Interrelations between heavy metals and carbon sequestration: Usual practices in the North-Western Region of Romania

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Abstract. This study investigates the effects of conventional and organic management practices on soil carbon sequestration, nutrient dynamics, and heavy metal concentrations in maize cultivation systems. Organic systems consistently demonstrated significantly higher soil carbon levels compared to conventional systems, emphasizing the benefits of organic matter enrichment and carbon sequestration through natural inputs. The conventional systems exhibited higher concentrations of heavy metals such as manganese, vanadium, and zinc, likely attributable to the use of synthetic fertilizers and other chemical inputs. The principal component analysis (PCA) revealed the multidimensional nature of soil and crop interactions, with Factor 1, t explaining the majority of variability (38.44%) and highlighting the dominant influence of specific variables such as manganese and vanadium. Factor 2 (25.36%) and Factor 3 (21.20%) captured additional layers of variance, reflecting secondary and tertiary influences on soil properties. The cumulative variance explained by the first three factors reached approximately 85%, demonstrating the effectiveness of PCA in identifying critical soil and crop parameters. The results underline the ability of organic systems to enhance soil health by improving carbon content and reducing heavy metal accumulation, while conventional systems maintain higher nutrient availability but exhibit greater environmental risks.
Key Words: contamination, crop, inputs, pasture, principal components analysis.

Introduction. Soils act as both a sink for heavy metals and a reservoir for carbon. While carbon sequestration is limitative for climate mitigation, heavy metals in the soil can alter microbial activity, organic matter stability, and carbon storage dynamics. Understanding these interactions is vital for developing strategies to manage contaminated soils sustainably (Friedlová 2010; Zeng et al 2024). The interrelations between heavy metals and carbon sequestration are multifaceted, with both positive and negative implications for soil health and climate mitigation. Proper management of heavy metal-contaminated soils can enhance carbon sequestration while mitigating heavy metal risks, contributing to sustainable land use and environmental remediation (McLaughin et al 2000; Chen et al 2018).

Heavy metals in soil include elements like lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), often introduced through industrial activities, mining, and agricultural inputs. These metals can be toxic to plants and soil microorganisms, impacting soil functions (Dragovic et al 2008; Dube et al 2001; Varol 2011). High concentrations of heavy metals can suppress microbial activity, reducing the decomposition of organic matter and, paradoxically, increasing carbon sequestration by limiting carbon release. They can bind to organic matter, forming stable complexes that enhance the persistence of carbon in soils (Liu et al 2023). Over time, some microbial communities adapt to heavy metal stress, maintaining their role in carbon cycling (Giller et al 2009; Kowalska et al 2018).

Toxic heavy metals reduce plant growth, lowering biomass inputs to the soil and potentially decreasing carbon inputs. Soil organic matter (SOM) can immobilize heavy metals, reducing their bioavailability and toxicity to soil microbes. The stabilization of heavy metals in SOM enhances carbon sequestration by slowing organic matter turnover (Absu et al 2017; Six et al 1998). Heavy metals interact with functional groups in SOM, influencing carbon stabilization pathways. In contaminated soils, heavy metal toxicity limits the potential for carbon sequestration due to reduced plant and microbial activity (Wu et al 2022).

Remediation strategies, such as phytoremediation or biochar application, can reduce heavy metal toxicity while promoting carbon storage (Adriano et al 2004; Song et al 2022). Long-term monitoring is needed to understand the trade-offs between carbon sequestration and heavy metal accumulation in soils (Chibuike & Obiora 2014; Marques et al 2009).

The research presented in this study was carried out for emphasizing the soil heavy metals content and carbon contents when maize and pastures are maintained on organic and conventional systems. The study also aims to identify the influence of complex factors on interrelations between heavy metals and carbon sequestration.

Material and Method. The research was conducted in 2024 on four private farms in Romania: two located in Alba County and two in Bistrița-Năsăud County. The farms in Alba County are dedicated to crop cultivation, both focusing on cereals. One farm employs a conventional agricultural system, while the other uses an organic system. In Bistrița-Năsăud County, the farms manage natural pastures, with one practicing conventional methods and the other organic methods. Soil probes were used for obtaining soil samples from the A horizon of each farm. Laboratory analyses included the determination of organic soil carbon content using gravimetry, and heavy metals using X-ray spectrometry. SPSS for Windows was used for raw data were processing. Descriptive statistics were applied to highlight means, dispersion parameters, and Multivariate Analysis for performing the Principal Components Analysis.

Results and Discussion. For heavy metals, organic systems generally show lower concentrations compared to conventional systems. Manganese (Mn), vanadium (V), chromium (Cr), zinc (Zn), copper (Cu), and lead (Pb) are all significantly reduced in organic soils (Table 1). This indicates that organic management limits the accumulation of these elements, possibly due to reduced use of synthetic inputs or fertilizers that can introduce heavy metals. Elements like tin (Sn), nickel (Ni), and cadmium (Cd) do not show significant differences between systems, though their concentrations are slightly lower in organic soils. This suggests that while organic practices may reduce some heavy metal levels, other factors might also influence their concentrations, such as soil type or historical land use (Table 1). Thus, our results show that organic farming practices enhance soil carbon levels and reduce heavy metal concentrations, promoting healthier and more sustainable soils. However, the variability in some parameters underscores the need for consistent monitoring and management to optimize soil quality in organic systems.

When soil corresponding to pasture maintaining is analyzed in organic versus conventional systems it is found that in organic systems generally exhibit lower concentrations of manganese (Mn), vanadium (V), and zinc (Zn), with significant differences observed. This suggests that organic practices reduce the accumulation of these elements, likely due to the absence of synthetic fertilizers or other external inputs that may introduce heavy metals into the soil. For chromium (Cr), tin (Sn), lead (Pb), nickel (Ni), and cadmium (Cd), no significant differences were observed between the two systems, although concentrations are slightly lower in organic soils. This could reflect inherent soil characteristics or long-term land management histories that influence metal accumulation. The coefficients of variation (CV%) indicate a higher variability for some elements in both systems, such as vanadium and cadmium. Organic systems, however, generally show slightly reduced variability, suggesting that these practices might contribute to more stable soil conditions (Table 2).

Table 1

The basic statistics for soil carbon and heavy metals content corresponding to maize cultivation, when conventional and organic practices are used

Crop	*Cultivation system*	*N*	*X*	*s*	*CV, %*
C, %	Conventional	5	2.02a	0.26	12.73
C, %	Organic	5	4.87b	0.19	3.95
Mn, ppm	Conventional	5	106.80a	4.66	4.36
Mn, ppm	Organic	5	84.04b	4.40	5.24
V, ppm	Conventional	5	27.40a	1.52	5.53
V, ppm	Organic	5	26.00b	1.58	6.08
Cr, ppm	Conventional	5	22.40a	1.82	8.11
Cr, ppm	Organic	5	20.00b	1.87	9.35
Zn, ppm	Conventional	5	14.28a	1.48	10.37
Zn, ppm	Organic	5	13.00b	1.58	12.16
Sn, ppm	Conventional	5	9.56a	1.13	11.78
Sn, ppm	Organic	5	8.76a	1.26	14.39
Cu, ppm	Conventional	5	10.64a	1.07	10.07
Cu, ppm	Organic	5	9.64b	1.12	11.59
Pb, ppm	Conventional	5	5.32a	1.19	22.34
Pb, ppm	Organic	5	4.32b	0.84	19.53
Ni, ppm	Conventional	5	3.92a	0.73	18.61
Ni, ppm	Organic	5	3.02a	0.81	26.74
Cd, ppm	Conventional	5	2.42a	0.70	28.98
Cd, ppm	Organic	5	1.84a	0.44	23.88

Different letters correspond to significant differences at 5% threshold.

Except for cadmium, all heavy metals identified in soil samples frame within normal limits (Order of the Ministry of Waters, Forests, and Environmental Protection no. 592, 2002). Even in lower concentration (1.84 ppm) in soil from organic culture, compared with soil where conventional system is practiced (2.42 ppm), cadmium concentrations are over normal values (1 ppm), but in both cases under the alert thresholds (3 ppm).

Similar with the situation identified in maize crop, when pasture soil is analyzed, except for cadmium, all heavy metals identified frame within normal limits (Order of the Ministry of Waters, Forests, and Environmental Protection no. 592, 2002). Cadmium concentrations (1.90 ppm corresponding to organic maintained pasture, and 2.44 ppm corresponding to conventionally maintained pasture) are over normal values (1 ppm), but under the alert thresholds (3 ppm).

The results of the current study show that organic pasture management enhances soil carbon levels and reduces the accumulation of certain heavy metals, promoting more sustainable and environmentally friendly soil conditions. The slight reductions in metal variability further underscore the potential for organic practices to foster more balanced soil systems. However, ongoing monitoring is recommended to ensure the long-term benefits of these practices.

Table 2

The basic statistics for soil carbon and heavy metals content corresponding to pasture maintaining, when conventional and organic practices are used, ppm

Crop	*Cultivation system*	*N*	*X*	*s*	*CV, %*
C, %	Conventional	5	1.96a	0.06	2.91
C, %	Organic	5	2.43b	0.18	7.32
Mn, ppm	Conventional	5	94.80a	3.11	3.29
Mn, ppm	Organic	5	92.60b	2.07	2.24
V, ppm	Conventional	5	13.14a	2.12	16.14
V, ppm	Organic	5	11.02b	1.99	18.04
Cr, ppm	Conventional	5	22.26a	1.51	6.78

Crop	Cultivation system	N	X	s	CV, %
Cr, ppm	Organic	5	21.58a	1.42	6.57
Zn, ppm	Conventional	5	14.12a	0.73	5.17
Zn, ppm	Organic	5	12.66b	0.88	6.97
Sn, ppm	Conventional	5	8.54a	1.05	12.33
Sn, ppm	Organic	5	7.96a	0.88	11.12
Pb, ppm	Conventional	5	4.60a	0.92	20.10
Pb, ppm	Organic	5	4.32a	0.82	18.91
Ni, ppm	Conventional	5	6.12a	0.89	14.54
Ni, ppm	Organic	5	5.42a	0.55	10.14
Cd, ppm	Conventional	5	2.44a	0.56	22.93
Cd, ppm	Organic	5	1.90a	0.22	11,57

Different letters correspond to significant differences at 5% threshold.

Lower values were reported by Dragovi�a et al (2001) for Cd (1.42 ppm), Cu (8.64 ppm) but higher and much higher for Mn (953 ppm), Ni (320 ppm), Pb (41.5 ppm), Cr (46.3 ppm), and Zn (21.8 ppm).

The Principal Components Analysis (PCA) is a useful tool for analyzing the relationships between different heavy metals distribution in soil (Liu et al 2023). According to PCA conducted in our study, we identified four factors involved in soil carbon and heavy metals content. They are: the type of cultivation system, the crop, the climatic conditions, and geographical area.

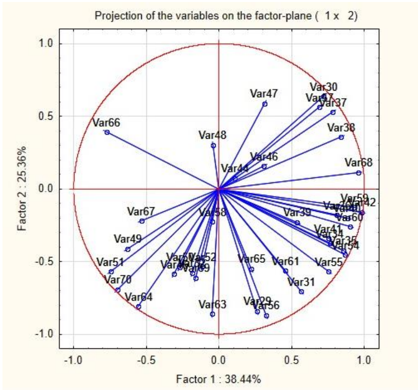
The Eigenvalues and total variance explained by the principal components for maize crop and pasture maintained under both conventional and organic systems are presented (Table 3). The first principal component (PC1), the type of the cultivation system, respectively, explains the largest portion of the total variance, accounting for 38.44%, followed by the second principal component, the crop (PC2) with 25.36%. Together, these two components capture 63.80% of the total variance, demonstrating their combined strength in summarizing the dataset. The third (PC3 - the climatic conditions) and fourth (PC4 - geographical area) components further explain an additional 21.20% and 15.00% of the variance, respectively, leading to a cumulative explanation of 100% of the total variance across all components. These results highlight the dominant role of the first two components in describing the variability in soil and crop data, with the remaining components contributing less but still significant portions of the overall variance. This distribution of variance underscores the multidimensional nature of the dataset and the effectiveness of principal component analysis in reducing dimensionality while retaining essential information.

Table 3

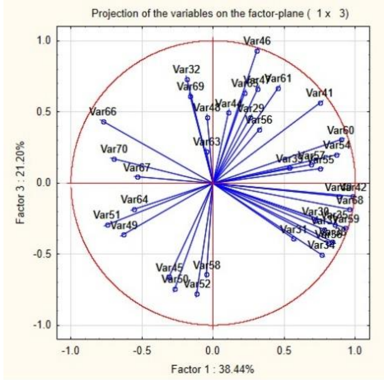
The Eigenvalues and total variance corresponding to maize crop and pasture maintained in both conventional and organic systems

Crt. No.	Eigenvalue	% Total variance	Cumulative - Eigenvalue	Cumulative, %
1	14.60542	38.43531	14.60542	38.4353
2	9.63758	25.36206	24.24300	63.7974
3	8.05635	21.20092	32.29935	84.9983
4	5.70065	15.00171	38.00000	100.0000

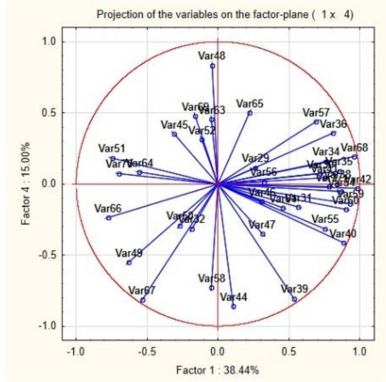
The projections of variables onto factor planes derived from principal component analysis (PCA) for maize and pasture systems in both conventional and organic management are illustrated (Figure 1).



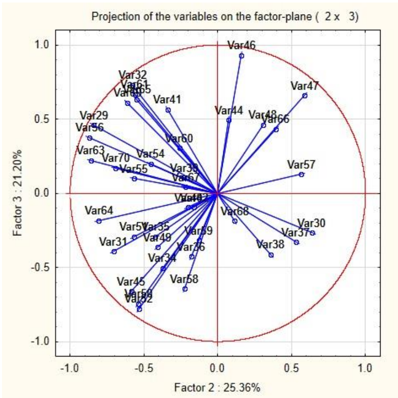
a.PC1 x PC2



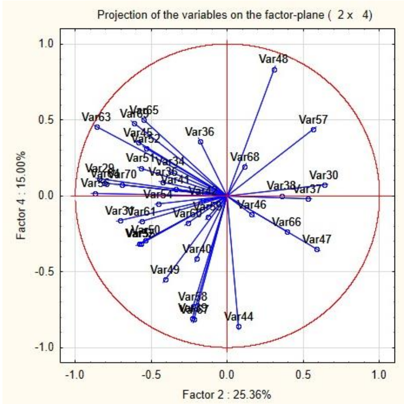
b.PC1 x PC3



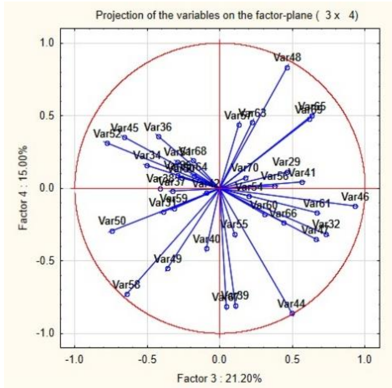
c.PC1 x PC4



d.PC2 x PC3



e.PC2 x PC4



f.PC3 x PC4

Figure 1. The variables representation in PC1 x PC2, PC1 x PC3, PC1 x PC4, PC2 x PC3, PC2 x PC4, PC3 x PC4, Factors, corresponding to maize crop and pasture maintained in both conventional and organic systems.

Factor 1, the type of the cultivation system, which explains the highest variance (38.44%), is prominently associated with variables that exhibit high loadings on this component, such as vanadium (Var45), nickel (Var60), and lead (Var68) soil concentrations reported for maize cultivation in organic system, on one hand, and for pasture cultivated in both systems, on the other hand (Table 4), reflecting their dominant influence. The maize cultivation in conventional system is responsible for carbon soil sequestration (Var30) and zinc soil content (Var37), which, also, align closely with Factor 1, indicating strong correlations with the primary axis of variation.

Table 4

The Factor loadings corresponding to maize crop and pasture maintained in both conventional and organic systems

Issue	*Variable*	*Factor 1*	*Factor 2*
C	Var 29	0.26259	-0.840956
Mn	Var 34	0.71977	0.636692
V	Var 35	0.56552	-0.707373
Cr	Var 36	-0.18728	-0.577122
Zn	Var 37	0.76076	-0.375773
Sn	Var 38	0.85276	-0.423624
Cu	Var 39	0.81141	-0.181195
Pb	Var 40	0.78286	0.526604
Ni	Var 41	0.83867	0.354994
Cd	Var 42	0.53503	-0.229494
C	Var 30	0.88185	-0.201925

Issue	Variable	Factor 1	Factor 2
Mn	Var 44	0.75049	-0.340929
V	Var 45	0.98172	-0.161881
Cr	Var 46	0.10629	0.073380
Zn	Var 47	-0.31041	-0.587139
Sn	Var 48	0.30643	0.157899
Cu	Var 49	0.31041	0.587139
Pb	Var 50	-0.04489	0.303368
Ni	Var 51	-0.62861	-0.411066
Cd	Var 52	-0.26976	-0.537175
C	Var 31	-0.74676	-0.569453
Mn	Var 54	-0.11578	-0.534291
V	Var 55	0.86580	-0.455484
Cr	Var 56	0.75224	-0.570104
Zn	Var 57	0.32054	-0.868804
Sn	Var 58	0.69053	0.563384
Pb	Var 59	-0.04830	-0.226831
Ni	Var 60	0.92890	-0.129788
Cd	Var 61	0.89810	-0.260171
C	Var 32	0.45698	-0.563412
Mn	Var 63	-0.04659	-0.861178
V	Var 64	-0.55419	-0.808092
Cr	Var 65	0.22264	-0.548667
Zn	Var 66	-0.77611	0.390171
Sn	Var 67	-0.53634	-0.219556
Pb	Var 68	0.95716	0.113909
Ni	Var 69	-0.15999	-0.611742
Cd	Var 70	-0.69775	-0.691603

In the Factor 1 × Factor 2 projection (Figure 1a), Factor 2 accounts for 25.36% of the variance and highlights the secondary relationships among variables. Here, manganese (Var34) and lead (Var40) soil content contribute notably to Factor 2 (crop), signifying their independent role in influencing system variability alongside Factor 1 (of the cultivation system). The clustering of variables near the origin, such as chromium (Var46) and lead (Var50) soil concentration when organic system is practiced for maize cultivation, suggests minimal contribution to the primary components, reflecting weaker associations.

The Factor 1 × Factor 3 plane incorporates Factor 3 (the climatic conditions), which explains 21.20% of the variance, revealing additional variability not captured by the first two components. Variables such as chromium (Var56) and cadmium (Var61) soil concentration when pasture is maintained in organic system shift prominence toward Factor 3, indicating their significance in the tertiary layer of variation. Factor 4, geographical area, respectively (responsible for 15.00% of variation) in subsequent projections further refines the variability structure, where tin soil concentration when conventional system is practiced, regardless the crop, (Var48 and Var67) display notable associations, reflecting nuanced but critical influences (Table 4, Figure 1.f). These visualizations collectively reveal the multidimensional structure of the dataset, with specific variables exerting dominant, secondary, and tertiary influences. High-loading variables along Factor 1 and Factor 2 primarily drive the variability in soil and crop parameters, while Factors 3 and 4 capture subtler variations.

Conclusions. According to our study, the improvement in soil organic matter is accompanied by lower concentrations of heavy metals such as manganese, vanadium, and zinc in organic systems, suggesting reduced accumulation due to the absence of synthetic fertilizers. Conversely, conventional systems exhibit higher levels of these metals, likely due to the reliance on chemical inputs that can introduce or exacerbate heavy metal presence in the soil. Variability in heavy metal concentrations is generally more pronounced in conventional systems, indicating a less uniform distribution of nutrients and potential imbalances. These findings underline the capacity of organic systems to enhance soil health while minimizing potential environmental risks associated with heavy metal accumulation. However, both systems present unique dynamics that require careful management to ensure sustainable crop production and soil quality preservation. The Principal Components Analysis reveals a complex multidimensional structure in soil and crop parameters under conventional and organic management systems for maize and pasture. Factor 1 accounts for the largest portion of variability, dominated by variables such as manganese, vanadium, and copper, highlighting their significant influence on overall system variability. Factor 2 captures secondary relationships, particularly emphasizing the role of variables like lead and cadmium, which show distinct interactions independent of Factor 1. Factor 3 and Factor 4 uncover additional layers of variability, with nuanced contributions from variables like zinc and tin, reflecting their tertiary significance in shaping soil and crop dynamics. Organic systems tend to exhibit a stronger association with carbon-related variables, indicating the enhanced role of organic matter in these systems. In contrast, conventional systems show higher correlations with heavy metals, suggesting greater inputs or accumulation. The Principal Components Analysis underscores the intricate relationships among soil properties, where key variables interact differently across management systems, reflecting distinct processes and influences.

Acknowledgements. This research work was carried out with the support of the Ministry of Agriculture and Rural Development, and was also financed from the Project ADER Partnership No. 19.1.1/2023.

Conflict of interest. The authors declare no conflict of interest.

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Received: 01 November 2024. Accepted: 02 December 2024. Published online: 11 December 2024.
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How to cite this article:
Oroian C., Odagiu A., Vizitiu O., Burduhos P., Petrescu-Mag I. V., 2024 Interrelations between heavy metals and carbon sequestration: Usual practices in the North-Western Region of Romania. AAB Bioflux 16(1):40-47.