SOIL COMPACTION IN FOREST NURSERIES FOLLOWING TWO TILLAGE METHODS

Nicuşor Boja[1]*
Florinel Boja[1]
Alin Teuşdea[2]
Rudolf Derczeni[3]
Stelian Alexandru Borz[3]
Ilie Popescu[3]

[1] **Department of Forestry and Agrotourism, Faculty of Natural Sciences, Engineering and Informatics**, “Vasile Goldiş” Western University of Arad, Liviu Rebreanu 86, 310426, Arad, Romania
[2] **Faculty of Environmental Protection, University of Oradea**, Gen. Magheru 26, 410396, Oradea, Romania
[3] **Faculty of Silviculture and Forest Engineering**, Transilvania University, Braşov no.1 Şirul Beethoven St., 500123, Braşov, Romania

Abstract
Soil compaction supposes the soil volume compression under the action of external factors. As the solid particles cannot be compressed, the porous spaces between them are reducing and therefore through compaction the dimensions of pores, their distribution as well as the soil’s durability are modified. The degree of soil compaction can be estimated by using its bulk density, total porosity and settling compaction degree. The aim of this study was to identify the best soil tilling equipment to be used in forest nurseries in terms of reducing the soil compaction and increasing the operations quality, by introducing that kind of equipment that has the capability to minimize the soil compaction. A study has been carried out in three forest nurseries located in the area managed by the Forest Administration of Arad, during 2010-2014, on different soil types. Some of the physical and mechanical properties following the classical (plow, disc harrow) and minimum tillage (scarifier and harrow) options were taken into study. The soil compaction in the forest nurseries was characterized by the increment of bulk density and the reduction of total porosity, hydraulic conductivity and the air permeability. These modifications influenced the air and water mobility in the soil. Mechanical tilling may either trigger or avoid the soil compaction. Excessive soil tilling may favor the degradation of soil structure with immediate effects on the surface compaction. Repeated plowing and harrowing of some soils at the same depth may trigger the formation of compacted layers beneath the working depth. In general, the ability of soils to resist compaction was reduced as their moisture increased. When the soil was too wet, its plasticity and adherence were increased, generally leading to the deterioration of structural aggregates, resulting in compaction.

Keywords: compaction, soil tillage, bulk density, total porosity, compression degree.

INTRODUCTION

The soil, as a system, is the subject of different modifications which are triggered in certain proportions by climate and other anthropogenic causes. Particular modifications are caused by the action of climate and the influences of mechanical nature, related on one hand to the tillage process and, on the other hand, to the equipment passing. At the same time, the characteristics of the equipment used as well as the operational conditions are extremely diverse. In

* Author to whom all correspondence should de addressed: e-mail: bojanicu@yahoo.com

general, the used equipment is conceived to fragmentize and break up the superior part of the soil. Under operational conditions and depending on the weather state the equipment passing may alter the texture of the soil, a fact that can favour the apparition of compaction.

In the last decades, a lot of effort has been given at a global level to reduce the negative influences of soil compaction caused by anthropogenic activities, as this attempt was justified by the existence of a great agricultural area characterized by compressed soils having a poor aeration, causing a reduced root development of the forestry saplings[1].

The soil compaction occurs at a certain degree of soil deformation. This fact can be noticed in the mass of the soil through the diminution of the structural pores, when the structural aggregates take the form of continuous facies[2]. Also, the soil degradation is influenced by a series of factors of mechanical, physicochemical and biological nature, while the inappropriate mechanical operations performed on it contribute to its structural destruction[3]. Some of the soil compaction consequences are the limitation of root growth and inhibition of plant development, generally leading to the reductions in growth and production[4, 29]. Deep compaction can persist for a long period of time and, therefore, it can affect the soil's long term productivity[4, 22, 23, 24, 29]. Efforts to improve the deep soil structure, by its loosening are often expensive and inefficient. Under these circumstances, preventing the soil compaction by using appropriate or conservative technologies seems to be more efficient[6]. The results reported by many researchers have emphasized that the risk of undesirable changes in soil's structure can be reduced by limiting the mechanical stress applied to the soil[8,9,11] and by limiting the pre-compression stress[26]. Nowadays, the impact of agricultural machinery on soil properties can be simulated[28] by using compaction models[4,5,10,12,14,19,20,23,25], which are considered to be important tools for developing strategies to prevent the soil compaction[4,16,18,21,27]. Compacted soils are denser and more rigid, therefore more difficult to operate, a fact that involves increased energy consumption during operations. Furthermore, the increased soil stiffness leads to increased traction forces and additional fuel consumption when working, which ultimately contribute to the global warming processes[4]. From this point of view, a more efficient approach would require to decrease the number of tillage operations and thereby of the energy expenditure by conducting the tillage operations more efficiently under proper conditions. Since the soil's post-operational structure is strongly affected by moisture, the tillage operations should be conducted under the optimum moisture conditions. In this regard, Dexter[4,15] showed that the proportion of lumps produced by soil processing at optimum moisture is higher in the case of degraded soils. Prevention of soil compaction is a significant measure that helps maintaining or improving the soil's quality. Increased quality soils, with good physical properties are easily to mechanically operate, and they would require less energy expenditures.

The compaction degree represents a static property of the soil[4, 17]. Other properties of a particular soil type, as a material, generally do not change when its compaction state undergoes changes. Compaction is defined as the soil's dynamic behaviour by which its degree of compaction increases[4, 17]. The soil's structure and, implicitly, the properties which derive from it, represent both a morphological index, characterizing different genetic types of soil, and an agronomic index, determining, in an indirect way, its fertility. The agronomic value of the soil structure is given by its influence on the settlement, water and air[7]. The soil degradation consists of several phenomena such as the elongation and flattening of the aggregates, the apparition of the edges and corners, through a stocky settlement, the increase of the ratio of dusty material which, through the rain action, forms mud and goes through different states of plasticity, to finally harden and crack[13].

Similar to other soils, the ground compaction in forest nurseries is characterized by increments of bulk density, reduction of total porosity, hydraulic conductivity and of air permeability, modifications which influence the air and water mobility in the soil. Soil compaction presupposes the compression of its volume as an effect of external factors. As the solid particles can not be compressed, the porous spaces are reduced and consequently, the compaction modifies the dimension of the pores, their distribution and the soil's durability. The soil compression degree can be estimated through its bulk density, total porosity and compression degree. At the beginning, the compaction is caused by mechanical forces created under traffic of the layouts and/or operations of soil processing with a high rate of humidity. The traffic of the layouts on arable surfaces represents the main factor that contributed to the severe compaction of soils, especially in the last 10-20 years when the weight and dimension of the layouts grew considerably. When the potential compaction of a layout is assessed, one must take into consideration the contact pressure generated by the wheels on the soil as well as the total upload on the axis[4].

MATERIAL AND METHODS

A study has been carried out in three forest nurseries, in the area managed by the Forest Administration of Arad, Romania, (figure 1) during 2010-2014, on different soil types (*Iarac*: alluvial vertic - gleyed; *Agrisul Mare*: luvisol; *Iosasel*: eutricambosol). The physical and mechanical properties were studied for tow tillage options: the classical tillage system and minimum tillage system on the physical and mechanical properties. The applied operational systems were the following: classical tillage system (plough + disc 2X) and minimum tillage system (paraplow + harrow). The usefulness of this paper lays in the research data gathered, processed, analyzed and exploited in order to provide a pertinent study material, which could be effectively used by the specialists in the design of obtaining saplings in the forestry nurseries and the choice of the tillage system for the optimal soil.

Samples were taken form the natural settlement by using metallic cylinders of 100 cm^3, in order to determine the physical properties at three levels in depth (0-10, 10-20 and 20-30 cm); for each depth and location, the sampling was repeated six times, after the execution of each tilling operation.

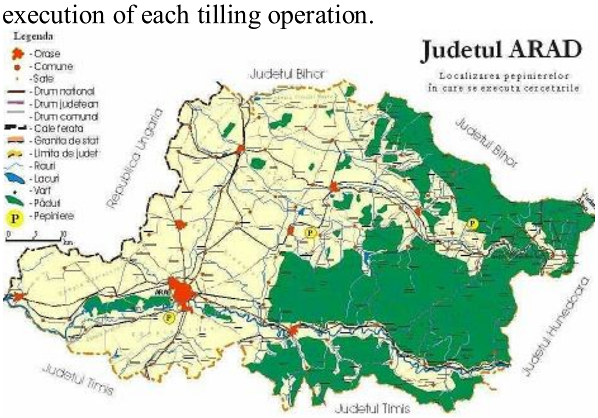


Fig. 1 The localization of nurseries

In order to assess the compression degree the following relations was used:

$$G_T = \frac{P_{MN} - P_T}{P_{MN}} \times 100 \text{, [\%]} \qquad (1)$$

where: GT is soil compression degree;

P_{MN} - porosity minimum required, %; P_{MN}= 45+0,163 x A

A – clay content < 0,002 mm;

P_T – total porosity, %.

Statistical analysis

All data were subjected to descriptive statistics KyPlot (Kyplot Version 5.0.2, http://www.kyplot.software.informer.com)[32]. Multivariate analysis: multivariate analysis of variance (MANOVA), canonical variates analysis (CVA) and hierarchical cluster analysis (HCA) was performed with P.A.S.T. version 3.04 statistical software, (Palaeontology Statistics, Copyright Oyvind Hammer and D.A.T. Harper (November 2014), http://folk.uio.no/ohammer/past/)[33].

RESULTS AND DISCUSSION

The bulk density is one of the main indicators of the settlement of the soil and also one of the determining factors of some of the properties of the soil. High values of the bulk density signify the decrease of the capacity to retain water, of the permeability, of aeration and the increase of the mechanical resistance opposed by the soil at works and moreover at the penetration of the roots; low bulk density can reduce sometimes the bearing, making difficult the traffic and the execution of the processing works of the germination bed.

The total porosity registers higher values while the content of the soil grows in organic matter and offers some important indications in relation with some of the properties of the soil. Thus, high values indicate a high capacity to retain water.

The determination of the settlement of the soil is well taken by using a synthetic indicator which shows that the compression level and the deficit of total porosity are met. The indicator which includes the bulk density (total porosity) and takes into account the soil texture is the compression degree[1].

The mean values of bulk density, total porosity and compression degree are given for each studied locations and soil depth in figures 2-4.

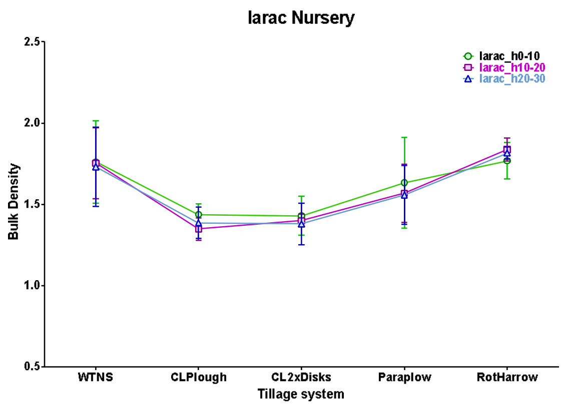


Fig. 2 Bulk density for nursery location Iarac, at different depths and for different tillage systems

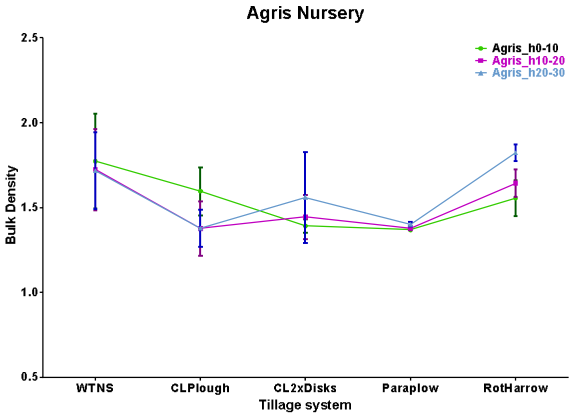


Fig. 3 Bulk density for nursery location Agris, at different depths and for different tillage systems

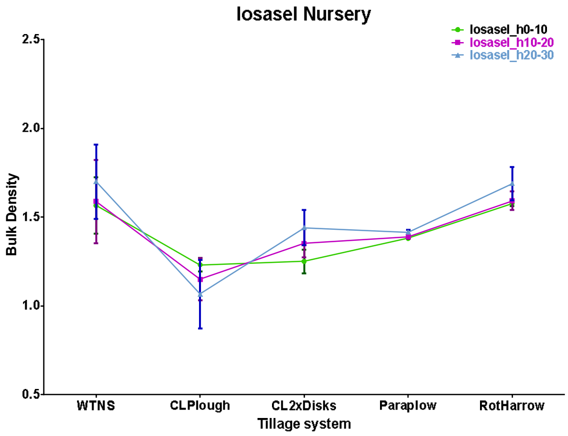


Fig. 4 Bulk density for nursery location Iosasel, at different depths and for different tillage systems

To synthesize more efficiently the data taken and to be able to describe completely the intrinsic characteristics of the sample, it was chosen a statistic processing with the aid of the program KyPlot. The results obtained are given in tables 1…3, having as a purpose to underline the variance of soil compression degree, comparative with the tillage system (minimum/classical systems)

Table 1. Statistical indexes of variation of soil compression degree in Iarac nursery

Statistical indicator	Soil compression degree				
	Witness sample	Classical system		Minimum system	
		Classical plough	2X Disks	Paraplow	Rotary harrow
Mean	27.940	0.737	1.397	15.523	32.130
S.E.M.	0.376	1.545	0.627	1.484	1.787
Standard deviation	0.651	2.675	1.086	2.571	3.095
Coefficient of variation	0.023	3.632	0.778	0.166	0.096
Minimum	27.190	-1.960	0.630	13.940	28.640
Maximum	28.360	3.390	2.640	18.490	34.540
The nr. of feature values	138	138	138	138	138
Skewness	-0.692	-0.030	0.651	0.702	-0.563
Curtosis	-1.500	-1.500	-1.500	-1.500	-1.500
Mean Deviation	0.750	2.697	1.243	2.967	3.490
Median	28.270	0.780	0.920	14.140	33.210
Range	1.170	5.350	2.010	4.550	5.900
Confidence Level(0,95)	1.617	6.646	2.699	6.387	7.688
Lower Confidence Limit	27.564	-0.808	0.769	14.039	30.343
Upper Confidence Limit	28.316	2.281	2.024	17.008	33.917

Table 2. Statistical indexes of variation of soil compression degree in Agrisul Mare nursery

Statistical indicator	Soil compression degree				
	Witness sample	Classical system		Minimum system	
		Classical plough	2X Disks	Paraplow	Rotary harrow
Mean	26.083	4.100	5.177	1.960	23.690
S.E.M.	1.135	5.350	4.127	0.662	5.746

Standard deviation	1.965	9.267	7.149	1.146	9.952
Coefficient of variation	0.075	2.260	1.381	0.585	0.420
Minimum	24.860	-1.360	-1.190	1.030	15.130
Maximum	28.350	14.800	12.910	3.240	34.610
The nr. of feature values	138	138	138	138	138
Skewness	0.700	0.707	0.338	0.509	0.411
Curtosis	-1.500	-1.500	-1.500	-1.500	-1.500
Mean Deviation	2.267	10.700	7.733	1.280	10.920
Median	25.040	-1.140	3.810	1.610	21.330
Range	3.490	16.160	14.100	2.210	19.480
Confidence Level(0,95)	4.881	23.021	17.758	2.846	24.722
Lower Confidence Limit	24.949	-1.250	1.049	1.298	17.944
Upper Confidence Limit	27.218	9.450	9.304	2.622	29.436

Table 3. Statistical indexes of variation of soil compression degree in Iosasel nursery

Statistical indicator	Soil compression degree				
	Witness sample	Classical system		Minimum system	
		Classical plough	2X Disks	Paraplow	Rotary harrow
Mean	27.940	-20.463	-4.880	-1.663	1.717
S.E.M.	0.376	3.430	4.466	0.878	0.728
Standard deviation	0.651	5.940	7.735	1.520	1.261
Coefficient of variation	0.023	-0.290	-1.585	-0.914	0.735
Minimum	27.190	-26.420	-13.050	-3.020	0.490
Maximum	28.360	-14.540	2.330	-0.020	3.010
The nr. of feature values	138	138	138	138	138
Skewness	-0.692	-0.010	-0.224	0.334	0.097
Curtosis	-1.500	-1.500	-1.500	-1.500	-1.500
Mean Deviation	0.750	5.957	8.170	1.643	1.293
Median	28.270	-20.430	-3.920	-1.950	1.650
Range	1.170	11.880	15.380	3.000	2.520
Confidence Level(0,95)	1.617	14.756	19.214	3.777	3.133
Lower Confidence Limit	27.564	-23.893	-9.346	-2.541	0.988
Upper Confidence Limit	28.316	-17.034	-0.414	-0.786	2.445

Table 4. Two-way ANOVA; factor Tillage (5 levels) and factor Depth (3 levels) separately for each nursery locations

Nursery Location	Tillage system	Depth (cm)		
		0-10	10-20	20-30
Agris	CL2xDisks	1.39 B | a ±0.04	1.45 B,C | a ±0.13	1.56 A,B | a ±0.27
	CLPlough	1.60 A,B | a ±0.14	1.38 C | b ±0.16	1.38 B | b ±0.11
	Paraplow	1.37 B | b ±0.01	1.38 C | b ±0.01	1.40 B | a ±0.01
	RotHarrow	1.56 A,B | b ±0.11	1.64 A,B | b ±0.08	1.82 A | a ±0.05
	WTNS	1.77 A | a ±0.28	1.73 A | a ±0.24	1.72 A | a ±0.23
Iarac	CL2xDisks	1.43 B | a ±0.12	1.40 C | a ±0.04	1.38 B | a ±0.13
	CLPlough	1.44 AB | a ±0.07	1.35 C | a ±0.07	1.39 B | a ±0.10
	Paraplow	1.63 AB | a ±0.28	1.57 BC | a ±0.18	1.56 AB | a ±0.18
	RotHarrow	1.77 A | a ±0.11	1.84 A | a ±0.07	1.82 A | a ±0.04
	WTNS	1.76 AB | a ±0.25	1.75 AB | a ±0.22	1.73 A | a ±0.24
Iosasel	CL2xDisks	1.25 BC | b ±0.07	1.35 BC | ab ±0.08	1.44 BC | a ±0.10
	CLPlough	1.23 C | a ±0.04	1.15 C | a ±0.12	1.07 D | a ±0.19
	Paraplow	1.38 B | b ±0.01	1.39 AB | b ±0.01	1.42 C | a ±0.01

	RotHarrow	1.58 A | b ±0.02	1.59 A | b ±0.05	1.69 AB | a ±0.09
	WTNS	1.57 A | a ±0.16	1.59 A | a ±0.23	1.70 A | a ±0.21

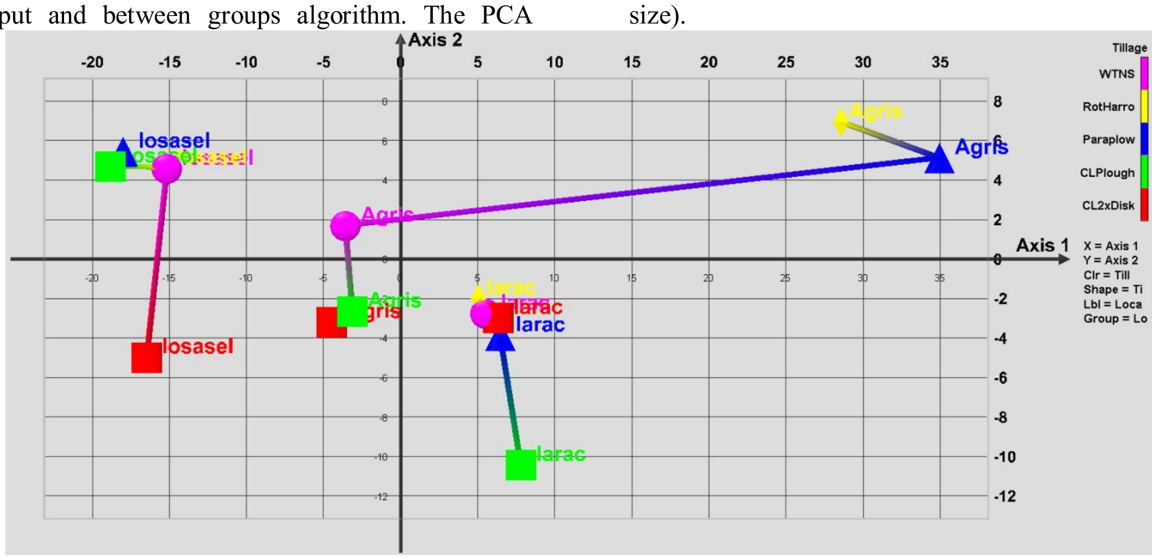
ANOVA table	SS	DF	MS	% of total variation	F (DFn, DFd)	P value
Interaction	1.531	32	0.04784	10.87	F (32, 180) = 2.312	P = 0.0003
Tillage	6.420	4	1.605	45.58	F (4, 180) = 77.56	P < 0.0001
Depth/Nursery	1.390	8	0.1737	9.866	F (8, 45) = 7.660	P < 0.0001
Subjects (matching)	1.020	45	0.02268	7.244	F (45, 180) = 1.096	P = 0.3307
Residual	3.725	180	0.02069			

Worldwide, there is the tendency to replace the classical tillage system of the soil, through the extension of the minimum work system, method recommended both from the point of view of the preservation of the soil and for the reduction of energy consumption.

Multivariate analysis

Multivariate analysis was performed in order to obtain information about the tillage systems statistical differences when considering all variable at the same time. The considered variables are: the total porosity (i.e. TotPoros) and soil compression degree with values at three depth levels: 0-10 cm (i.e. d0), 10-20 cm (i.e. d1), 20-30 cm (i.e. d2).

At first point, there was performed the principal component analysis (PCA) with the correlation matrix as input and between groups algorithm. The PCA biplot doesn't come with consistent information about how considered tillage systems modify the soil properties in quantitative and qualitative ways. However, PCA results shows that soil bulk density and compaction degree are strong correlated and the first variable can be excluded from further analysis. Thus, the multivariate analysis of variance (i.e. MANOVA) followed by canonical variates analysis (i.e. CVA) were performed. The CVA is a generalized version of linear discriminant analysis (LDA) when there are more than two groups involved – as in our case, with 15 samples of combined nursery location and tillage systems. In order to have a consequent samples grouping in CVA, the MANOVA pairwise between groups multicomparisons statistical significance *p*-results were done considering the sequential Bonferroni correction (data not shown due table huge size).



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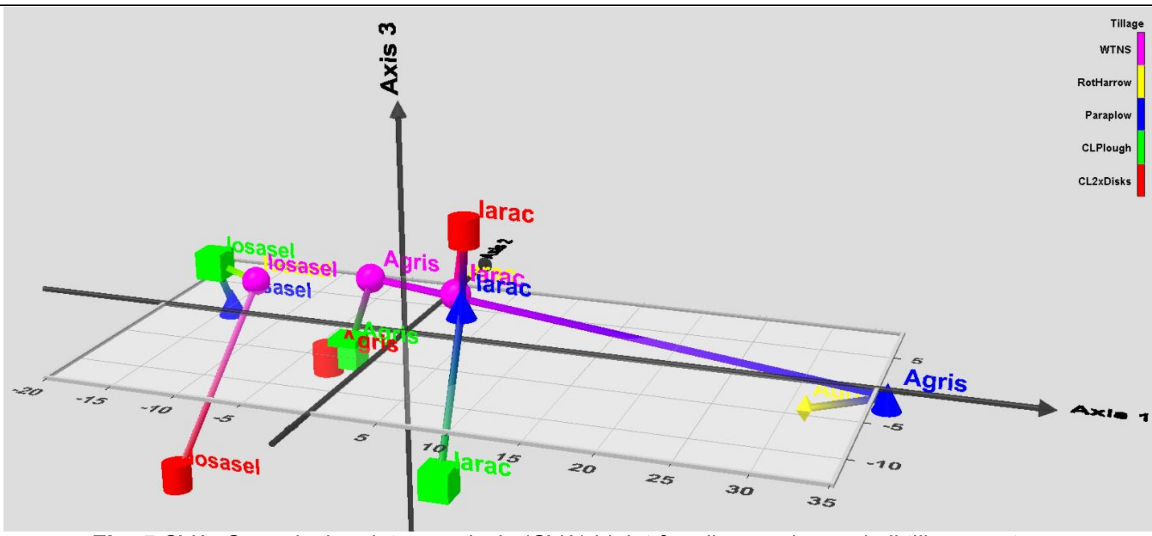

Fig. 5 CVA. Canonical variates analysis (CVA) biplot for all nurseries and all tillage systems

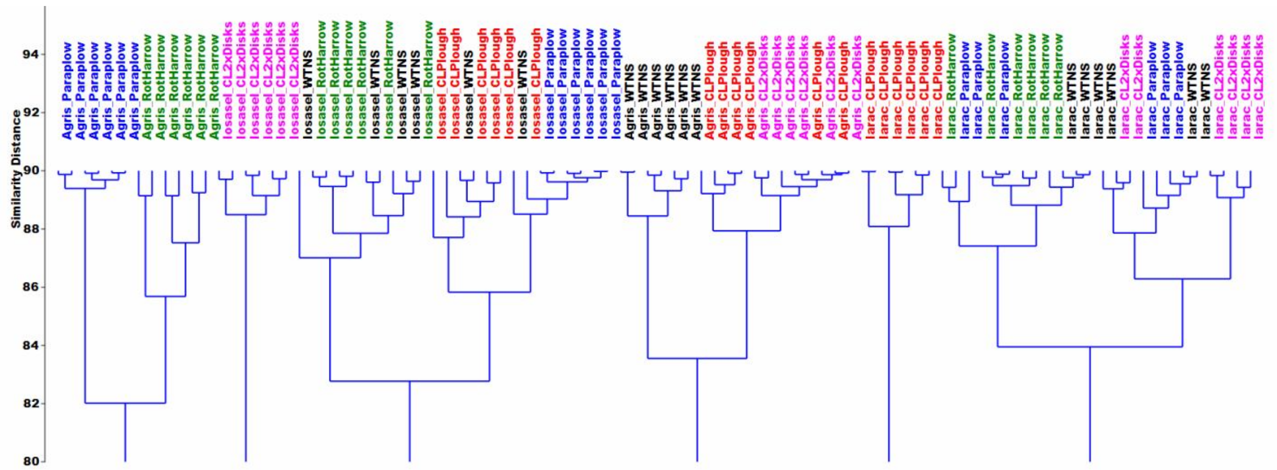

Fig. 6 HCA. Hierarchical cluster analysis (HCA) dendrogram with the clustering information for all nurseries and all tillage systems.

CONCLUSIONS

From the compression degree, from all nurseries included in the experiment, the following conclusions can be inferred:

- ✓ during the experimental cycle, the values of the compression degree at a depth of 0-30 cm indicate a weakly or moderately fragmentized soil, vaguely or moderately compressed.
- ✓ at the level of asymmetries, there is a very strict, the experimental distributions are right, for the soil compression degree values in the minimum system and the left for soil compression degree in the classical system.
- ✓ the values of the compression degree registered in the classical tillage system are by far superior to the sample (undisloquated soil), where high values of this indicator were obtained.
- ✓ if taking into consideration the coefficient of variation, all the primary data belong to relatively homogeneous amounts both in the case of the witness sample and in that of the data obtained after the preparation of the germination bed in the classical tillage system and in the minimum tillage system.

The process of soil compaction due to natural factors appears under the form of some genetic consolidated horizons. The situations which lead to the occurrence of the phenomenon of soil compaction are divided between the action of natural and anthropogenic factors.

During the action of the wheeling system of the tractors and the agricultural equipments on the soil, it is subjected to some mechanical efforts, which, through their action, make it shift laterally (refulation), vertically (compression) and horizontally (shear). The effect of the compression is transmitted in the layers of the soil in all directions, under the form of a pressure, and thus their propagation is insignificant at depths greater than 80 cm.

The physical characteristics like: bulk density, total porosity and compression degree modify according to the soil works. The modification of these properties is hard to notice (except for the compression degree) during a year because the soil has the tendency, in normal conditions, to get back to the initial state and to estompate the negative effects which appeared after the impact produced by its processing with mechanical means. Several research show that in a long period of time, the evolution of the physical properties in a certain direction takes place at a slow rhythm, after a short period of time when they start to stabilize.

Using multivariate analysis we were able to highlight precious information about soil tillage executed in three nurseries for the three sampling depths considering the values of bulk density, total porosity and the degree of compaction. Finally the CVA and HCA analyses emphasized the samples clusters generated by variables total porosity and soil compaction degree, and the pattern of soil modifications after the analysed tillage systems.

REFERENCES

I. POPESCU: Mechanization of the forestry processing, Publishing House Ceres, Bucharest, 1984.

T. RUSU, P.GUŞ: Compaction of the soils– processes and consequences, Publishing House Risoprint, Cluj-Napoca, 2007.

A. CANARACHE, I. SERBANESCU, D. TEACI, L. SAVOPOL: Tutorial for the Study of the Soil on the Spot and in the Laboratory. Agro-Forestry Publishing House, Bucharest, 1990.

N.UNGUREANU, ŞT. CROITORU, S. BIRIŞ, GH.VOICU, V. VLĂDUȚ, K.Ç. SELVI, S. BORUZ, E. MARIN, M. MATACHE, D. MANEA, G. CONSTANTIN, M. IONESCU: Agricultural soil compaction under the action of agricultural machinery, Proceedings of the 43 International Symposium On Agricultural Engineering "Actual Tasks on Agricultural Engineering", Opatija 2015, 31-42.

T. BAUMGARTL, B. KÖCK: Modelling volume change and mechanical properties with hydraulic models, Soil Science Society of America Journal, 68, 57-65 (2004).

N. BOJA, F. BOJA, A. TEUŞDEA, M. CARȚIŞ, S. PUŞCAŞ: Study on the Impact of Soil Processing on Some Physico-mechanical Properties, Journal of Environmental Protection and Ecology, 13 (2A), 941-950 (2012).

P. GUŞ, T. RUSU, S. STANILA: Unconventional processing of the soil and the machine system, Publishing House Risoprint, Cluj-Napoca; 2003.

S. BIRIŞ, E. MAICAN, N. UNGUREANU, V. VLĂDUȚ, E. MURAD: Analysis of stress and strain distribution in an agricultural vehicle wheel using finite element method, Proceedings of the 39 International Symposium On Agricultural Engineering "Actual Tasks on Agricultural Engineering", Opatija 2011, 107-118.

S. St. BIRIS, V. VLADUT, N. UNGUREANU, M. MATACHE, I. VOICEA: Researches on the development of an equation for the contact area calculus for agricultural tires, Proceedings of the 40 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering", Opatija – Croația 2012, 181-194.

M.A. BHATTI: Finite Element Analysis. Theory and Applications, Zephyr Copier, Iowa State University, 2003.

J. BOUSSINESQ: Application des Potentiels à l'étude de l'équilibre et du Mouvement des Solides Élastiques, Gauthier-Villars, Paris, 1885.

A.M. BRITTO, M.J. GUNN: Critical State Soil Mechanics via Finite Elements, Ellis Horwood, Chichester, 1987.

D. ȚOPA, G. Jităreanu: The Influence of the systems of soil processing on the categories of porosity at the culture of the winter wheat, Compaction of the soils– processes and consequences, Publishing House Risoprint, Cluj-Napoca, 2007.

R.D. COOK, D.S. MALKUS, M.E. PLESHA: Concepts and Applications of Finite Element Analysis. 4th Edition, John Wiley, 2002.

A.R. DEXTER: Soil mechanical notes. Course in agricultural soil mechanics, Swedish University of Soil Sciences, Uppsala, Sweden, 2002.

V. TZENOVA, I. MITOVA: Influence of the soil moisture regime on the nitrogen and plastid pigments content in wheat varieties, Journal of Environmental Protection and Ecology 11 (2), 540-546 (2010).

W.R. GILL, G.E. VANDENBERG: Soil Dynamics in Tillage and Traction, U.S.A. Department of Agriculture, Handbook, 1968.

K. HAMMEL: Soil stress distribution under lugged tires, Soil and Tillage Research, 32, 163-181 (1994).
R. HORN, H. DOMZAL, A. SLOWINSKA-JURKIEWICZ, C. van OUWERKERK: Soil compaction process and their effects on the structure of arable soils and the environment, Soil and Tillage Research, 35, 23-36 (1995).
A.J. KOOLEN, H. KUIPERS: Agricultural Soil Mechanics: Advanced Series in Agricultural Sciences, 13. Springer, Heidelberg, 241 (1983).
M.F. O'SULLIVAN, J.K. HENSHALL, J.W. DICKSON: A simplified method for estimating soil compaction, Soil and Tillage Research, 49, 325-335 (1999).
A. TRAUTNER: On Soil Behaviour During Field Traffic, Doctoral Thesis, Agraria 372, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2003.
I. TENU, P. CARLESCU, P. COJOCARIU, R.ROSCA: Impact of Agricultural Traffic and Tillage Technologies on the Properties of Soil. Resource Management for Sustainable Agriculture, InTech, 263-296 (2012).
G. A. CIOROMELEA, V. CRISTEAB, M. CONTOMANB: Influence of Chemical Fertilisation on Soil Profile, Journal of Environmental Protection and Ecology 14 (3), 890-895 (2013).
S.K. UPADHYAYA, U.A. ROSA, D. WULFSOHN: Application of the finite element method in agricultural soil mechanic, Advances in Soil Dynamics,2, 117-153 (2002).
J.J.H. van den AKKER, SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil and Tillage Research 79, 113-127 (2004).
V. VLĂDUȚ, M. MATACHE, S. BUNGESCU, S. BIRIŞ: Determination of soil deformation due to pressure from the running gear of tractors and self-propelled agricultural machines, Scientific Papers, 40 (2), 505-512 (2008).
V. VLĂDUȚ, L. POPA, A. DANCIU, S. BUNGESCU, S. BIRIŞ, G. PARASCHIV: Considerations Regarding Soil Pressure Determination in Real-Field and Simulated Laboratory Conditions for Bringing out Soil Compaction, Proceedings of the 37 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering", Opatija - Croația 2009, 107-116.
T.R. WAY, A.C. BAILEY, R.L. RAPER, E.C. BURT: Tire lug height effect on soil stresses and bulk density, Transactions of the American Society of Agricultural Engineers, 38, 669-674 (1995).
http://www.kyplot.software.informer.com