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ILUȘCA MARINA

SOIL FERTILITY ASSESSMENT IN THE REPUBLIC OF MOLDOVA USING NEAR-INFRARED REFLECTANCE SPECTROSCOPY

411.01 – AGROTECHNICS

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Scientific supervisor:
BOINCEAN Boris, corresponding member of the Academy of Sciences of Moldova, Professor Dr habil. in agricultural sciences

Scientific adviser:
SCHMIDHALTER Urs, Emeritus Professor Dr habil., Department of Life Sciences, Technical University of Munich, Germany

Members of the Doctoral Commission for public defense of the PhD thesis:

RUSU Teodor	– Professor Dr, UȘAMV Cluj-Napoca, Romania, *president*
DUBIȚ Daniela	– Associate Professor Dr, UTM, *scientific secretary*
BOINCEAN Boris	– Research Professor Dr habil., RIFC Selecția, *member*
POPOV Leonid	– Research Associate Dr, IPAPS Nicolae Dimo, *member*
CERBARI Valerian	– Professor Dr habil., IPAPS Nicolae Dimo, *official reference*
DENT David	– Dr, Independent scientist, Great Britain, *official reference*
HU Yuncai	– Dr habil, Department of Life Sciences, Technical University of Munich, Germany, *official reference.*

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The PhD thesis and the summary can be consulted at the Library of the Technical University of Moldova and on the ANACEC website (www.cnaa.md).

Scientific Secretary of the Doctoral Commission,
DUBIȚ Daniela, Assoc. Prof. Dr ____________

Scientific supervisor,
BOINCEAN Boris, Research Prof. Dr habil. ____________

Author
ILUȘCA Marina ____________

CONTENT

CONTEXT

Importance and relevance of the topic

Precision farming – that is to say applying the right inputs at the right time at the right place in the field – emerged in the USA more than thirty years ago (Robert *et al.* 1995). The idea is to take advantage of natural variation – rather than ignoring it and compensating with brute force and blanket application of agro-chemicals. It has been made possible by the development of technology to adjust inputs automatically across the field; on the one hand by global positioning systems; and on the other hand by variable-rate application of seeds, fertilizers, pesticides, and irrigation. Application of inputs according to soil variability will enable optimal uptake of nutrients and water by crops (Geesing *et al.* 2014) which should yield both economic and ecological benefits. However, collecting the fundamental information on soil spatial variability at a reasonable cost remains a challenge (Schmidhalter *et al.* 2008, Selige & Schmidhalter 2005 Wetterlind 2009).

Simply scaling-up existing soil mapping and sampling practices will not do. In the first place, it is necessary to collect enough geolocated soil samples to determine the effective variation in soil properties and the effectiveness of different management practices. The common practice of combining several sub-samples to make an average sample is obviously inappropriate when we need to know point-to-point soil variability and, yet, performing standard laboratory analyses on many samples is costly and time consuming. We need both spatially dense sampling and a rapid, cost-effective technique to determine a range of key soil attributes at field or local level and, also, for landscape-level monitoring of large areas (Wetterlind *et al.* 2015).

For this purpose, *near-infrared reflectance spectroscopy (NIRS)* offers an alternative to conventional analytical methods. It measures diffuse reflectance in the near-infrared region of the electromagnetic spectrum (780-2500nm) and correlates this signal with soil chemical and physical properties. It is quick, non-destructive and requires no hazardous chemicals; and several constituents can be estimated simultaneously (Brown *et al.* 2006, Islam *et al.* 2003, Van Vuuren *et al*. 2006, Viscarra *et al.* 2006). Diffuse reflectance spectra of soil result from the bending, twisting, stretching or shearing of various chemical bonds (*e.g.,* CH, OH, NH) under near-infrared radiation, which yields useful information about soil chemical composition, especially soil organic matter (Wetterlind *et al.,* 2013) which is strongly and swiftly affected by agriculture and by climate change. Soils are the most important carbon pool that we know how to manage

(Boincean & Dent 2020); information is needed urgently but standard laboratory analyses requiring sophisticated and costly skills and equipment.

NIRS for soil analysis is new for the Republic of Moldova but has been well-proven in the Technical University of Munich (Prof. Urs Schmidhalter) and several other research institutions worldwide. Studies have shown its capacity to estimate as total carbon (C), soil organic carbon (SOC), SOM, total and organic nitrogen (N), and even soil reaction (Chang *et al*. 2001, Heil *et al.* 2021, Heinze *et al*. 2013, Ludwig *et al.* 2002, Munawar *et al.* 2020, Selige & Schmidhalter 2005, Selige *et al.* 2006, Stevens *et al*. 2013, Terhoven-Urselmans *et al.* 2008, Todorova 2014, Todorova & Atanassova 2016, Van Vuuren *et al.* 2006, Viscarra *et al.* 2016, Wetterlind *et al.* 2015); as well yielding some information on soil texture (Bilgili *et al.*, 2010, Chang *et al,* 2001, Curcio 2013, Iluşca 2021**,** Islam *et al.* 2003, Tóth *et al.* 2013, Wetterlind *et al.* 20151). Bearing in mind the sparse soil survey information in the Republic of Moldova, NIRS offers a viable solution at reasonable cost.

The spectral data of Chernozem and Dark Grey Soils from the Northern area of Moldova obtained through this study is a first step in creating a national spectral library of soil properties using a standard protocol for chemical and spectral analyses following the EU LUCAS soil database (JRC 2022, Stevens *et al.* 2013) as well as comparable soil databases and spectral libraries worldwide. At the same time, this initiative will support soil management that takes account of site-specific soil fertility, as well as future monitoring soil quality and harmonization of agriculture of Moldova with the requirements of food agricultural practices in Europe.

Aim of the research: To study the capacity and practicability of NIRS to estimate the agrophysical and agrochemical indicators of soil fertility in Chernozem and Dark Grey Soils in the Northern area of Moldova.

Objectives:

- Study the evolution of soil fertility and the current situation in the agrarian sector
- Determine the physical and chemical indicators of soil fertility
- Test the accuracy of the predictive model depending on soil type and geography
- Comparative analysis of physical and chemical indicators of Chernozems and Dark Grey soils in the Northern area of Moldova
- Evaluate the action and interaction of crop rotation, tillage and soil fertilisation on SOM and crop yields
- Evaluate NIRS for mapping soil variability at field and farm level to support precision agriculture and reduce the negative impact of farming on the environment.

Scientific hypothesis: NIR spectroscopy can be a quick, cost-effective analytical tool for monitoring arable land management practices and evaluating the quality and responsiveness of Chernozem and Dark Grey Soils in Moldova.

Methodology: Research was carried out according to approved research methods in the field of soil science. Field and laboratory research involved morphological descriptions, spectroscopic measurements, chemical analyses, and statistical processing of the results. Reference analyses of soil samples were carried out in the laboratory of the Chair of Plant Nutrition *(Lehrstuhl für Pflanzenernährung, Department für Pflanzenwissenschaften, Wissenschaftszentrum Weihenstephan)* of the Technical University of Munich (Freising, Germany). Soil texture was determined in the laboratory of the Department of Soil Physics (*Bodenphysik*) of the LfL (*Bayerische Landesanstalt für Landwirtschaft*) – Bavarian State Centre for Agricultural Research (Freising) based on the KÖHN analysis as per German standard DIN ISO 11277. Spectral analysis was performed in the laboratory of the Hans Eisenmann Centre for Agricultural Sciences *(Hans Eisenmann-Zentrum für Agrarwissenschaften Weihenstephan)*, Technical University of Munich. Principal component analysis, spectral data analysis, correlation, and all statistical analyses were performed using Unscrambler®X 10.5 software and Microsoft Excel 2010.

Approval of results: The results were presented, discussed and approved at meetings of the Scientific Council of Selectia RIFC; at meetings of the Chair of Phytotechnics of the Faculty of Agronomy, State Agrarian University of Moldova; at the *Current guidelines in doctoral research* colloquium, December 7, 2017 in Bălți; at the tenth *Tradition and innovation in scientific research* conference with international participation, October 8, 2021; at the international seminar within *Supporting information exchange and capacity building in the field of agricultural research* under the FAO-Turkey Partnership Program for Food and Agriculture on October 12, 2022; and at meetings of the Chair of Plant Nutrition at the Technical University of Munich.

SYNTHESIS OF CHAPTERS

1. SOIL FERTILITY AND ITS ASSESSMENT reviews the literature on evaluation and monitoring of soil fertility and argues the need to determine the main indicators of fertility. Of all soil indicators, organic matter can be manipulated to the greatest extent. Particular attention is paid to the potential of alternative, non-destructive methods of analysis, mainly to NIRS, as a quick, cost-effective tool for the reliable and accurate estimation of soil fertility indicators and for monitoring of changes under management.

2. MATERIALS AND METHODS

2.1 Weather

The 2015-2016 agricultural year was dry (-47.5mm compared to the multi-year average) with spring and summer of 2016 receiving -10.3mm and -45.3mm, respectively. 2016-2017 was warm; total precipitation was 444.6mm, unevenly distributed with the driest months being June, July and September. 2017-2018 experienced dry periods in the autumn of 2017 and spring 2018 (-21.8mm).

2.2 Study sites and soil profile sampling

The study was carried out in 10 districts in the north of the Republic of Moldova: Briceni, Ocniţa, Donduşeni, Edineţ, Drochia, Glodeni, Rîscani, Floreşti, Soroca, Sîngerei, as well as on the experimental field of the Selectia Research Institute for Field Crops (RIFC), Bălți. After studying the specific sub-types of Chernozem and Dark Grey Soils in each district, 84 soil profiles were sampled in June-July 2016.

Thirty-six further soil profiles were sampled from field No. 3 (under winter barley in rotation 1 and peas in rotation 2) of the long-term multifactorial trial of the Selecţia RIFC that aims to optimize crop rotation, tillage and fertilisation systems so as to cut production costs, restore soil fertility and adapt to climate change. The trial embraces:

- Two crop rotations: (1) *with perennial grasses and legumes*: Winter barley → three years of Lucerne + ryegrass → Winter wheat → Sugar beet → Corn for grain; (2) *without perennial grasses and legumes*: Peas → Winter wheat → Sunflower → Corn for silage → Winter wheat → Sugar beet → Corn for grain;
- Two soil tillage systems: (1) mouldboard plough; and (2) non-inversion tillage;
- Three soil fertilisation systems: (a) unfertilized; (b) farmyard manure; (c) farmyard manure + NPK.

- Simultaneously, continuous monocropping of winter wheat, winter barley, sugar beet, sunflower and corn for grain is undertaken with the same tillage and fertilization systems.
- No chemical sprays are used to control weeds and pests.

Soil profiles were sampled using a Humax auger (Martin Burch AG, Switzerland) to extract volumes of soil in plastic tubes from 0-50cm and 50-100cm. The 120 soil profiles were divided by layers, air-dried, and passed through a 2mm sieve. The resulting 554 soil samples were analysed in the laboratory to determine soil texture, pH, total C, organic C, inorganic C, and total N contents using the NIRS method as well as standard chemical analysis as a reference.

2.3 Near-infrared reflectance spectroscopy

Each soil sample was tipped into a Petri dish and placed into a sample holder with a quartz window in the spectrophotometer. The reflected light was measured with an NIR Systems 6500 instrument equipped with a vertical transport module (Foss NIR System, Silver Spring MD). Reflectance measurements were made in the wavelength ranges 400-700nm (visible light) and 700 to 2500nm (NIR region) with 2nm spectral resolution between the collected data points. The Vis-NIR spectra were obtained as apparent absorbance (log (1/reflectance)). The NIR data analysis and statistics were performed with Unscrambler®X 10.5 software (CAMO Software AS).

Based on *principal component analysis (PCA)* carried out with the spectral values of the 554 samples within the command *Tasks* $\rightarrow$ *Analyze* $\rightarrow$ *PCA* in Unscrambler, samples representative of the spectral variations observed were selected as the *calibration set*. The validation set consisted of soil samples selected randomly and separate from those used for calibration. A total of 234 soil samples were analysed for various chemical and physical properties using standard methods in the laboratory, as reference data.

2.4 Reference chemical analyses

Total C and N were determined with a Europa 20-20x continuous flow isotope ratio mass spectrometer following combustion at 1000 °C using a Europa ANCA-GSL CN analyser. Organic C was determined by the same method as the total C after the removal of carbonates by acid fumigation; and inorganic C calculated by difference. Soil reaction was measured in suspension of soil and 0.01M $CaCl_2$ at a ratio of 1:2.5. Soil texture (fractions of clay < 0.002 mm, silt 0.002-0.06 mm and sand 0.06-2 mm) was determined by sedimentation on the automatic instrument SEDIMAT 4–12 (Umwelt-Geräte-Technik GmbH), on the basis of the KÖHN analysis to DIN ISO 11277, using 12 samples with 4 fractions.

3. EFFECTIVENESS OF NIR REFLECTANCE SPECTROSCOPY

3.1. Chemical and physical composition reference data

The soil samples selected to build the calibration models were characterized by a wide variation in the contents of total N, total C and carbonate and reaction, and a moderate variation of particle size distribution. This offered the possibility of testing the influence of soil diversity on the ability of the NIRS method to estimate these soil properties.

3.2. Spectral data processing

Figure 3.1 depicts the absorbance spectra of 554 soil samples, all of similar shape but displaying different intensities in the Vis and NIR regions. The soil spectra were transformed and smoothed by a pre-treatment (Figure 3.2) to ensure better accuracy and precision of regression models. The best fit was delivered by the first derivative transformation with Savitzky-Golay smoothing with 2^{nd} polynomial order and a search window of 11 smoothing points (5 points on the left and 5 points on the right) within the command "*Transform* > *Derivative* > *SG*" in Unscrambler.

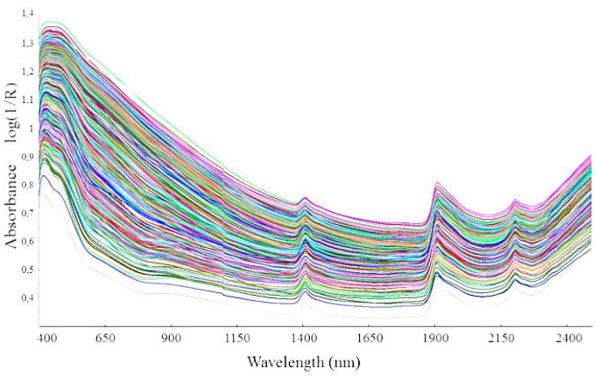

Fig. 3.1. Representative absorbance soil spectra of 554 soil samples (Iluşca *et al.* unpublished)

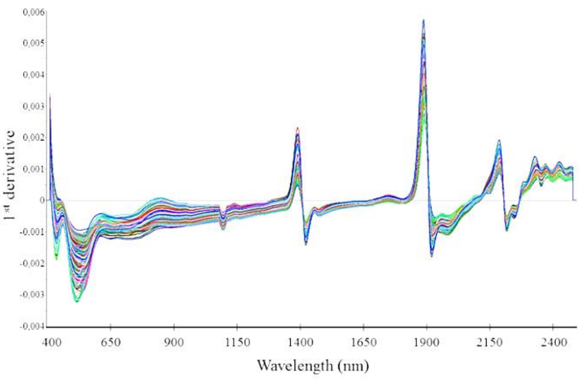

Fig. 3.2. Spectral data of the soil samples after pre-treatment (Iluşca 2021)

The absorbance spectra of all soil samples showed high absorption peaks in the NIR region at approximately 1400, 1900, and 2200nm, which are considered important wavelengths for predicting C and N so, in this study, only the NIR spectral range from 1110 to 2490nm was used.

3.3 Calibration model development

For prediction modelling, calibration was performed by a partial least squares regression (PLSR) algorithm that relates soil spectral data with the reference data obtained by classical methods, and which extracts information about the soil indicators from the absorption spectra in the NIR region (Iluşca 2021, 2022). Calibration with the PLSR algorithm for predictive modelling was performed within the command "*Tasks* > *Analyze* > *PLSR*" in Unscrambler.

A full internal cross-validation procedure was applied for optimized calibration, followed by model testing and validation. The models were assessed for predictive quality based on: (1) *the root mean square error of prediction* (RMSE), which is used to measure differences between the calculated and observed values from the measured model; (2) *the coefficient of determination* (R^2), which is used to measure the goodness of fit; and (3) *the ratio of performance to deviation* (RPD), which is used to measure the model accuracy (Heil & Schmidhalter 2021). The RPD value is the ratio of the standard deviation (SD) of the reference data analysed by standard methods to the RMSE. The higher the RPD value, the higher the probability that the built model will accurately estimate the chemical concentrations of the soil samples. RMSE should be less than SD, and RPD should ideally be ≥ 4. The validated calibration models with the lowest values of RMSE, the highest values of RPD and R^2 were selected, and used to predict the soil texture, pH, total C, organic C, carbonates, and total N contents of the remaining soil samples.

3.3.1 Regional calibration and prediction models

To build universal regional calibration models for the prediction of targeted soil properties, the dataset of 234 samples was divided into 137 samples for the calibration set and 97 samples for the validation set. The prediction equation was developed using a calibration set and validated by the validation set. The results of PLSR calibration technique used for predictive modelling of targeted soil properties from NIR spectra are shown in Figure 3.3.

The scatter plots present the linear relationship between the total N, organic C, carbonates, pH, clay and sand contents predicted by NIRS method and those measured by classical analysis (reference data), for the calibration (blue) and validation (red). A model providing a good fit will generate a graph where the points are almost in a straight line through the origin and with a slope close to 1 (Iluşca 2022).

The scatter plots show that most of the points fell close to the 1:1 line for total N, organic C, carbonates, soil pH and clay fraction (<0.002 mm); but for the sand (0.06-2 mm) fraction, the slope was significantly different from the ideal 1:1 line and the NIRS calibration for sand content showed a higher dispersion of data points.

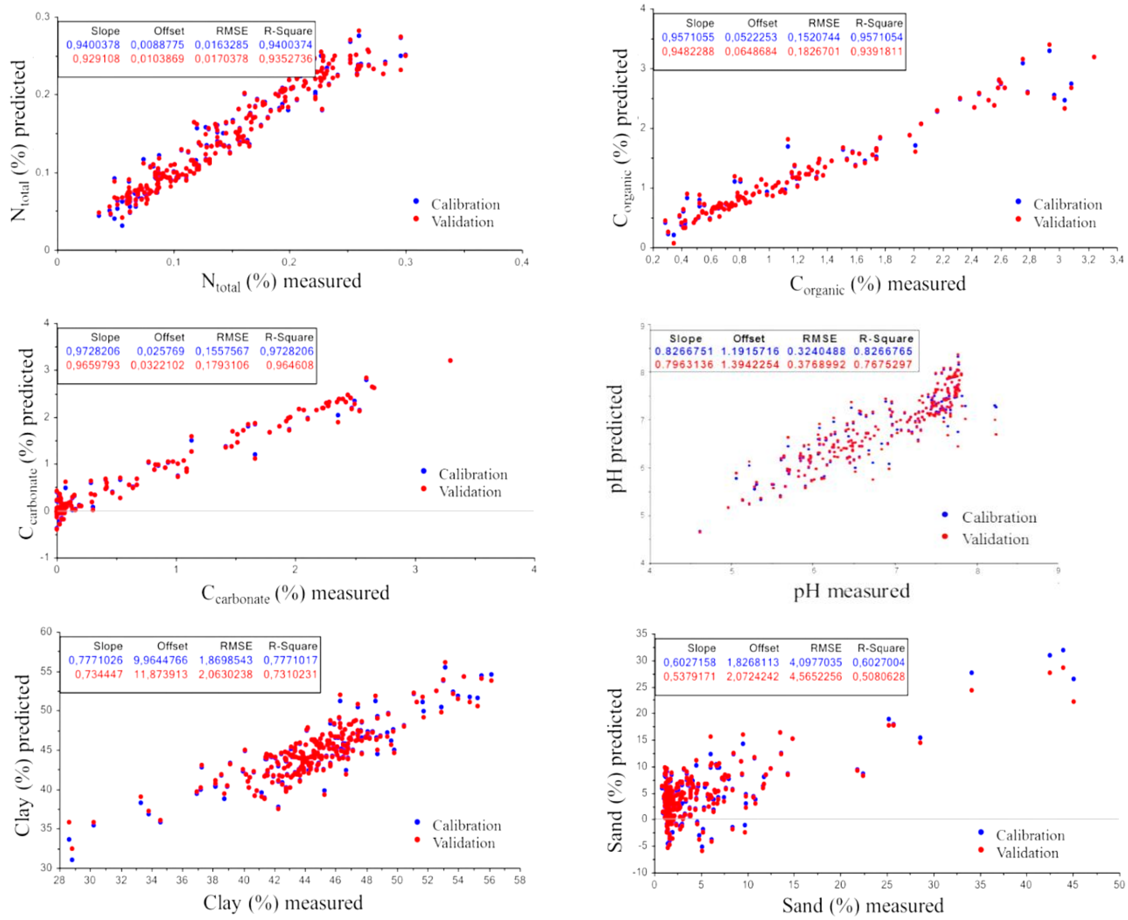

Fig. 3.3. Measured *vs* predicted total N, organic C, carbonates, pH, clay and sand contents (Ilușca 2021)

Table 3.1 presents the statistics of the PLSR calibration models and the results of the validation tests for the soil properties investigated. It indicates a strong relationship between the NIR spectra and the measured chemical soil properties, but a weak relationship for the particle-size fractions (Ilușca 2021). Calibrations for soil pH, clay, silt and sand contents showed lower R^2_{cal} (0.60-0.83), compared to N_{total}, C_{total}, $C_{organic}$ and $C_{inorganic}$ that had the best R^2_{cal} (≥0.92) and gave the lowest $RMSE_{CV}$.

Table 3.1. Prediction performance of PLSR calibration models and validation results

Soil indices	PLS factors	Calibration			Validation		
		RMSE	R^2	RPD	RMSEP	R^2	RPD
Total N, %	5	0.02	0.94	4.38	0.02	0.94	3.87
Total C, %	7	0.22	0.92	3.64	0.24	0.90	3.17
Organic C, %	5	0.15	0.96	5.75	0.18	0.94	4.60
Inorganic C, %	6	0.16	0.97	5.41	0.18	0.96	4.32
pH ($CaCl_2$)	9	0.32	0.83	2.34	0.38	0.77	2.16
Clay (<0.002 mm), %	9	1.87	0.78	2.83	2.06	0.73	1.41
Silt (0.002-0.06 mm), %	10	2.71	0.66	1.85	3.22	0.52	1.20
Sand (0.06-2 mm), %	9	4.10	0.60	1.58	4.57	0.51	1.04

For *soil chemical properties* (N_{total}, C_{total}, $C_{organic}$, carbonates and soil reaction, the validation of calibration models was very successful, achieving excellent prediction accuracies for carbonates (R^2=0.96, RPD=4.3) and organic C (R^2=0.94, RPD=4.6) contents. Although, the validation of calibration model for organic C generated a lower coefficient of determination, the RPD value was higher. Good prediction accuracies were achieved for total C (R^2=0.90, RPD=3.2) and total N (R2=0.94, RPD=3.9). Moderate prediction accuracy was achieved for soil pH (R^2=0.77, RPD=2.2).

For *soil texture*, validation of the calibration models yielded good prediction accuracy for clay content (R^2=0.73, RPD=1.41), but poor prediction for silt (R^2=0.52, RMSE=3.22%, RPD=1.20) and sand (R^2=0.51, RMSE=4.57%, RPD=1.04) contents. The obtained results showed a weak correlation between the NIR spectra and the measured values of some fractions of soil texture, which is unsurprising since the silt and sand fractions of the soil are characterised by quartz, felspars and heavy minerals that lack chemical bonds that may be stretched or sheared by near-infrared radiation.

The results reported here are consistent with others on the capacity of NIRS to estimate total N, total C, organic C, and carbonates in various soil types (Chang *et al.* 2001, Heil & Schmidhalter 2021, Heinze *et al.* 2013, Islam *et al.* 2003, Ludwig *et al*. 2002, Munawar *et al*. 2020 Terhoven *et al*. 2008, Zornoza *et al.* 2008), as well as in Chernozem (Ilieva *et al.* 2013; Todorova 2014; Vohland *et* al 2022). Good estimation of total and organic C, carbonates, total N and, to some extent, clay minerals, may be attributed to their physical composition, molecular bonds, light transmission and reflection that have a direct influence on the spectra (Chang *et al.* 2001, Ludwig *et al.* 2002, Zornoza *et al.* 2008). Soil reaction has no primary response in the NIR region, its prediction depends on the relationship with organic matter and clay content (Zornoza *et al.* 2008).

Figure 3.4 plots predicted versus measured values of total N, organic and inorganic C, soil pH, clay and sand fractions, highlighting that most of the values predicted from the spectral data were almost identical to the measured values but, also, the significant deviation in the case of sand.

There was excellent correlation between the values of carbonate, organic C, total C and N contents predicted by the NIRS method and those measured by conventional methods, obtaining a coefficient of determination $R^2 \geq 0.90$ and a very small deviation for validation (Iluşca 2021, 2022). Therefore, the model with 137 samples in the calibration set is robust, even when using different soil types and sub-types, as well as soil layers at different depths.

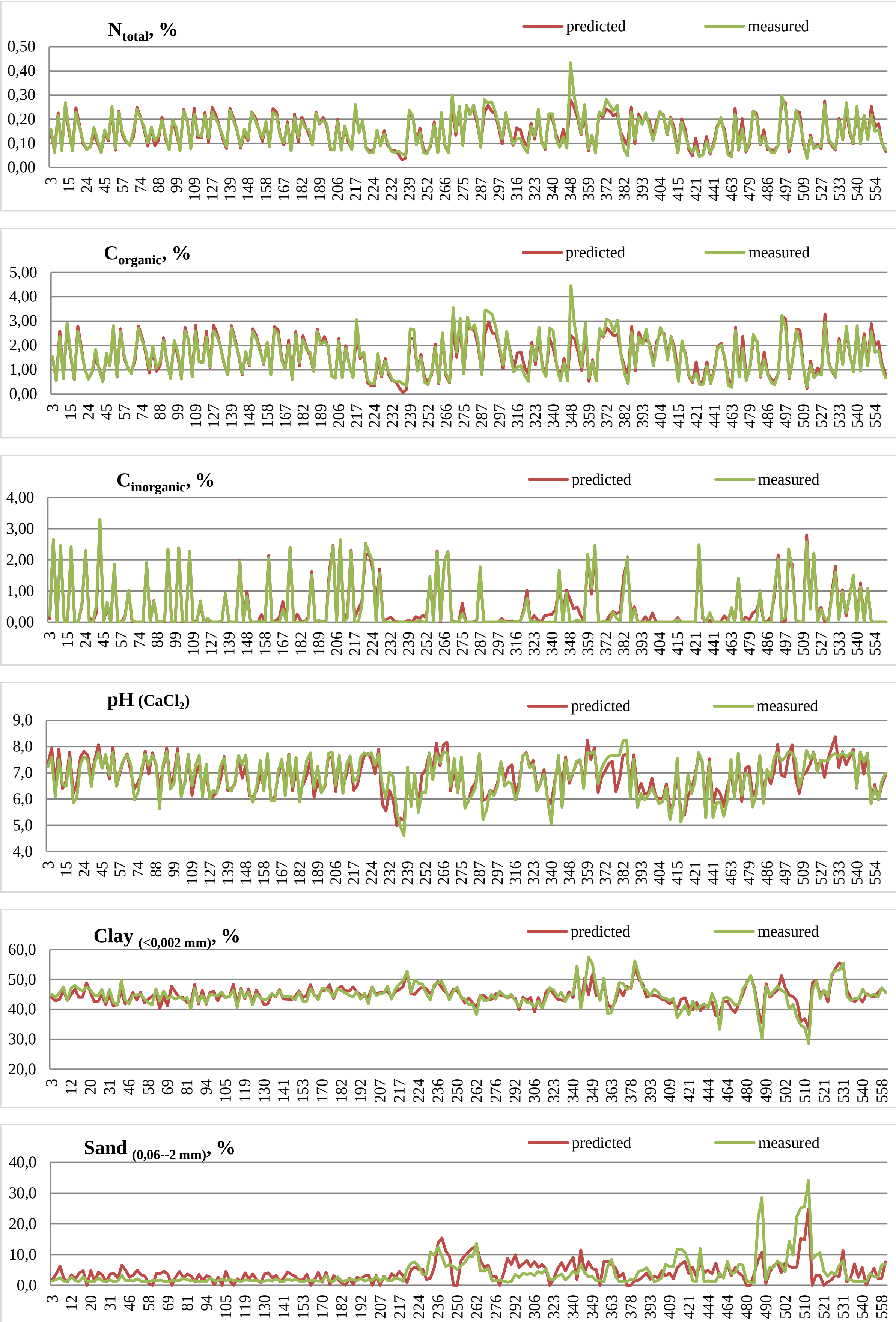

Fig. 3.4. Overlay of predicted and measured values of total N, organic C, carbonate, pH, clay and sand contents of soil samples

3.3.2 Local calibration and prediction models

Several studies have shown that the geographic area from which the soil sample set is taken affects the accuracy of NIR estimation of soil properties, and that local or field-level modelling provides the highest accuracy (Kuang & Mouazan 2011, Stenberg *et al.* 2010, Todorova & Atanassova 2016, Vohland *et al.* 2020, Wetterlind *et al*. 2013). Therefore, it was decided to separate the soil samples taken from the Selecţia experimental plots from those taken from the Northern area districts which represent a variety of sub-types of Chernozem and Dark Grey Soils. To assess the prediction accuracy, new calibration and prediction models were created on the smaller set of 211 soil samples representing one soil sub-type, namely *Typical chernozem*. To build local calibration models, 56 samples comprised the calibration set; 29 samples the validation set for the prediction of soil pH, total N, total C, organic C and carbonates; and 34 samples the validation set for soil texture prediction. The calibration and validation of the prediction model was performed in the same way as for the universal calibration at the regional level, described in sub- chapter 3.3.1.

Figure 3.5 presents the linear relationship between the total N, organic C, carbonates, pH, clay (<0.002 mm) and sand (0.06-2 mm) contents predicted by NIRS and those measured by reference analysis, for the calibration (blue) and validation (red).

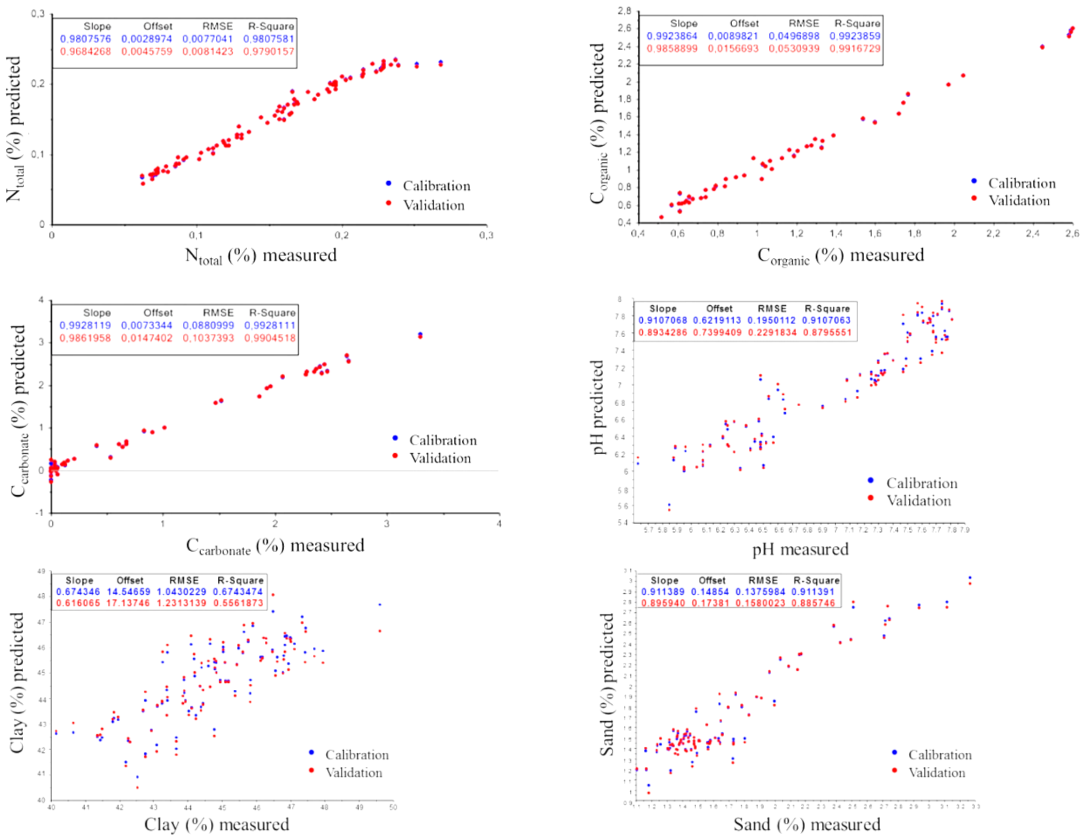

Fig. 3.5. Measured *v* predicted values of total N, organic C, carbonates, pH, clay and sand contents obtained by local calibration models and validation results

According to the slope of the regression line, these soil indicators fit significantly with the 1:1 line, except for soil pH, which slope parameter recorded lower value (Iluşca 2022). Compared to universal calibration, local NIRS calibration resulted in a narrower dispersion of data from the 1:1 line for the sand content but wider dispersion for clay content; for sand content, most of the points fell in the vicinity of the 1:1 line but for clay content the slope was significantly different from the 1:1 line.

Table 3.2 presents the statistics of the PLSR calibration models and the results of the validation tests. Based on R^2, RPD and RMSE statistics in the cross-validation, the calibration was excellent for organic C, carbonates, total C and N; successful for pH and sand content; modest to unreliable for silt and clay contents.

Table 3.7. Prediction performance of PLSR calibration models and validation results

Soil indices	**PLS factors**	**Calibration**			**Validation**		
		RMSE	**R^2**	**RPD**	**RMSEP**	**R^2**	**RPD**
Total N %	1	0.01	0.98	7.24	0.01	0.98	6.87
Total C, %	6	0.06	0.99	10.10	0.07	0.98	7.15
Organic C, %	2	0.05	0.99	14.01	0.05	0.99	13.42
Carbonates, %	4	0.09	0.99	10.66	0.10	0.99	8.94
pH ($CaCl_2$)	6	0.20	0.91	3.25	0.23	0.88	3.09
Clay (<0.002 mm), %	7	1.04	0.67	1.9	1.23	0.56	1.3
Silt (0.002-0.06 mm), %	7	1.07	0.71	2.0	1.27	0.61	1.3
Sand (0.06-2 mm), %	6	0.14	0.91	3.4	0.16	0.89	2.8

The models achieved excellent prediction accuracy for carbonates, organic C, total C and total N contents, with a coefficient of determination $R^2 \geq 0.98$ and RPD > 6; and achieved good prediction accuracy for soil pH ($R^2 \geq 0.88$ and RPD ≥ 3). However, the RMSEP values for C contents were reduced by dividing the entire dataset to create a more homogeneous soil type.

For soil texture, local calibration did not greatly improve the accuracy of prediction. The local calibration model achieved moderate prediction accuracy for sand content (R^2 = 0.89, RPD = 2.8) compared to poor prediction by regional calibration (R^2 = 0.51, RPD=1.04). For silt, we see a slight improvement in R^2 value from 0.52 to 0.61, but RPD value was not improved by local calibration. Validated local calibration for clay, reduced the predictive performance of the model, achieving a R^2 = 0.56 and RPD of 1.3, which indicates poor prediction accuracy.

Figure 3.6, which overlays the predicted *v* measured values of the total N, organic C, carbonate, pH, clay and sand contents, shows that most of the values predicted from the spectral data were almost identical to the measured values. In short, separating the entire range of soil samples into more homogeneous sub-groups according to soil type and agricultural practice generally improved prediction accuracy.

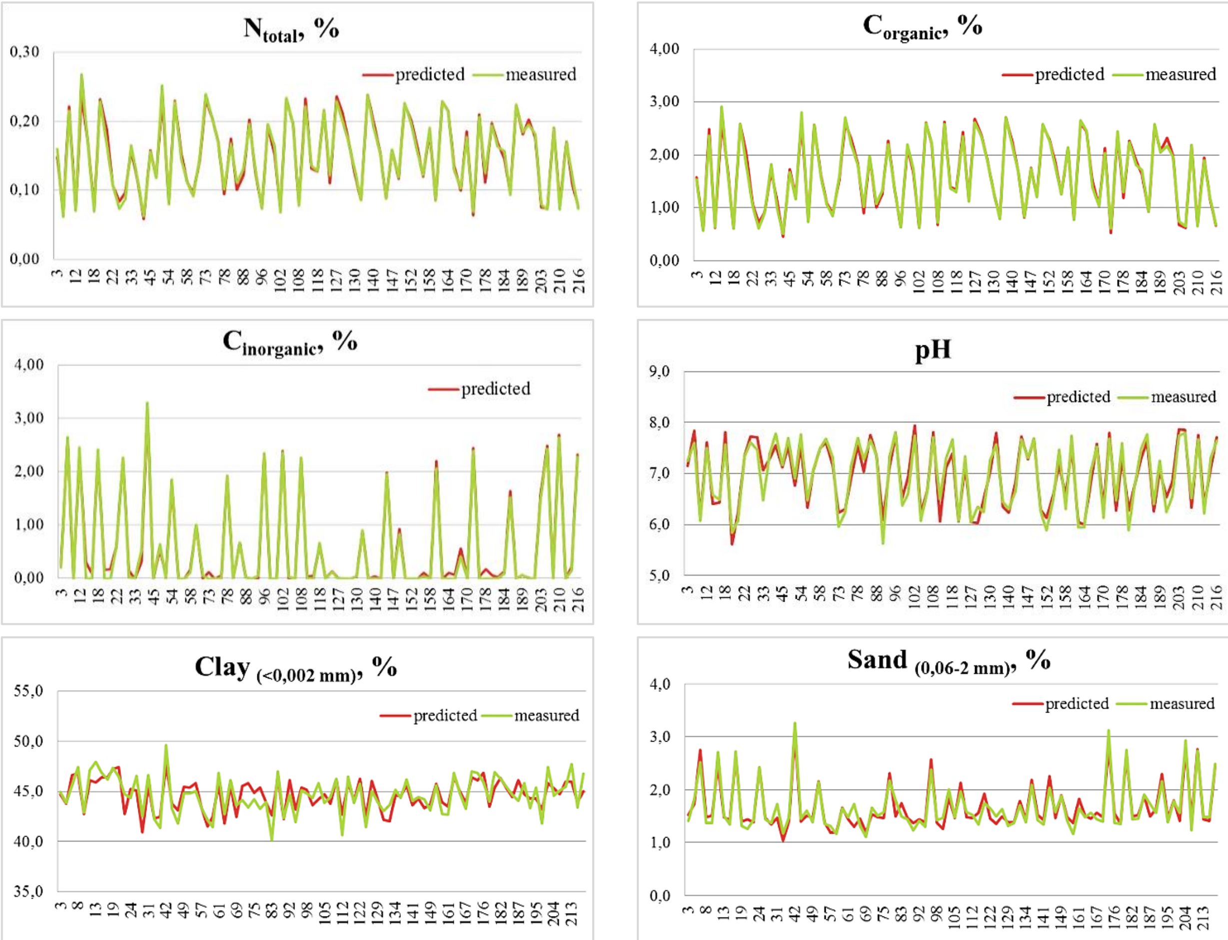

Fig. 3.6. Overlay of measured *v* predicted values of total N, organic C, carbonates, pH , clay and sand contents in the soil of Selecția RIFC multifactorial trial

4. COMPARATIVE ANALYSIS OF SOIL FERTILITY IN THE NORTH OF MOLDOVA ACCORDING TO DIFFERENT INDICATORS

Variability of soil quality across the North of Moldova was investigated by examining 84 soil profiles, of which 71 were *Chernozem (Typical, Common, Clay-illuvial, Leached and Calcareous)* and 13 were *Dark Grey Soils (Typical and Mollic*), according to the classification of Moldova's soils given by academician A. Ursu (2011).

Typical chernozem, Haplic chernozem in World Reference Base (IUSS 2015). The average content of soil organic carbon (hereafter SOC) in the *Typical chernozem* varied from 2.0-2.8% in the plough layer (0-25cm) and from 0.5-1.0% in the 75-100cm layer (Figure 4.1). The total nitrogen content correlates with SOC, varying from 0.28% in the 0-50cm layer to 0.05% in the 50-100cm layer.

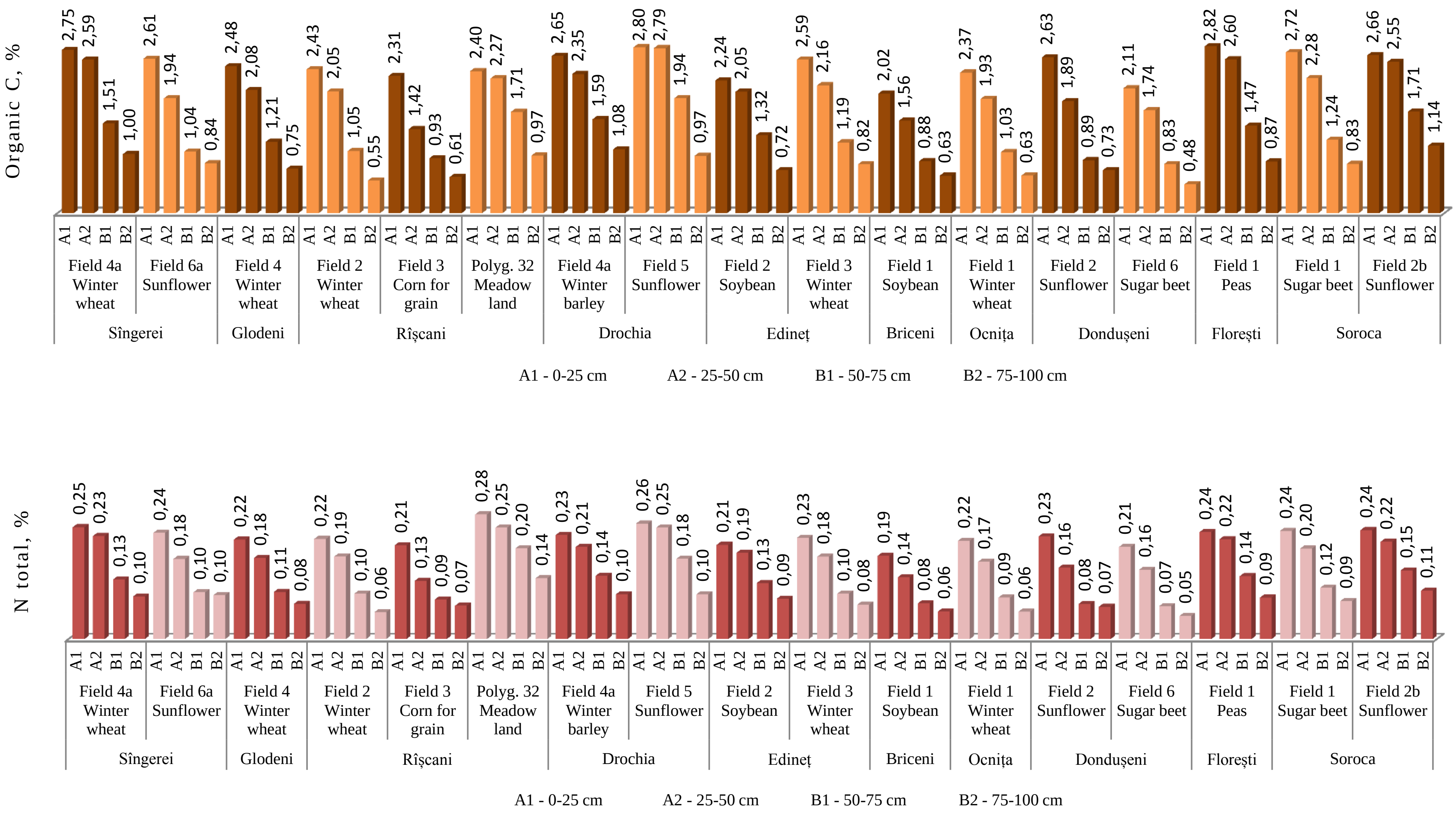

Fig. 4.1. Organic carbon and total nitrogen content of *Typical chernozem* from the Northern area (Iluşca 2022)

Figure 4.2 illustrates *Typical chernozem* profiles under arable and meadow. Whereas the profile from field no.2 under winter wheat had a loose arable layer over weakly compacted subsoil, and that from field no.3 under maize was slightly compacted to compact throughout, meadow soils exhibited a characteristic granular structure.

0-50 cm 50-100 cm	0-50 cm 50-100 cm	0-50 cm 50-100 cm
Field 2 (winter wheat)	Field 3 (maize for grain)	Polygon no. 32
Arable Typical chernozem	*Arable Typical chernozem*	*Typical chernozem under meadow*

Fig. 4.2. Soil profiles *of Typical chernozem* in Rîscani district

Comparing the data from Ursu (2011) and Cerbari (2010) on chernozem under meadows with the results obtained in this study under arable in the North of Moldova, soil organic carbon has decreased by about 1% in the 0-50cm soil layer. According to the data obtained on plots under meadow grassland, plots under continuous monoculture, and plots under a diverse crop rotation in the Selecţia long-term field experiments, it would take 31 years under unfertilised meadow or 25-30 years under fertilised meadow to restore the SOC content to its something like its original level (Boincean and Dent 2020). At the same time, greater diversity in crop rotation ensures a better quality of the soil organic matter, and the cultivation of perennial legumes in the crop rotation enriches the soil with SOC and N.

Common chernozem (Haplic chernozem in WRB). The average SOC content in the investigated profiles varied from 3.2% in the plough layer (0-25 cm) to 0.6% in the 75-100 cm soil layer (Figure 4.3). Comparing the data of Dokuchaev (1883), Kovda (1983), Cerbari (2010) and Ursu (2011), on uncultivated *Common chernozem*, with the results obtained on arable variants from North Moldova, SOC has decreased by about 1% in the plough layer (0-25cm)

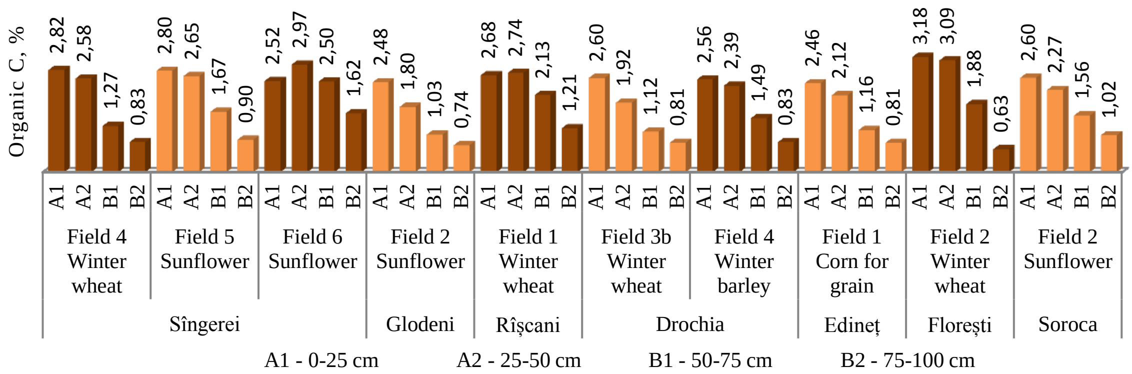

Fig. 4.3. Organic carbon content in *Common chernozem* from the Northern area.

Clay-illuvial chernozem (Luvic chernozem in WRB). The average SOC content in the Clay-illuvial chernozem profiles varies from 1.6-2.8% in the 0-25cm plough layer to 0.2-1.0% in the 75-100 cm soil layer (Figure 4.4).

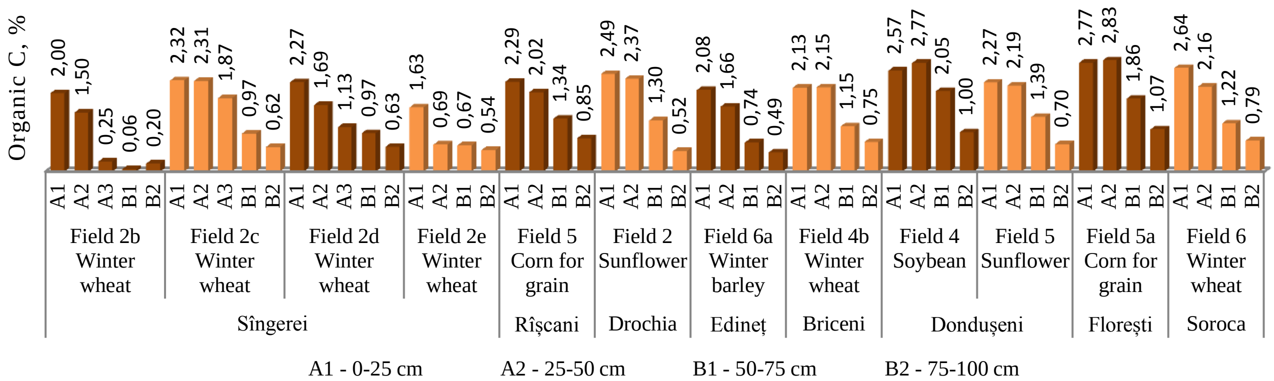

Fig. 4.4. Organic carbon content of *Clay-illuvial chernozem* in the Northern area

Leached Chernozem (Haplic phaeozem in WRB). The average SOC in the profiles of *Leached chernozem* varied from about 2-3% in the arable 0-25cm soil layer, to 0.6-1.3% in the 75-100cm soil layer (Figure 4.5).

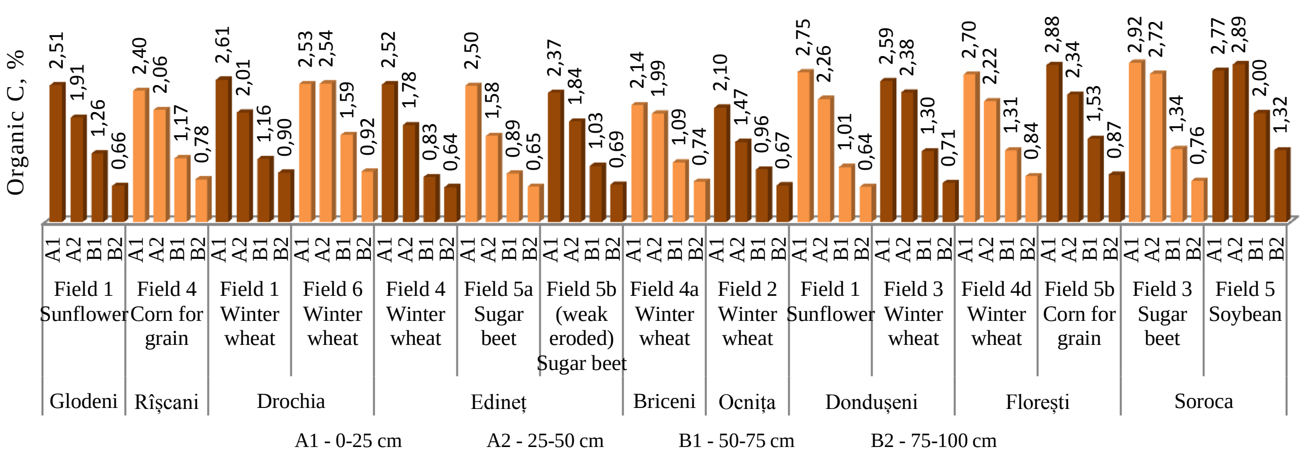

Fig. 4.5. Organic carbon content of *Leached chernozem* from the Northern area

Calcareous chernozem (Calcic chernozem in WRB). The average SOC content in *Calcareous chernozem* profiles ranged from 2.3-2.7% in the 0-25cm layer, to 0.4 -1.3 in the 75-100cm layer (Figure 4.6).

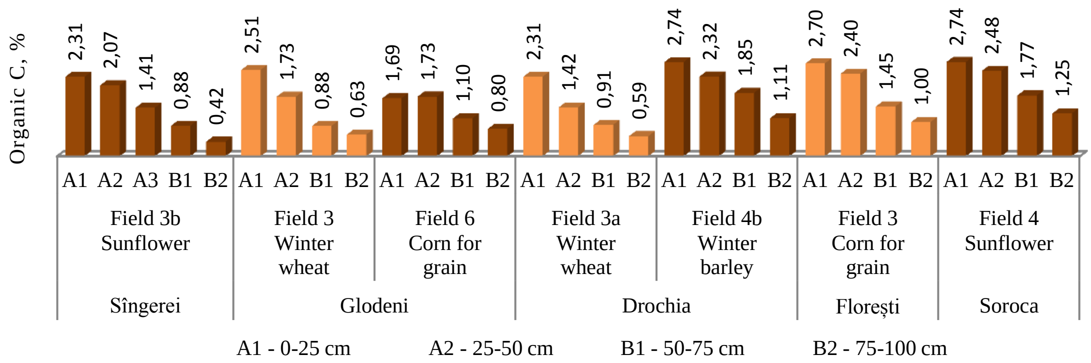

Fig. 4.6. Organic carbon content of *Calcareous chernozem* from the Northern area

Dark Typical Grey Soils (Luvic Luvisols in WRB). For analysis of the changes in arable Dark Grey Soils in the North of Moldova compared to uncultivated variants, 3 soil profiles of *Dark Grey Forest Soil* under herbaceous and woody vegetation, and 10 soil profiles of arable Dark Grey Soils were sampled. The average SOC content in the arable profiles was 1.6-2.5% in the 0-25cm plough layer and less than 1% in the 75-100cm (Figure 4.7). In the upper layers of the forest soil, SOC content reaches 3% and gradually decreases with depth, reaching 0.7% at 75-100cm. Compared with the forest soils, SOC content in the 0-25cm layer is less by 1.0-1.5%. Total N content is strongly correlated with SOC (Figure 4.7).

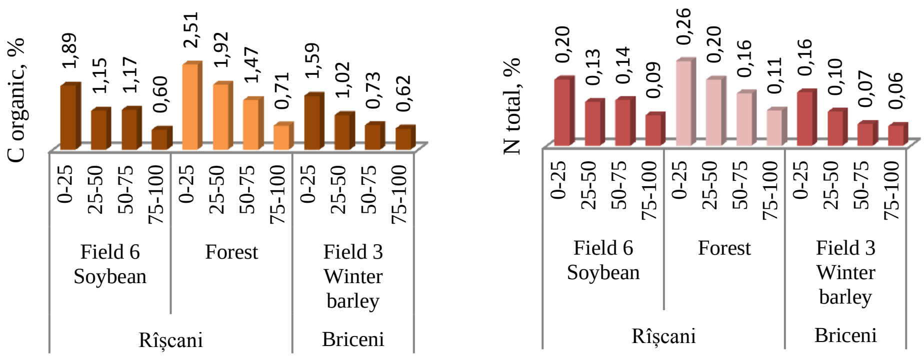

Fig. 4.7. Organic carbon and total nitrogen contents of typical *Grey Soils* in the Northern area

Dark Mollic Grey Soils (Phaeozems in WRB). The average SOC content in the *Mollic Grey Soils* investigated varies from 1.5-3.3 in the plough layer 0-25 cm, to below 1% in the 75-100cm layer (Figure 4.8). Compared with the equivalent layer in forest soils SOC decreased by about 1%. The profiles of mollic grey soils sampled in Sîngerei, Ocnița and Dondușeni districts recorded the lowest SOC values.

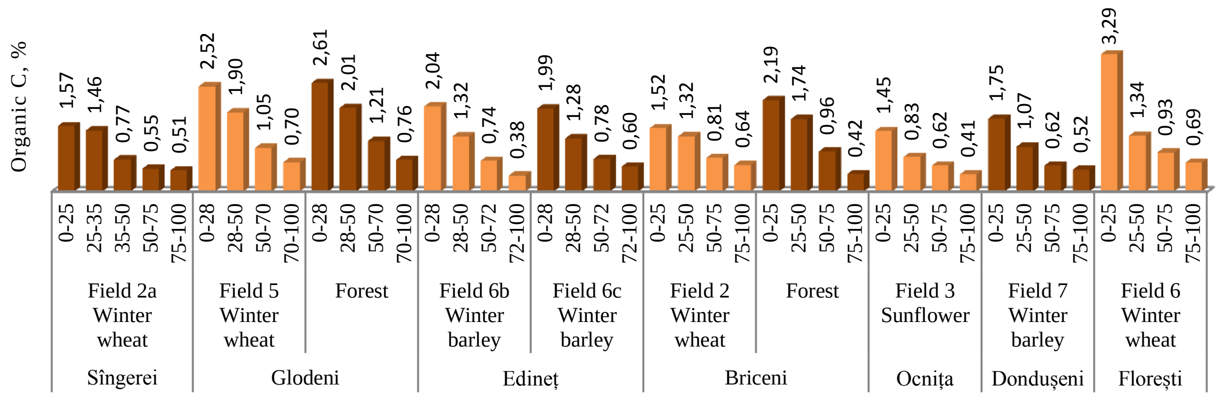

Fig. 4.8. Organic carbon content of *Mollic Grey Soils* in the Northern area

The cultivation of Typical and Mollic Grey Soils has led to the considerable reduction of SOC reserves, worsening soil properties and productive potential in some regions.

5. HORIZONTAL VARIABILITY OF SOIL PROPERTIES

To study the horizontal, within-field soil variability, several soil profiles were taken across selected fields.

Field no. 1 (Sg-F1), located on the territory of Bilicenii Vechi commune (Sîngerei district) is clearly affected by soil erosion on account of its slope gradient. This was reflected by the corn crop at the time of examination and in air photos from earlier years (Figure 5.1-5.2).

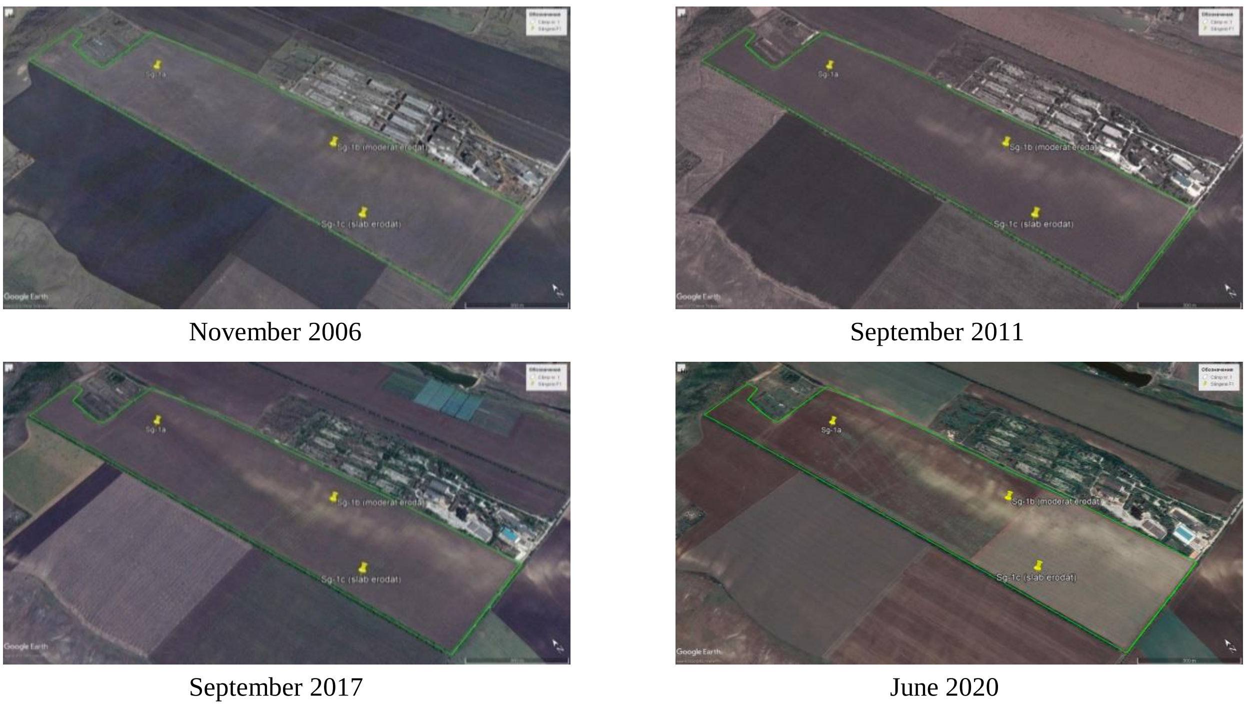

Fig. 5.1. Orthophoto field no. 1, with sampling points of the soil profiles

Sg-1a – Typical chernozem (flat surface)

0-50 cm 50-100 cm

Sg-1b – Typical chernozem (moderate eroded)

0-50 cm 50-100 cm

Sg-1c – Typical chernozem (weak eroded)

0-50 cm 50-100 cm

Fig. 5.2. Typical arable chernozem profiles and sampling positions on field no. 1, Sîngerei

Although there was no difference in soil texture between the sampling points; there was evident variability in total N, SOM, carbonates (Table 5.1).

Table 5.1. The agrochemical indicators of the soil on field no. 1, Sîngerei district

Soil profile	Soil type	Soil layer, cm	pH ($CaCl_2$)	Total N, %	SOM, %	C:N	$CaCO_3$, %	Clay, <0,002	Silt, 0,002-0,06
Sg-F1a	*Typical chernozem* (flat site)	0-27	6.3	0.24	4.39	10.7	1.2	46.6	51.4
		27-50	6.3	0.20	3.50	10.3	2.4	49.0	50.4
		50-70	6.5	0.15	2.52	9.7	3.5	47.6	52.4
		70-100	7.0	0.12	1.88	8.8	5.0	47.9	52.6
Sg-F1b	*Typical chernozem* (moderately eroded)	0-27	7.2	0.19	2.86	8.8	5.6	52.5	48.5
		27-50	7.7	0.08	0.83	5.9	17.9	45.1	46.6
		50-70	7.7	0.07	0.59	5.0	18.2	45.0	46.4
		70-100	7.5	0.07	0.58	5.0	14.4	46.6	46.9
Sg-F1c	*Typical chernozem* (weakly eroded)	0-30	6.7	0.21	3.71	10.5	1.1	47.4	51.7
		30-50	7.0	0.15	2.49	9.6	3.3	48.1	50.9
		50-70	7.6	0.12	1.82	8.9	6.1	46.9	52.5
		70-100	7.9	0.09	1.23	7.7	14.3	48.3	49.1

Soil erosion has removed soil from the slope shoulders (sampling points 1b, 1c). Some of it is deposited downslope but overall, there is a loss of fertility. Thus, in soil profile *Sg-F1a* from a flat part of the field, carbonates are practically absent and the reaction is neutral; SOM in the plough layer is more than 4% and decreases only gradually with depth to 1.88% at 70-100cm. Soil profile *Sg-F1b* has a carbonate content of 5.6% in the plough layer and a great deal more in the subsoil that has been exposed by removal of the topsoil: SOM content is sharply decreased with less than 3% in the plough layer and less than 1% in the lower horizons, including the sub-arable soil.

The high spatial variability of soil fertility within individual agricultural fields means that the usual practice of combining several sub-samples to form a composite sample does not reflect the real state of soil quality in the field. Thus, the soil sampling scheme and procedure play a crucial role in providing reliable data for digital soil mapping (DSM) and increasing its effectiveness in precision farming.

6. EVALUATION OF AGRICULTURAL SOIL MANAGEMENT PRACTICES

6.1. Influence of crop rotation, tillage and fertilization on soil fertility indicators

The results obtained in the Selecţia long-term multifactorial trials confirm the fundamental roles of crop rotation, tillage and fertilisation in the SOM cycle and crop-yield formation. The application of farmyard manure has led to an increase of the SOM and total N contents in the soil under both crop rotations, and in the plots with non-inversion tillage compared to the plots under the mouldboard plough. The additional application of mineral fertilizers to the manured plots in the crop rotation that includes perennial legumes and grasses has led to decrease of the SOM and total N contents in the plots with non-inversion tillage but an increase in the plots under the mouldboard plough, especially for the 0-50 cm soil layer. In the crop rotation without perennial grasses, the additional use of mineral fertilizers on the manured plots led to the accumulation of SOM and total N.

The data confirm the benefits of crop rotation, especially the inclusion of perennial legumes and grasses in rotation, and the application of organic fertilizers and modest rates of mineral fertilizers. The evidence on tillage is equivocal but the long-term trials have not systematically evaluated zero tillage.

6.2. Production of field crops in multifactorial trial

After several complete 6-field rotations of the Selecţia multifactorial trial beginning in 1971, the yield of winter wheat sown after three years of lucerne and perennial grasses is significantly higher compared to the winter wheat yield following maize for silage (Table 6.2), regardless of tillage. The average increase in the yield of winter wheat yield in the crop rotation with perennial grasses and legumes was +2.89 t/ha on plots under the mouldboard plough, and +2.40 t/ha on plots with non-inversion soil tillage.

The additional application of mineral fertilizers on the plots benefitting from the post-action of farmyard manure does not significantly increase the wheat yield from the crop rotation with perennial legumes and grasses, but it does significantly increase the yield from the crop rotation *without* perennial grasses, regardless of tillage. This highlights a real opportunity to cut mineral fertiliser application when perennial legumes and grasses are included in the crop rotation – thereby saving time, labour, money, and carbon emissions.

Table 6.1. Soil indicators in the multifactorial trial on interaction of tillage and fertilisation in crop rotation with and without perennial grasses, 2016

Soil tillage	Fertilisation	Soil layer, cm	Crop rotation 1 – with perennial grasses (winter barley in 2016)					Crop rotation 2 – without perennial grasses (peas in 2016)				
			N_{total}, %	SOM, %	$CaCO_3$, %	pH_{CaCl2}	C/N	N_{total}, %	SOM, %	$CaCO_3$, %	pH_{CaCl2}	C/N
Non-inversion tillage	Control	0-26	0.24	4.76	-	6.3	11.3	0.24	4.74	-	6.2	11.4
		26-38	0.20	3.92	-	6.6	11.4	0.22	4.33	-	6.4	11.3
		38-50	0.15	2.78	-	7.0	11.0	0.17	3.28	-	6.6	11.1
		50-100	0.11-0.08	2.01-1.29	6.6-17.1	7.5-7.7	10.4-9.4	0.12-0.08	2.27-1.27	1.4-19.5	7.1-7.8	10.9-9.2
	Farmyard manure	0-27	0.24	4.81	-	6.3	11.5	0.24	4.74	-	6.3	11.5
		27-37	0.22	4.45	-	6.4	11.5	0.22	4.24	-	6.4	11.3
		37-50	0.16	3.20	-	6.7	11.3	0.17	3.23	-	6.9	11.1
		50-100	0.12-0.08	2.16-1.23	1.7-18.9	7.3-7.7	10.7-8.9	0.12-0.08	2.17-1.24	5.5-17.5	7.4-7.8	10.6-9.3
	Farmyard manure + NPK	0-29	0.25	4.81	-	6.3	11.3	0.24	4.77	-	6.3	11.4
		29-39	0.21	4.08	-	6.5	11.4	0.21	4.18	-	6.5	11.4
		39-50	0.15	2.88	-	6.7	11.1	0.16	3.13	-	6.8	11.2
		50-100	0.11-0.08	2.00-1.25	1.4-18.7	7.3-7.7	10.5-8.8	0.11-0.08	1.97-1.25	4.7-16.9	7.3-7.7	10.6-9.4
Mouldboard plough	Control	0-28	0.25	4.81	-	6.2	11.4	0.24	4.72	-	6.2	11.5
		28-40	0.20	3.98	-	6.3	11.3	0.19	3.82	-	6.3	11.4
		40-50	0.16	2.97	-	6.8	11.0	0.15	2.82	-	6.5	11.1
		50-100	0.12-0.08	2.18-1.22	1.7-18.7	7.2-7.8	10.9-9.0	0.11-0.08	2.01-1.24	1.4-18.5	7.0-7.7	10.6-8.8
	Farmyard manure	0-28	0.24	4.70	-	6.4	11.4	0.24	4.75	-	6.3	11.5
		28-36	0.18	3.59	-	6.6	11.4	0.19	3.70	-	6.4	11.2
		36-50	0.13	2.59	-	6.9	11.2	0.14	2.70	-	6.7	10.9
		50-100	0.10-0.07	1.93-1.09	2.7-20.3	7.5-7.8	10.7-8.7	0.09-0.08	1.73-1.25	5.5-22.0	7.5-7.6	10.7-8.9
	Farmyard manure + NPK	0-29	0.24	4.72	-	6.4	11.5	0.24	4.74	-	6.3	11.4
		29-39	0.22	4.40	-	6.4	11.6	0.20	4.01	-	6.3	11.4
		39-50	0.16	3.18	-	6.7	11.4	0.15	2.86	-	6.7	11.1
		50-100	0.10-0.08	1.90-1.22	2.6-19.7	7.3-7.7	10.6-8.8	0.10-0.08	1.92-1.24	2.0-19.3	7.2-7.6	10.9-9.1

Table 6.2. Yield of winter wheat in crop rotations with and without legumes and perennial grasses under different fertilisation, 2016-2018, t/ha

Year	Crop rotation with perennial grasses			Crop rotation without perennial grasses			DL_{05}, t/ha	Yield increase under crop rotation with perennial grasses		
	control	farmyard manure	farmyard manure + NPK	control	farmyard manure	farmyard manure + NPK		control	farmyard manure	farmyard manure + NPK
Mouldboard plough										
2016	6.37	6.22	5.90	2.87	4.29	5.42	0.29	+3.50	+1.93	+0.48
2017	4.93	5.12	5.32	3.20	3.42	5.30	0.26	+1.73	+1.70	+0.02
2018	6.04	5.73	6.45	2.59	4.94	5.81	0.42	+3.45	+0.79	+0.64
Mean	**5.78**	**5.69**	**5.89**	**2.89**	**4.22**	**5.51**		**+2.89**	**+1.47**	**+0.38**
Non-inversion tillage										
2016	5.94	6.27	6.08	3.02	4.26	5.45	0.29	+2.92	+2.01	+0.63
2017	4.79	5.11	5.33	3.07	3.89	5.22	0.26	+1.72	+1.22	+0.11
2018	5.25	5.30	6.08	2.70	4.51	6.35	0.42	+2.55	+0.79	-0.27
Mean	**5.33**	**5.56**	**5.83**	**2.93**	**4.22**	**5.67**		**+2.40**	**+1.34**	**+0.16**

CONCLUSIONS AND RECOMMENDATIONS

1. Validation of regional-scale calibration models on a dataset with various soil types and sub-types achieved successful results for several key agrochemical indicators. Excellent prediction accuracy was achieved for carbonates (R^2=0.96, RPD=4.3) and organic carbon (R^2=0.94, RPD=4.6). Good prediction accuracy was obtained for total nitrogen (R^2=0.94, RPD=3.9) and total carbon (R^2=0.90, RPD=3.2) contents. Only moderate precision was achieved for soil pH (R^2=0.77, RPD=2.2) and clay content (R^2=0.73, RPD=1.4); and for silt and sand contents the prediction performed poorly (R^2 of 0.52 and 0.51, respectively, RPD <2).
2. Validation of the local-scale calibration on a data set with a single soil sub-type provided a better predictive performance than the universal calibration at regional scale, achieving excellent accuracy for carbonates, organic C, total C and N ($R^2 \geq 0.98$ and RPD > 6), and a moderate prediction for soil pH (R^2=0.88 and RPD > 3). For soil texture, local calibration and validation results provided an improvement in the prediction accuracy for the sand content, indicating a moderate accuracy compared to poor prediction of universal regional calibration but for the silt content, the improvement was insignificant and for the clay content the performance of the predictive model decreased significantly compared to the regional calibration. A possible cause of these results could be the smaller standard deviation and narrower range of the local calibration set.

3. The key indicators of soil fertility were estimated with high precision, which confirms the usefulness of NIR spectroscopy for predicting the chemical properties of Chernozem and Dark Grey Soils of the Republic of Moldova. Therefore, NIR spectroscopy could be used as a rapid analytical tool for soil management monitoring and soil fertility assessment.
4. Comparing the results of previous studies on Chernozem under steppe vegetation or meadows with the new results on arable Chernozem from the North of Moldova, soil organic matter has decreased significantly. Likewise, the SOM content in the 0-30cm plough layer of Dark Grey Soils (3.2%-2.8%) decreased by about 1.0-1.5% compared to the SOM content in the same layer of Dark Grey Forest Soils (4.4%).
5. In long-term field experiments on *Typical chernozem* comparing crop rotations with and without perennial legumes and grasses, different systems of fertilisation and different systems of tillage running since 1971, plots under the crop rotation that includes perennial legumes and grasses treated with farmyard manure increased the SOM content by 2.5-4.8%) in the 0-50 cm soil layer. The additional use of mineral fertilizers on the background of manure application reduced the SOM content on plots with non-inversion tillage (ranging between 2.8-4.0%), but increased the SOM content on the plots under the mouldboard plough (ranging between 3.2-4.4%). Additional application of mineral fertilisers was more beneficial under the rotation without perennial legumes and grasses.
6. The efficiency of crop rotation with a mixture of legumes and perennial grasses on the yields of all other crops in the rotation link is demonstrated by the yields of all the other crops in the rotation receiving only manure or its post-action. This benefit disappears when mineral fertilizers are applied.

RECOMMENDATIONS

1. To improve the accuracy of predictive models based on NIR spectra and multivariate techniques, it is recommended to group heterogeneous data according to soil taxonomic classes and spectral similarity, so as to create more stable and robust local calibration models

2. NIRS could be successfully applied in conjunction with imaging spectroscopy (IS), which uses airborne or satellite hyperspectral sensors to produce high-resolution digital maps of soil properties. This may facilitate precision agriculture technologies to adjust the inputs of fertilizers, herbicides, pesticides, etc. according to the responsiveness of different soils and crops, to implement appropriate management to arrest land degradation, and maintain or increase soil fertility.

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BOINCEAN, B.; KASSAM, A.H.; BASCH, G.; REICOSKY, D.C.; GONZÁLEZ-SÁNCHEZ, E.J.; REYNOLDS, T.; **ILUŞCA, M.**; CEBOTARI, M.; RUSNAC, G.; CUZEAC, V.; BULAT, L.; PASAT, D.; STADNIC, S.; GAVRILAŞ, S.; BOAGHII, I. Towards Conservation Agriculture Systems in Moldova. In: *AIMS Agriculture and Food*. 2016, nr. 1(4), pp. 369-386. ISSN 2471-2086. DOI: 10.3934/agrfood.2016.4.369

Articles in international scientific journals

ILUȘCA, M.; BUCHHART, C.; HEIL, K.; BOINCEAN, B.; SCHMIDHALTER, U. Soil fertility assessment by Near Infrared Reflectance Spectroscopy in the North of Republic of Moldova. (*Unpublished*)

Articles in journals from the National Register of professional journals, category B

ILUŞCA, M. Estimating the accuracy of the NIRS prediction model based on soil types. In: *Revista de Ştiinţă, Inovare, Cultură şi Artă* „*Akademos*". 2022, vol. 2(65), pp. 93-98. ISSN 1857-0461. DOI: 10.52673/18570461.22.2-65.08. (Romanian)

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ILUŞCA, M. Evaluation of soil fertility in the Republic of Moldova. In: *Orientări actuale în cercetarea doctorală*. Ediţia 7, 7 decembrie 2017, Bălți. Bălți, Republica Moldova: Tipografia "Indigou Color", 2017, pp. 75-76. (Romanian)

ILUŞCA, M. The potential of the NIRS method in determining the texture of soils from the Northern area of the Republic of Moldova. In: *Tradiție şi inovare în cercetarea ştiinţifică*. Ediția 10, Vol. I, 8 octombrie 2021, Bălți. Bălți: Universitatea de Stat „Alecu Russo" din Bălți, 2021, pp. 183-189. ISBN 978-9975-50-271-9. (Romanian)

ADNOTARE

Ilușca Marina „*Evaluarea fertilității solurilor în Republica Moldova (cu folosirea analizei spectrale)*", teză de doctor în științe agricole, Chișinău, 2023

Structura tezei: introducere, 6 capitole, concluzii generale și recomandări, 120 pagini de text de bază, bibliografie din 220 surse, 24 tabele, 46 figuri, 22 anexe. Rezultatele obţinute sunt publicate în 6 lucrări ştiinţifice.

Cuvinte-cheie: fertilitatea solului, materia organică a solului, textura solului, agricultura de precizie, NIRS, spectru, predicție, calibrare, variabilitate spațială, tip de sol, monitorizare.

Scopul lucrării: studierea potențialului spectroscopiei de absorbție în regiunea infraroșu apropiat (NIRS) în estimarea indicatorilor agrofizici și agrochimici ai fertilității solului pe cernoziomurile și solurile cenușii din zona de Nord a Moldovei, pentru evaluarea și monitorizarea stării de calitate a acestora în timp.

Obiectivele cercetării: stabilirea rolului indicatorilor fertilității solului, în special, a materiei organice a solului în asigurarea unei dezvoltări durabile a sectorului agricol; determinarea indicatorilor agrofizici și agrochimici ai fertilității solului prin metoda NIRS; estimarea preciziei modelului de predicție în dependență de variația tipului de sol și dimensiunea arealului geografic studiat; studierea posibilităţii de utilizare a metodei NIRS în cartografierea variabilităţii spaţiale a solului, la nivel de câmp sau gospodărie agricolă, în scopul sporirii preciziei în producerea agricolă și reducerii impactului negativ asupra mediului ambiant; evaluarea aptitudinii utilizării datelor spectrale în evaluarea și monitorizarea impactului managementului agricol în timp asupra calității solurilor.

Noutatea şi originalitatea ştiinţifică. A fost efectuată analiza comparativă a stării de calitate a solurilor cenușii și cernoziomurilor din zona de Nord a Moldovei, în baza studierii profilelor de sol extrase volumetric până la adâncimea de 1 m. Pentru prima dată a fost efectuată estimarea spectroscopică a indicatorilor fertilității solului, prin metoda NIRS, fiind una rapidă, cost-efectivă și alternativă la analizele clasice de laborator. A fost studiată variabilitatea orizontală și verticală la nivel regional și în cadrul câmpului individual, cu evaluarea impactului managementului agricol asupra calității solului și amplificării proceselor de degradare.

Rezultatul obținut care contribuie la soluționarea unei probleme științifice importante constă în *argumentarea* potențialului *spectroscopiei de absorbție în regiunea infraroșu apropiat* ca instrument în evaluarea și monitorizarea fertilității solului, *ceea ce a condus la elaborarea modelelor* statistice de predicție pentru estimarea proprietăților agrochimice și agrofizice a solului, *fapt care a permis* colectarea și analiza unui număr mare de probe pentru a obține o informație detaliată privind heterogenitatea orizontală și verticală a solului la nivel regional și local.

Semnificația teoretică: Cercetările științifice efectuate au contribuit la fundamentarea și aprofundarea cunoștințelor în domeniul statisticii multivariabile, pentru a modela relația dintre datele spectrale și proprietățile solului, cu o precizie rezonabilă. Analiza evoluției în timp a stării de calitate a solurilor în Republica Moldova a confirmat necesitatea extinderii practicilor de management durabil și rezilient a solurilor de cernoziom.

Valoarea aplicativă: Rezultatele obținute vor servi drept bază inițială pentru instituirea unui sistem complex de monitorizare a calității solului în timp și spațiu, în Republica Moldova, prin utilizarea metodelor alternative și cost-efective de analiză a solului. Informația privind heterogenitatea fertilității solului poate fi folosită în cartografierea digitală a câmpului ca un instrument în managementul culturilor de câmp specific locației, în scopul utilizării raționale a resurselor de sol din gospodărie, cu reducerea cheltuielilor de producere și a impactului negativ asupra mediului ambiant.

Implementarea rezultatelor științifice: Rezultatele cercetărilor au fost implementate în procesul didactic la Universitatea Agrară de Stat din Moldova, la Universitatea de Stat „Alecu Russo" din Bălți, precum și de Agenția Națională de Relații Funciare și Cadastru.

ANNOTATION

Ilușca Marina: *Soil fertility assessment in the Republic of Moldova (using spectral analysis*)
PhD thesis in agricultural sciences, Chisinau, 2023

Thesis structure: Introduction, 6 chapters, Conclusions and recommendations; 120 pages of text, Bibliography of 220 sources, 24 tables, 46 figures, 22 annexes. The obtained results are published in 6 scientific papers.

Keywords: soil fertility, soil organic matter, soil texture, precision agriculture, NIRS, prediction, calibration, spatial variability, soil type, monitoring.

Purpose: To study the potential of near infrared reflection spectroscopy (NIRS) in the estimation of agrophysical and agrochemical indicators of soil fertility on Chernozem and Dark Grey Soils in the North of Moldova, for the assessment and monitoring of their quality.

Objectives: Establishing the role of soil fertility indicators, in particular, soil organic matter in ensuring a sustainable development of the agricultural sector; determining the agrophysical and agrochemical indicators of soil fertility by the NIRS method; estimating the prediction model accuracy based on the soil type variation and size of the geographical area studied; studying the possibility of using the NIRS method in mapping the spatial variability of the soil at field or farm level in order to increase precision in agricultural production and reduce the negative impact on the environment; assessing the suitability of spectral data for use in monitoring the impact of agricultural management practices on soil quality.

Scientific novelty and originality: The comparative analysis of the quality status of Chernozem and Dark Grey soils in the North of Moldova was carried out, based on the study of volumetrically extracted soil profiles up to a 1m depth. For the first time, the spectroscopic estimation of soil fertility indicators was carried out using the NIRS method: a quick, cost-effective alternative to conventional laboratory analyses. Horizontal and vertical variability at the regional level and within the individual field was studied, with the assessment of the agricultural management impact on soil quality and the amplification of degradation processes.

The obtained result that contributes to the solution of an important scientific problem consists in *arguing* the potential of *near infrared reflectance spectroscopy* as a tool for soil fertility assessment and monitoring, *which led to the development* of statistical prediction models for the estimation of agrochemical and agrophysical soil properties and *which allowed* the collection and analysis of a large number of soil samples to obtain detailed information on the horizontal and vertical soil variability at regional and local levels.

Theoretical significance: The scientific research carried out has contributed to the foundation and deepening of knowledge in the field of multivariable statistics to model the relationship between spectral data and soil properties with reasonable accuracy. The analysis of the evolution over time of the state of soil quality in the Republic of Moldova has highlighted the role and importance of extending sustainable and resilient soil management practices on Chernozem soils.

Application value: The obtained results will serve as an initial basis for the establishment of a complex system for monitoring soil quality in time and space in the Republic of Moldova through application of alternative, cost-effective methods in soil analysis which, in turn, will support farmers with good advice. Information on the soil fertility heterogeneity can be used in digital field mapping as a tool in site-specific field crop management with the aim of rational use of farm's soil resources, reducing production costs and the negative impact on the environment.

Results implementation: The research results were implemented in the teaching process at the State Agrarian University of Moldova, at the Alecu Russo Balti State University, as well as by the National Agency for Land Relations and Cadastre.

АННОТАЦИЯ

Илушка Марина *«Оценка плодородия почв в Республике Молдова (с применением спектрального анализа)»*, диссертация на соискание ученой степени доктора сельскохозяйственных наук, Кишинёв, 2023 г.

Структура: введение, 6 глав, выводы и рекомендации, 120 страниц основного текста, библиография из 220 источников, 24 таблиц, 46 графиков, 22 приложений.

Ключевые слова: плодородие, органическое вещество почвы, механический состав почвы, точное земледелие, БИКС, прогноз, калибровка, пространственная изменчивость, тип почвы, мониторинг.

Цель работы: изучение возможностей спектроскопии поглощения в ближней инфракрасной области (БИКС) при оценке агрофизических и агрохимических показателей плодородия почв на черноземах и серoземах северной части Молдовы, для оценки и мониторинга их качественного состояния во времени.

Задачи работы: установление роли показателей плодородия почв, в частности органического вещества почв, в обеспечении устойчивого развития аграрного сектора; определение агрофизических и агрохимических показателей плодородия почвы методом БИКС; оценка точности прогностической модели в зависимости от вариации типа почвы и размера изучаемой географической области; изучение возможности использования метода БИКС при картографировании неоднородности почвы на уровне поля или фермы с целью повышения точности сельскохозяйственного производства и снижения негативного воздействия на окружающую среду; оценка пригодности спектральных данных для использования в мониторинге воздействия систем земледелия и ведения хозяйств на качество почвы с течением времени.

Новизна и научная оригинальность: Проведен сравнительный анализ качественного состояния серoземов и черноземов в северной части Молдовы на основе изучения объемно извлеченных почвенных профилей до глубины 1 м. Впервые проведена спектроскопическая оценка показателей плодородия почв методом БИКС, который является быстрым, экономичным и альтернативным классическим лабораторным анализам. Изучена горизонтальная и вертикальная изменчивость почв с оценкой влияния агротехники на качество почвы и усиление деградационных процессов.

Полученный результат, способствующий решению важной научной задачи, заключается в *обосновании* перспективности спектроскопии БИК как инструмента оценки и мониторинга плодородия почв, *что привело к* разработке моделей статистического прогноза для определения свойств почвы, *что позволило* собрать и анализировать подробную информацию о горизонтальной и вертикальной неоднородности почв на региональном и локальном уровнях.

Теоретическая значимость работы: Проведенные научные исследования способствовали формированию и углублению знаний в области многомерной статистики для моделирования взаимосвязи между спектральными данными и свойствами почвы с достаточной точностью. Анализ эволюции состояния качества почвы в Республике Молдова с течением времени выявил роль и значимость расширения методов устойчивого управления почвами.

Практическая значимость работы: Полученные результаты послужат исходной основой для создания комплексной системы мониторинга качества почвы во времени и пространстве в Республике Молдова путем использования альтернативных и экономически эффективных методов анализа почвы. Информация о неоднородности почвенного плодородия может быть использована в цифровом полевом картографировании как инструмент технологии точного земледелия с целью рационального использования земельных ресурсов фермы, снижения себестоимости продукции и негативного воздействия на окружающую среду.

Внедрение полученных результатов: Результаты исследования были внедрены в учебный процесс в Государственном аграрном университете Молдовы, в Бельцком государственном университете им. Алеку Руссо, а также Агентством Земельных отношений и Кадастра Республики Молдова.

ILUȘCA MARINA

SOIL FERTILITY ASSESSMENT IN THE REPUBLIC OF MOLDOVA (USING SPECTRAL ANALYSIS)

411.01 – AGROTECHNICS

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