently the tractors performance during ploughing. In fact, in low water content plots, the area specific consumption, the global energy employed, fossil-fuel energy requirements and CO_2 emission were significantly higher during ploughing at 0.40 m and 0.20 m depth compared to high water content plots. Better tractors performance during ploughing at 0.20 m with high water content and during harrowing were found. Regarding soil quality, treatments P20 LH and P40 LH showed good effects on structural stability and on grain yield, furthermore soil structure created by treatment P20 LH allowed an optimal water infiltration rate, meaning that runoff was reduced, high percentage of rainwater was stored. [17] Suggested to only traffic and tillage when soil moisture is less than 60% of field capacity. Vehicle traffic conducted when soil moisture is greater than approximately 60% of field capacity can lead to excessive soil compaction that may be battled for many cropping seasons or worse, the damage may be permanent. Results showed that in the field condition of tests, according with other studies carried out by [10], tillage can be carried out at the water content up to 0.8 of field capacity as the P40 HH treatment showed.

Besides, according with other studies [18], the highly significant linear relationship between grain yield and soil penetration resistance (P≤0.01) found, highlighting how soil physical-mechanical parameters may be good indicators of its productivity. In fact, results showed that in the field conditions of the tests, the crop yield decreases when the soil strength, in terms of Cone Index, increases (Fig. 6). Even, if do not exists the best tillage operation ever, it exists a compromise among targets: machineries, meteorological conditions, yield, soil status, costs. Obtained results allowed considering MT and P20 treatments suitable in these field conditions in climate change scenarios because MT was not affected by soil water content and P20 was a good compromise among targets.

5. Conclusions

In the present study, two georeferenced sampling tests of some soil properties were carried out before and after tillage to investigate on soil strong. Soil tillage was performed in different times, at low and high water content (58% and 80% of field capacity respectively). The quality of the work and performance of the tractors carrying out tillage operations were evaluated, wheat harvesting was carried out by hand into the sampling areas and meteorological data of the experimental site were acquired since 2006 to indicate the climatic average.

According to the planned objectives, the following results were obtained: (i) soil water content had significantly influenced soil strong and consequently the tractors performance during ploughing. Due both to the tillage effects and to the soil water content that is highly correlated with soil strength, values of penetration resistance and shear strength decreased significantly (Δ>50%) in the sampling tests carried out after tillage; (ii) During tillage, three field oriented performance indicators were found: time efficiency, area specific consumption and tractor slip. In the tests carried out at water content of 58% of the field capacity, the results of the three performance indicators were very high particularly during ploughing at 0.40 m depth while in the tests carried out at water content of 80% of the field capacity, these results were significantly best. Between the two different field conditions (low and high water content), no differences were found in the performance of the tracked tractor during harrowing (MT treatment). (iii) According with structural stability of soil aggregates, results of wheat yield of each treatment LH was higher than the respective treatment HH. In each conditions (LH and HH), P40 treatment has obtained the highest yield, MT the lowest and P20 the mean value of grain yield. A significant linear correlation between soil penetration resistance and yield for different treatments and each soil condition was found.

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Conflicts of Interest: The authors declare no conflict of interest.

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