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Soil Compaction in Harvesting Operations of *Phalaris Arundincea* L.

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Abstract: Tillage and harvesting operations of perennial forage crops have problems with soil compaction. The effects of this phenomenon are soil deterioration with reduced crop performance and yield. This study aims to assess soil disturbance by measuring the level of compaction caused by the harvesting operations of *Phalaris arundinacea* L. *P. arundinacea* is a species that lends itself to biomass production and phytoremediation of contaminated soils; it adapts to difficult soil conditions, outperforming other species in terms of ease of planting, cost, maturity time, yield, and contamination levels. The crop was sown in three plots of the experimental teaching farm of the University of Tuscia, Viterbo, Italy. Following a detailed analysis of the chemical–physical characteristics of the soil, minimum tillage was chosen in order to concentrate on harvesting operations, which were carried out with a disc mower coupled to a tractor. This was followed by penetration resistance and soil moisture measurements to verify the incidence of the operations and the effect of the type of crop on compaction. On the study site, measurements were taken at points that the wheels of the tractor had gone over and at points that they had not. The soil analysis results indicate different chemical–physical characteristics between the two areas, the texture being frankly sandy to clayey. Penetration resistance measurements indicated differences for the first 20 cm between the part that was covered by the tractor's tyres and the part that was left touched but also between the three plots. Moisture influenced penetration resistance. This study provides an evaluation of the first data obtained from a project that will last four years and which will explore the dynamics between soil, cultivation, and harvesting operations, giving a fundamental basis for further investigation of further harvesting operations and soil characteristics, which are crucial for planning and managing crops and reducing impacts on the soil in order to preserve it.

Keywords: penetration resistance; soil protection; minimum tillage; mechanisation; European law

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1. Introduction

Soil is usually defined as the topmost layer of the Earth's crust. It is an extremely dynamic system that performs numerous functions and that plays a fundamental role in human activity and in the survival of ecosystems. The process of formation and regeneration of the soil is very slow and for this reason it is essentially a nonrenewable resource.

The main degradation processes to which soils are exposed are erosion, decrease in organic matter, contamination, salinization, compaction, decrease in soil biodiversity, waterproofing, floods, and landslides, for which the soil formation interval of 370–1290 kg ha-t yr^{-1} must be considered [1,2].

Soil degradation is a major problem in Europe, and it is caused or exacerbated by human activities, such as inadequate agricultural and forestry practices, industrial activities, tourism or urban and industrial development and land use planning [3].

This results in lower soil fertility, a loss of carbon and biodiversity, a lower capacity to hold water, disruption of gas and nutrient cycles, and less degradation of contaminants.

Soil degradation has direct repercussions on water and air quality, biodiversity, and climate change, but it can also affect the health of European citizens and endanger the safety of products for human and animal consumption [4,5].

Confirming the importance of the problem, on 17 November 2021, the European Commission approved the "Soil Strategy for 2030" which is an integral part of the implementation of the European Green Deal. The strategy defines measures to protect and restore soils and guarantee that they are used sustainably [6].

In particular, the strategy aims at the restoration of degraded soils and remediation of contaminated sites through specific measures; the prevention of desertification through the development of a common methodology to assess its level and prevent soil degradation; and enhance research, data collection, and soil monitoring.

The main objective is to ensure that, by 2050, all Member States of the European community avoid consuming land (zero net land take) and that their soils are "healthy" through concrete actions, many of which will have to be implemented as early as 2030. The EU Thematic Strategy for Soil Protection proposes measures to protect the soil and preserve its ability to perform its ecological, economic, social, and cultural functions [7].

Coordinated action at the European level is necessary given the impact of the state of the soil on other environmental aspects or related to food safety, which is regulated at a community level, the risks of distortion of the internal market linked to the remediation of polluted sites, any cross-border impact, and the international dimension of this problem.

The European Parliament reports that overall, 60–70% of soils within the Union are unhealthy due to current management practices, and that a further but still uncertain percentage of soils are unhealthy due to pollution problems; this has yet to be precisely quantified. The Common Agricultural Policy (CAP) was found to be effectively ineffective in ensuring its good management.

In this work, the analysis was focused on the impact that the harvesting of *Phalaris arundinacea* L. exerts on the soil and, consequently, on its compaction [8,9].

The choice of *Phalaris arundinacea* L. was made because this species is part of the forage crops and presents interesting aspects to be studied such as its ductility in agriculture and its chemical and physical characteristics. In fact, processing and harvesting operations of perennial forage crops have been shown to have problems with soil compaction, and we wanted to analyse the consequences of the collection operations [6].

Furthermore, the choice of *Phalaris arundinacea* L. is part of the research activities envisaged by a Horizon 2020 project called CERESiS (ContaminatEd land Remediation through Energy crops for Soil improvement to liquid fuel Strategies). The aim of the project is to create, through this crop, biomass aimed at the production of clean energy.

The choice was also justified by the excellent phytoremediation abilities of *Phalaris arundinacea* on contaminated soils, such as those of the University of Tuscia in Viterbo.

In fact, perennial forage crops have been shown to have problems with soil compaction. Compaction is defined as the compression of soil particles into a smaller volume as a result of the reduction in the spaces existing between the particles themselves. It is usually accompanied by significant changes in the structural properties and behaviour of the soil, as well as in its thermal and water regime, in the equilibrium, and in the characteristics of the liquid and gaseous phases that compose it [10].

Therefore, the main consequence of soil compaction is, in addition to a decrease in yield, the drastic reduction in water infiltration with a consequent increase in surface runoff. The frequent stagnation in the lowland areas during intense and concentrated rainfall and the sliding surfaces of superficial landslides, in correspondence with the compacted layers along the soil profile, underline and demonstrate how the problem is widespread in both lowland and hilly Italian agricultural areas.

Currently, there are few quantitative data and they are limited to some areas of study. The only national cartography available is that relating to the natural susceptibility of soils to compaction, which can be extracted from the European report of the JRC-IES; this, however, does not provide information on the real extent of the phenomenon [11].

Soil compaction is a problem that can be effectively limited and prevented through innovative agricultural systems and machinery. In Italy, thanks to various research that was carried out, it emerged that one of the main causes of soil erosion is agriculture, and in particular the reckless use of mechanical means during harvesting operations. Furthermore, it has been shown that grazing and breeding activities can also generate soil compaction: in fact, an excessive number of cattle for the size of a given plot (livestock load) generates compaction [11].

Similarly, in some European countries, including Spain and the Czech Republic, it has been shown that the inappropriate use of heavy agricultural machinery and the tillage of a soil that is too wet are causes of compaction [10].

It has been shown, in fact, that the types of tires and the inflation pressures can be chosen in such a way as to attenuate the compacting effect of the passages of agricultural machinery. More generally, it would be necessary to reconsider the adoption of less heavy and powerful agricultural machines, perhaps equipped with tracked vehicles instead of wheels, when going over wet soils [10,11].

The adoption of alternative soil tillage systems to traditional ploughing is capable of reducing the formation, within the soil profile, of the compact layer with low permeability that is generated at the lower limit of tillage in soils affected by continuous conventional tillage [12].

The solutions must therefore be sought in "good agricultural practices" which help to maintain the optimal soil structure. From this point of view, deep processing should be avoided, especially since scientific results indicate that the use of alternative processing systems, replacing the traditional tested ones, does not penalise production and can even improve its quality [13,14].

One of these solutions, applied to the case under examination at the experimental teaching farm of the University of Tuscia, can be minimum tillage applied to the harvesting operations. In the agronomic field, minimum tillage represents a method of soil management based on the adoption of techniques aimed at less tillage of the soil. This technique falls into the large category of conservation agriculture, also called blue agriculture in Italy. Alongside minimum tillage, there are other techniques that guarantee minimal influence on the soil: for example, permanent soil cover (cover crops, residues, and protective coulters) to protect the soil and help eliminate weeds or diversified crop associations and rotations, which favour soil microorganisms and fight weeds, parasites, and plant diseases [15].

In general, the term minimum tillage still means a series of soil management techniques based on the adoption of processes that prepare the seedbed with the least number of steps [15].

In fact, from a technical point of view, minimum tillage does not meet a standard criterion; this proves it difficult to find a shared definition [16].

However, minimum tillage is inspired by some basic criteria associated with processing, carried out according to traditional schemes which, as a rule, require repeated machine passes in order to carry out the main processing and complementary processing before sowing.

In Italy, for example, a minimum tillage technique can be the replacement of ploughing with tillage or nontillage (sowing on sod), which favours the natural mixing of soil layers by the fauna of the soil layers (earthworms), roots, and of other soil organisms, which also develop the balance of nutrients present in the soil. The fertility of the soil (nutrients and water) is managed by covering through the earth, crop rotation, and weed control [16].

Minimum tillage has the following objectives: (1) reducing the number of machine passages required for sowing; (2) minimising the interference on the physical fertility of the soil; (3) streamlining the preparation times for crop rotation; and (4) reducing cultivation costs [17].

In summary, the use of conservation agriculture techniques compared with conventional ones allows for a protective approach to the chemical–physical characteristics of the soil, preventing erosion and degradation of the soil itself [16].

In fact, many advantages derive from the application of Conservative Agriculture, some of which become evident when the system stabilizes.

In particular, the reserves of organic carbon, biological activity, aerial and underground biodiversity, and soil structure, all find an improvement. Greater biological activity leads to the formation of well-connected and essentially vertical macrobiopores, which increase water infiltration and soil resistance to compaction. Soil degradation—in particular erosion and runoff—decreases significantly, often leading to an increase in yield. A lower loss of soil and nutrients, together with a more rapid degradation of pesticides and greater adsorption (determined by an increase in the organic substance content and biological activity) in turn, leads to an improvement in water quality. Carbon dioxide (CO2) emissions decrease as a result of a reduced use of machinery and an increased accumulation of organic carbon [17].

Conservative farming practices could sequester between 50 and 100 million tons of carbon per year in European soils, the equivalent of the emissions produced by 70–130 million cars.

Furthermore, compared with conservative agriculture, the costs of labour and energy that are related to the operations of preparation and weeding of the land decrease significantly, and the need for fertilizers and interventions for the recovery of the land also decreases [17].

The same authors have shown that minimal tillage has less invasive consequences on the soil [17,18]. They used four different tractors and adapted the tillage and seeding technologies. Thanks to the minimum tillage technique, they recorded, first of all, a reduction in fuel consumption (i.e., a reduction in greenhouse gas emissions), working hours, and the number of tractors operating in the soil.

Furthermore, after analysing the chemical–physical composition of the soil, they recorded an optimal soil quality with a sufficient crop yield [19].

Other studies have shown that an additional method to reduce soil compaction, on top of reducing the transit of agricultural vehicles on it, is the use of tires with reduced air pressure [20].

In fact, with flat tires: (1) the contact surface with the ground surface increases by more than a third; (2) the tracks are wider but less deep, reducing the severity of compaction; (3) the traction capacity increases; the floating of the wheels also increases, especially in soft soils, because they have just been worked; and (4) the tire deforms in place of the ground surface.

All these advantages must not be misleading, there is also a downside. e.g., if you travel on paved roads with flat tires, the wear and the danger of overheating increase remarkably. In this regard, pressure regulation systems are a good solution [21,22].

Therefore, in consideration of the negative consequences that soil compaction can have on the environment and on the quality of the crop, it is necessary to adopt and experiment with innovative techniques of tillage, preferably the least invasive possible.

Only in this way can the objectives set by the European strategy for soil protection 2030 be met and, more generally, the soil itself be safeguarded.

The aim of this work was to verify, after a detailed soil analysis, the compaction resulting from the harvesting of *Phalaris arundinacea* L., managed with minimum tillage, on two areas with different soil characteristics.

2. Materials and Methods

The experiment was conducted at the "Nello Lupori" Teaching and Experimental Farm of the University of Tuscia, on some plots cultivated with *Phalaris arundinacea*. The experimental site, with coordinates 42°25′16″ N; 12°04′42″ E, is divided into two areas located within a 250 m distance of each other. These have an area of: Biomass Area 1 = 2978 m^2; Biomass Area 2 = 1954 m^2.

The experimental area is characterised by an average height above sea level of approximately 290 m, with volcanic soils (Andosol) deriving from the activities of the calderas of the current proximal lakes of Vico and Bolsena. These are agricultural soils, which, due to their pedological characteristics, present a risk of compaction that falls into the "very high" class; therefore, they fall within those soils at greater risk of compaction in the Compaction Index Map [21,22].

In terms of climate, Viterbo falls within the temperate region. This translates into average annual temperatures of around 14.7 °C, with average minimum values of 9.8 °C and average maximum values of 20.1 °C. The extreme values recorded are a maximum of 40 °C and a minimum of −8.6 °C. The average annual cumulative rainfall is approximately 710 mm, with the lowest values in summer and the highest in autumn.

The areas are mainly flat, without a marked slope. The first one is located close to the road (A) at a distance of only 10–15 m, while the second one (B) is located at a greater distance from the viaduct at about 150 m. All the areas were prepared for cultivation, using a minimum tillage system, with the aim of causing as little disturbance to the soil as possible. Specifically, only a secondary tillage of the field was carried out in the period in late winter using a disc harrow. Subsequently, in April 2021, they were sown with a multiyear culture, namely *Phalaris arundinacea*. The area located further inland (B) was sown by hand, while the first (A) was divided into three different types of sowing systems: manual, with a centrifugal fertiliser spreader applied to a tractor and finally using a self-propelled plot seeder. After seeding, a steam roller was used to reduce soil macroporosity and improve seed germination. During the year, both areas were visited on foot to check the phenology of the plant every 15 days, starting at the end of April 2021 until harvesting in December 2021. In the month of May, both areas were subjected to a phytosanitary treatment (weeding for dicotyledons), with a tractor–sprayer combination. In July, a total mowing was carried out on the same areas to standardise and stimulate the growth of the crop, using a self-propelled mower–harvester. Harvesting was then carried out by coupling the tractor with a disc mower.

The machines and equipment used are described below. A John Deere 5100 GF tractor, with a total weight of approximately 3100 kg and front tyres of 280/70 R18 and rear tyres of 420/70 R24. A disc harrow with a total weight of about 600 kg, consisting of 14 discs with a diameter of 55 cm and a unit weight of 10 kg. The centrifugal fertiliser spreader with a capacity of 200 L. The compressor roller with a total weight of approximately 300 kg. The self-propelled plot seeder with a total weight of approximately 900 kg. The sprayer with bars for phytosanitary treatments with a capacity of 300 L and an empty weight of approximately 130 kg. The disc mower with a total weight of 450 kg and a working width of 1.6 m. The self-propelled mower–loader with a weight of approximately 900 kg.

The soil was sampled for each area following an "X" transect, in which 5 samples were taken (for a total of 10 samples), two for each diagonal of the "X" (at the beginning of the 2nd and 4th quarters) and one at the intersection of the same (Figure 1). The single sample, in turn, was obtained by making a mixture of five subsamples taken near the identified point to a depth of 20 cm.

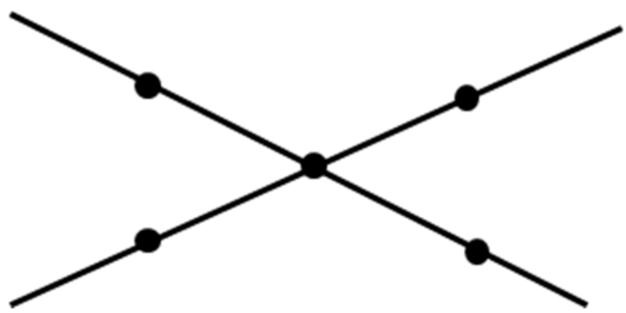

Figure 1. Diagram of the "X" transect.

Soil analyses were carried out, as better specified below, following the regulatory protocols in force in Italy on "Official methods of soil chemical analysis".

The skeleton, following the DM 13/09/99 G.U. n° 248 of 21/10/99 Method II.1 [21]; once the soil has been sieved and the fine soil (<2 mm) removed, what remains is the skeleton, expressed in g kg^{-1}, obtained from the report (1):

$$C = 1000 \cdot \frac{M_1}{M_2} \quad (1)$$

where: C = quantity of skeleton expressed in %; M_1 = mass of skeleton, expressed in g; M_2 = mass of raw sample for analysis, expressed in g. The soil texture was determined according to the DM 13/09/99 G.U. n° 248 of 21/10/99 Method II.6 [23]; following physical dispersion, the sample was transferred to a sedimentation machine where, after a series of sieves, solvent additions, and various sequential measurements better described in the standard, the quantities of the different fractions of particles (coarse sand, fine sand, coarse silt, fine silt, and clay) were obtained, again expressed in %. The pH reaction was obtained following the DM 13/09/99 G.U. n° 248 of 21/10/99 Method III.1 [23]; from 1 g of sample left to sediment and react with NaF, the degree of reaction expressed as a unit of pH is measured by electrode after about two minutes. The electrical conductivity following the DM 13/09/99 G.U. n° 248 of 21/10/99 Method IV.1 [23]; being able to operate with different methods, such as the preparation of the saturated paste extract, it is therefore possible to directly measure with a reader, the electrical conductivity reported at 25 °C of the ascertained value, expressing it in mS. The Total $CaCO_3$ following the DM 13/09/99 G.U. n° 248 of 21/10/99 Method V.1 [23]; through the gas-volumetric determination of CO_2 which is carried out by treating a sample of fine soil with HCl, with the result expressed in %. The Active $CaCO_3$ following DM 13/09/1999 SO n 185 GU n° 248 21/10/1999 Met V.2 [22]; obtained by reacting the fine soil with a solution with excess ammonium oxalate; the amount of salt that does not react is evaluated by titration with potassium permanganate solution, with the result expressed in %. The organic carbon, following the DM 13/09/99 G.U. n° 248 of 21/10/99 Method VII.3 [23]; following the oxidation of the organic carbon in solution with added potassium dichromate and H_2SO_4, titration is carried out with a solution of iron sulphate heptahydrate; the result is then expressed in %. The assimilable phosphorus is determined according to the DM 13/09/99 G.U. n° 248 of 21/10/99 Method XV.3 [24]; in this guideline, it is specified to use the Olsen method, with the result expressed in mg kg^{-1}. The exchange bases (calcium, magnesium, potassium, and sodium) are obtained according to the DM 13/09/99 G.U. n° 248 of 21/10/99 Method XIII.4 [23]; the content of ions removed from the exchange sites with ammonium acetate solution (pH 7) is determined by atomic absorption spectrophotometry with flame atomiser (FAAS), the results are expressed in ppm. The cation exchange capacity (CSC) is calculated according to the DM 13/09/99 G.U. n° 248 of 21/10/99 Method XIII.2 [24]; the proposed method is based on the use of chlorinated barium and triethanolamine, the result is in meq. Finally, the determination of carbon and hydrogen was carried out using the Costech ECS 4010 elemental analyser.

Two instruments were used to obtain the penetration resistance measurements, which were carried out immediately after harvesting. The first instrument was needed to verify the moisture content of the soil (Volumetric Water Content—VWC). This is specifically the TDR 300 Soil Moisture Meter from Field Scout™, which works by measuring the travel time of an electromagnetic wave along a waveguide in the soil. The ratio between the volume of water in a given volume of soil and the total soil volume is expressed as a percentage value and is representative of the first 16 cm of soil. The sampling scheme used in this case was subdividing each area into three replicas taken on an "X" transect (Figure 1) and carrying out 5 measurements, two on each diagonal and one at the intersection of the same. The instrument was then positioned at the chosen point. By applying a constant pressure to make the rods deepen completely, trying to keep them as parallel as possible to each other, the instantaneous soil data was acquired and recorded.

The second instrument used was an electronic penetrometer model Penetrologger (Royal Eijkelkamp Soil & Water; Giesbeek, The Netherlands). Data acquisition in the field was performed manually. The operator applied constant pressure on the instrument and inserted the conical tip and the penetrometer rod into the soil. The tapered tip used had a top angle of 60°, basal area of 2 cm^{2}, and nominal diameter of 15.96 mm. The borehole rod had a total length of 97 cm and was capable of recording up to a depth of 80 cm. The result given is reported as pressure expressed in MPa for each cm of soil explored vertically. The sampling scheme used, again, was choosing three plots for each area and taking 10 measurements on each plot. The first 5 were taken on the areas that were trampled by the tractor and the other 5 on the areas that were left untouched. All 10 measurements were carried out following a simple randomisation method. The instrument was positioned at the chosen point and deepened for the acquisition and recording of the instantaneous soil data.

Data analysis

The data were tested for normality and homogeneity using the Shapiro–Wilk test and Levene's test, respectively ($p = 0.05$ for both). The only parameter found to be nonsignificant in these two tests was soil moisture, which was analysed by one-factor analysis of variance (ANOVA, $p = 0.05$). Soil physical–chemical analyses, not having characteristics of normality and homogeneity, were compared with the nonparametric Kruskal–Wallis test for each variable ($p = 0.05$). Texture and structure, being nominal variables, were analysed with the chi-square test ($p = 0.05$). In order to verify the difference in penetration resistance, both global for the two areas, and then for the sites within the two areas on which the tractor has or has not gone over, not having characteristics of normality and homogeneity, the data were compared with the nonparametric Kruskal–Wallis test for each variable ($p = 0.05$).

A cubic spline smoother with lambda = 0.05 was applied to the compaction curves, with standardised x-values and 95% confidence interval. Analyses were performed with the JMP PRO 16 (Trial Version ©SAS Institute Inc.; Cary, NC, USA).

3. Results

3.1. 1st Biomass Area

The soil is sandy clay loam in texture, with no skeleton. The pH is subalkaline with a fair presence of limestone, both total (25.73%) and active (8.85%); salinity is negligible. The organic substance is 3.51%, which is very high for agricultural soils.

Macro- and micronutrients are average, except for potassium which, as is usual in volcanic soils, is very rich. The resulting Mg K^{-1} ratio is very low, around 0.40. The composition of the cation exchange capacity and the cation sufficiency rating sees a high presence of potassium and calcium, normal sodium, and low magnesium. This means that the cation exchange capacity in the soil is still high, with a CSC value of 27.27 (meq 100 g^{-1}).

3.2. 2nd Biomass Area

The soil is clay loam in texture, with traces of skeleton (1.3%). The pH is subalkaline with a reduced presence of limestone, both total (4.45%) and active (3.24%); salinity is negligible. Organic matter is 2.40%, which is an average value for agricultural soils.

Macro- and micronutrients are average, except for potassium which, as is usual in volcanic soils, is very rich. The resulting Mg K^{-1} ratio is low, about 0.88. The composition of the cation exchange capacity and the cation sufficiency rating sees a high presence of potassium and calcium, while a normal presence for magnesium and low for sodium. This means that the cation exchange capacity in the soil is still high, with a CSC value of 25.24 (meq 100 g^{-1}).

The results of the Kruskal–Wallis test indicate significant differences for some parameters of the soil physical–chemical analysis. Significant parameters between the two plots are pH and total nitrogen, with a 30% reduction between Biomass 1 and Biomass 2. There is a substantial difference between the amount of silt, with a percentage difference of about 19% and for clay of about 34%. The organic matter content also varies greatly by 31%. The parameter that varies the most is total calcium with a variation of 82% and also active calcium with 63%. Assimilable phosphorus, on the other hand, varies by 21% between the two surfaces (Table 1).

Table 1. Mean results of physical–chemical soil analyses. Standard deviation, *p*-value (α = 0.05), and significance are shown. The * indicates a statistically significant difference.

	Biomass 1		Biomass 2			
	M	**SD**	**M**	**SD**	***p* Value**	**Significance**
pH	7.70	0.00	7.78	0.05	0.0404	*
Total nitrogen %	0.20	0.00	0.14	0.02	0.0209	*
Organic matter %	3.51	0.06	2.40	0.33	0.0209	*
Organic carbon %	2.03	0.04	1.39	0.19	0.0209	*
Total CAO_3 %	25.73	15.44	4.45	2.42	0.0209	*
Active CAO_3 %	8.85	3.69	3.24	1.01	0.0209	*
Electrical conductivity mS	0.40	0.03	0.39	0.02	0.3094	
Assimilable phosphorus mg kg^{-1}	16.25	0.96	12.75	2.06	0.0275	*
Calcium ppm	4700.00	388.16	4325.00	622.33	0.3865	
Magnesium ppm	89.85	12.72	171.91	38.12	0.0209	*
Potassium ppm	903.73	496.99	692.69	167.49	0.3865	
Sodium ppm	163.15	33.44	93.97	58.56	0.0907	
CSC meq	27.27	2.79	25.24	3.07	0.2482	
Ratio Mg/K	0.40	0.18	0.88	0.41	0.0833	
C %	6.68	2.95	3.03	0.60	0.0209	*
H %	1.56	0.43	1.72	0.32	0.5637	
Total phosphorus mg kg^{-1} ss	640.00	28.58	512.25	49.03	0.0209	*
Available nitrogen mg kg^{-1}	97.86	72.44	58.40	23.83	0.3749	
mg NO_3/kg soil	9.83	3.75	4.94	2.73	0.0833	

Texture and structure were evaluated by Chi-square test and only texture was significant, Biomass area 1 was composed of 50% clay loam (CL) and 50% sandy clay loam (SLC), while Biomass area 2 was composed of 75% clay (C) and 25% clay loam (CL) (Table 2). For the structure of Biomass 1, 75% was negligible (Neg) and 25% considerable (Con), while for Biomass 2, 50% was negligible (Neg) and 50% trace (TRA) (Table 3).

Table 2. Percentage of soil texture of the two areas. C = Clay, CL = Clay loam, SCL = Sandy clay loam. The * indicates a statistically significant difference.

Soil Texture %	C	CL	SCL	*p* Value	Significance
Biomass 1	0	50	50	0.0264	*
Biomass 2	75	25	0		

Table 3. Percentage of structure of the two areas. Con = Considerable, Neg = Negligible, TRA = Trace.

Soil Structure %	Con	Neg	TRA	*p* Value	Significance
Biomass 1	25	75	0	0.113	
Biomass 2	0	50	50		

Moisture measured in the soil at the time of harvesting differed significantly at the variance analysis (one-way ANOVA) between Biomass Area 1 and Biomass Area 2 (p = 0.001). Biomass area 1, with a mean of 37.48%, a standard deviation of 3.95, a maximum of 43.4, and a minimum of 30.4, while Biomass area 2, with a mean of 47.4%, a standard deviation of 4.6, and a maximum of 54.8 and a minimum of 41.2%, were significantly different (Figure 2).

The statistical results of the Kruskal–Wallis test indicate significant differences (p = 0.0001) between the two areas examined (Figure 3). Biomass area 1 had a mean penetration resistance of 0.7 ± 0.34 MPa, while Biomass area 2 had 0.51 ± 0.22 MPa (mean ± standard deviation, respectively), with a percentage variation of 44%. The maximum penetration resistance values reached in the Biomass 1 area are 1.69 MPa, while in the Biomass 2 area are 1.5 MPa; area 1 is one-and-a-half times higher than area 2.

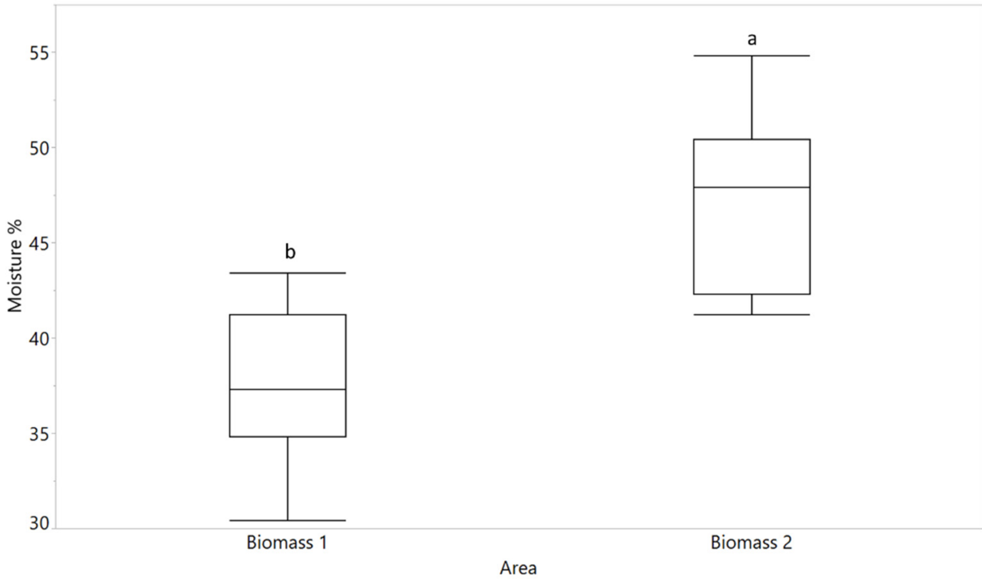

Figure 2. Moisture boxplot in the two cultivated areas. The letters indicate a significant difference between the moisture content at $p \leq 0.05$.

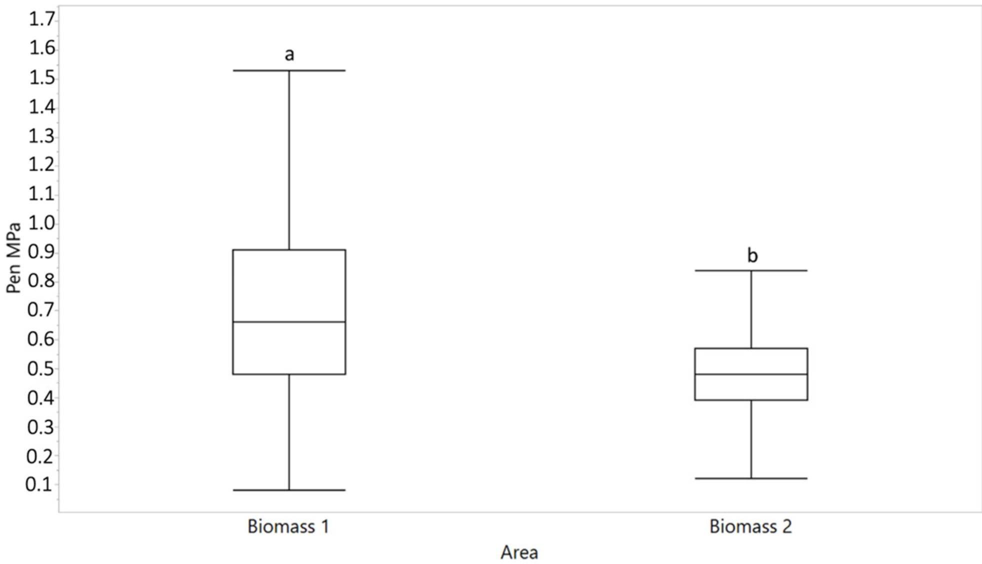

Figure 3. Penetration resistance of the two areas sown with *Phalaris arundinacea*. The letters indicate a significant difference between the penetration resistance at $p \leq 0.05$.

The same test applied to areas where the tractor has gone over and areas where it has not shows a significant difference ($p = 0.0001$). The areas with no tractor passage have a mean penetration resistance of 0.57 ± 0.27 MPa, compared with a mean of 0.63 ± 0.32 MPa for the areas where the machine has gone over, with a maximum of 1.59 MPa and 1.69 MPa, respectively (Figure 4).

As expected, the resistance to penetration increases with increasing depth but not entirely progressively. There are two areas, one between 20 and 25 cm and the other between 30 and 35 cm, where the slope of the curve changes, showing a need for more pressure to reach the lower layers. In the first case, we go from 0.35 to 0.55 MPa without going down in depth with a $\Delta = 0.2$ MPa. In the second case, we go from 0.8 to 0.9 MPa with a $\Delta = 0.1$ MPa (Figure 5).

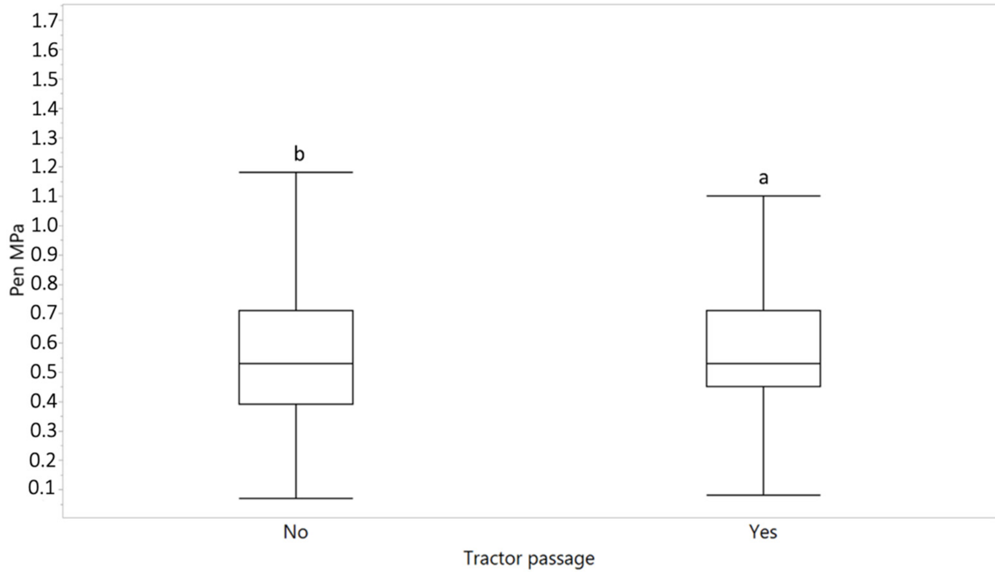

Figure 4. Penetration resistance in areas which the tractor has gone over and in areas not subject to the passage of tyres. The letters indicate a significant difference between these two areas at $p \leq 0.05$.

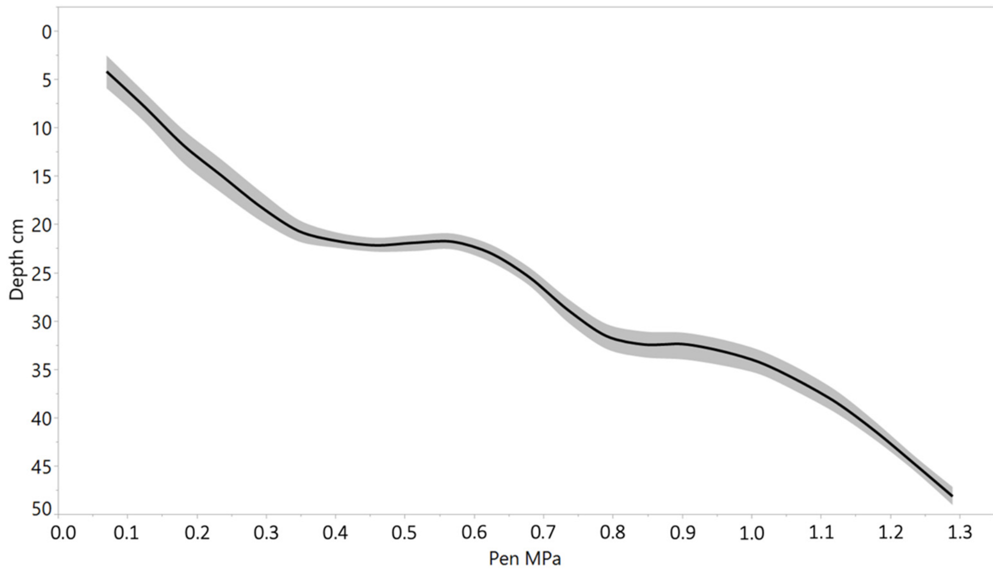

Figure 5. Penetration resistance curve in relation to depth. A cubic spline smoother with lambda = 0.05, with standardised x-values, and 95% confidence interval.

If you look at Figure 6 in more detail, you can see that there are differences between the two areas and especially how they differ when the tractor goes over them. Biomass area 1 has a penetration resistance of between 15 and 20 cm, both where the tractor has gone over and where it has not, but in the latter the resistance is much more pronounced.

In Biomass area 2, the situation is slightly different, at about 25 cm there is an increase in resistance to penetration in the points where the tractor has not gone over, but this is milder than in Biomass area 1; then, there is resistance again in the deeper portion. For the points where the tractor has gone over, there is a slight decrease in the curve's slope with an increase in resistance to penetration, and then a return to a regular pattern (Figure 6).

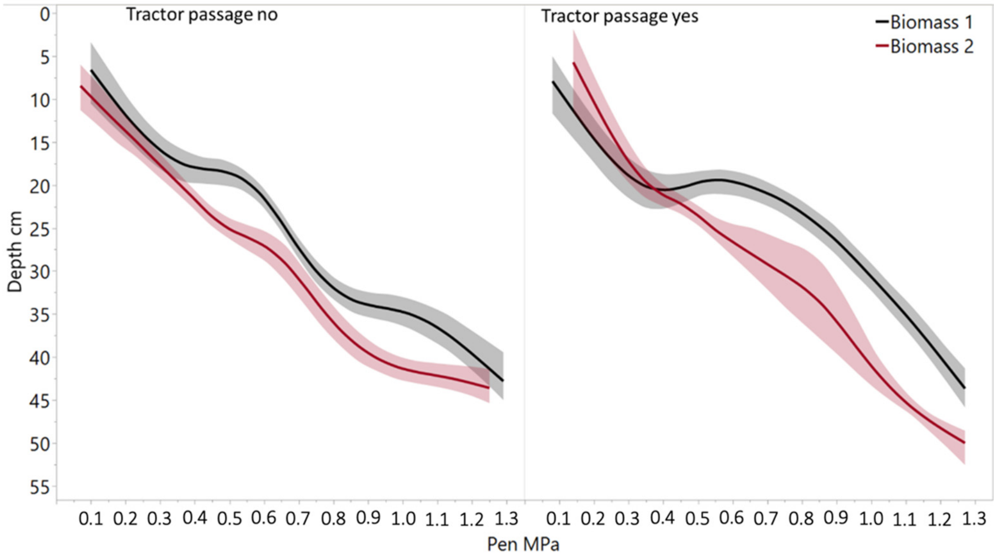

Figure 6. Penetration resistance curve in relation to depth differentiated by type of area and tractor passage. A cubic spline smoother with lambda = 0.05, with standardised x-values, and 95% confidence interval.

4. Discussion

The results of this study indicate good characteristics of the soils examined, in one case a mixed soil and in the other a more clayey soil. Organic matter levels are medium-to-high for both, considering that they are agricultural soils. The pH is subalkaline for both and they can be considered low or noncalcareous. The surfaces have a good supply of macronutrients with the exception of phosphorus in Biomass area 2. Skeleton is absent or present in traces. A difference in soil water content was found, probably due to the texture characteristics. The results of the penetration resistance tests indicate a higher resistance for the Biomass 1 area with average values of 0.63 MPa for the areas without tractor passage and 0.69 MPa for the areas where the machine has gone over, while for the Biomass 2 area, 0.46 MPa and 0.49 for the areas where the tractor did not go over and for those that it did, respectively (Figure 7).

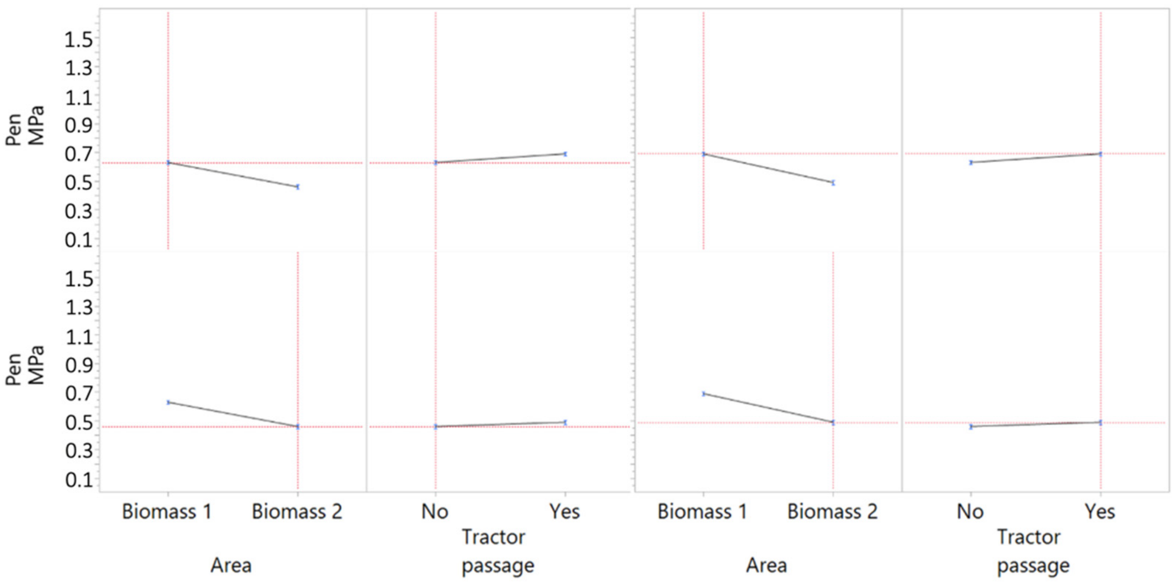

Figure 7. Interaction profiles between the factor areas (Biomass 1 and Biomass 2) and tractor passage (no and yes). The values shown are average values for each type of interaction.

Some authors found that in the first layer there were no differences between the various areas, while differences in penetration resistance began to occur between 18 and 35 cm in the areas with the greatest passage of machines, an effect that was verified in this work as resistances around 20 cm and 30 cm were observed [25]. The factors that may determine the difference in penetration resistance between the surface and deeper layers are pressure and weight of the machines. On the surface, this could depend on the pressure exerted on it by the machine, while in the lower layers, the weight could have the greatest effect. The practice of minimum tillage and the use of smaller or generally lighter machines would help with reducing soil compaction [26–28]. Other authors also attribute the frequency of traffic as a determining factor to the effect that a smaller tractor with frequent passages could do more damage than a large tractor with fewer passages [29]. With regard to crop yield, Biomass area 2 produced more than Biomass area 1, 7450.83 kg ha^{-1} and 3996.77 kg ha^{-1}, respectively. The reasons for this can be put down to the difference in soil texture and thus the consequent availability of water, but compaction could also have contributed, as the highest penetration resistance was recorded in Biomass area 1. Furthermore, it should be considered that in the first year of cultivation the plant needs to stabilise, and yields could be lower than in the second and third year. At the moment, the production values are in line with the literature, where some authors found yields from 3900 kg ha^{-1} to 12,900 kg ha^{-1} in a two-year cultivation period, while others in a five-year cultivation period observed an average of 4500 kg ha^{-1} per year [29–31]. At the moment, in this work, the number of operations and passes was limited, as can also be seen from the levels of penetration resistance. It will be interesting to see what will happen with subsequent harvests and how long it will take for the soil to return to its initial state. Moisture also plays a role and differs according to texture. In Biomass area 2, the texture allows for greater water retention and consequently changes the reaction to compaction as the machines goes through it. What seems to occur is that, at the beginning, the sandy soil compacts more and the clayey soil less, but over time, the sandy soil has the ability to return to a state closer to its initial state, while the clayey soil shows a more plastic behaviour. In fact, some authors found that penetration resistance increased much more when the soil water content is decreased than in soils with water content equivalent to field capacity [32].

Increased compaction affects bulk density and porosity of the soil and the resistance to soil penetration [33].

In addition, it also changes the distribution in the soil of the roots that, by adaptation, expand on the surface not exploring the substrata, and this is going to affect the water supply which, relegated to the surface layers, is limited and less durable over time, thus leading to a decrease in productivity [34].

Some studies have examined the effect of cover crops on penetration resistance giving excellent results in reducing this variable; consequently, in some circumstances, their use for improved soil conditions would be aspirational [35].

Another interesting study showed how biochar (pyrolysis or gasification residue) can be a great way to enhance the penetration resistance of soil by improving its chemical and physical properties [36].

Although these are the initial results of a larger, 4-year project and do not fall within a range of values that can still challenge plant growth, even if these values come close, crop root growth is often reduced when the soil resistance is around 1.5 MPa, while the root growth of many plants stops at values of 2 MPa for many of the authors proposed and for others when the soil resistance is around 2.5 MPa [37,38]. This work represents the fundamental knowledge base in the harvesting of *Phalaris arundinacea*, which will be followed by subsequent work that will also examine the permanence of compaction between the two surfaces in the absence of further disturbances.

5. Conclusions

In agriculture, the phenomenon of soil compaction is a problem that often occurs due to incorrect assessments of the moisture status and excessive tillage/machine passage over the terrain. The results of this work, although preliminary and subject to further investigation, provide information at the level of the soil pressure of mechanised harvesting on *Phalaris arundinacea* in the first year of cultivation. The effect of moisture and texture are decisive for the reaction of the soil to the pressure exerted by the machine. A minimum tillage system is certainly crucial in this respect, and a harvesting operation resulted in a statistically significant but not excessive compaction. This preliminary work provides a basis for further investigation into further harvesting operations and soil characteristics, which are fundamental for planning and managing crops that over time could lead to a worsening of soil conditions and consequently be less suitable for cultivation, conditions that should instead be preserved.

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