

Soil Fertility Assessment and Management Prioritization of Permanent Grasslands Using Agrochemical Indicators: A Case Study from Western Romania

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Abstract. Permanent grasslands represent agricultural ecosystems with an essential role in fodder production, biodiversity conservation and soil quality maintenance. The aim of this study was to assess the agrochemical status of permanent grasslands in Fârdea ATU (Timiș county) and to substantiate a differentiated management system based on soil fertility indicators. The analysis included 72 plots with a total area of 772.06 ha. The main agrochemical indicators were determined: soil reaction (pH), mobile phosphorus (P-AL), mobile potassium (K-AL), humus content (H), and nitrogen index (NI). Descriptive statistics, correlation analyses and synthetic indicators of soil quality were used to interpret the data. The area-weighted average values indicated a weakly acidic soil reaction (pH = 6.31), a medium level of phosphorus supply (26.54 ppm), a good potassium supply (218.82 ppm), as well as a favorable humus content (3.23%) and nitrogen index (2.74). Approximately 27.2% of the analyzed area has pH values below 6.0, and 26.1% of the area falls into phosphorus deficient classes, highlighting the need for differentiated interventions. Correlation analysis revealed a very strong relationship between humus content and nitrogen index ($r = 0.96$), confirming the role of organic matter in ensuring soil nitrogen reserves. The results obtained demonstrate that agrochemical zoning and site-specific management can contribute to optimizing fertilization and increasing the sustainability of permanent grasslands.

Keywords: agrochemical zoning, differentiated management, mobile phosphorus, permanent grasslands, soil fertility, soil quality index

INTRODUCTION

Permanent grasslands represent agricultural ecosystems of particular importance both for fodder production and for the conservation of biodiversity and the maintenance of ecosystem functions of rural landscapes. They contribute significantly to the storage of organic carbon in the soil, the protection of water resources and the reduction of land degradation and erosion processes (FAO, 2015; Lal, 2015). In the context of European strategies on sustainable agriculture and climate change adaptation, the efficient management of permanent grasslands is an essential component for the sustainable development of agricultural systems.

The functionality and productivity of grassland ecosystems are strongly influenced by the agrochemical properties of the soil. Soil fertility determines the availability of nutrients to plants and directly influences the structure of the vegetation cover, biomass productivity and the nutritional value of forages (Whitehead, 2000; Brady & Weil, 2017; Melo et al., 2022; Yu et al., 2025). Numerous researches have demonstrated that changes in soil fertility generate significant changes in the floristic composition and in the dynamics of dominant plant species (Tilman et al., 1996; Crawley et al., 2005; Ruiz-Llontop et al., 2024).

Soil reaction (pH) is considered one of the most important agrochemical indicators used to assess the fertility of agricultural land. It influences the processes of mineralization of organic matter, microbiological activity and the availability of macro- and micronutrients (Brady and Weil, 2017; Xia et al., 2024). In the case of permanent grasslands, low pH values are frequently associated with limiting phosphorus absorption and reducing the competitiveness of valuable legume species, while high values may favor phosphorus fixation processes in the form of compounds that are difficult for plants to access (Whitehead, 2000; Marschner, 2012; Estrella et al., 2026).

Phosphorus is recognized as one of the main limiting factors for plant production in grassland ecosystems. Due to its low mobility in soil, phosphorus distribution is strongly influenced by soil properties and fertilization history. Phosphorus deficiencies cause reduced root system development, decreased biomass production and reduced forage value of vegetation (Hopkins and Del Prado, 2007; Syers et al., 2008; Khan et al., 2023; Karpinska et al., 2024; McDowell et al., 2026). Similarly, potassium supply influences essential physiological processes, such as water balance regulation, enzymatic activity, and plant resistance to abiotic stress (Marschner, 2012).

Soil organic matter is one of the most important indicators of soil health and quality. It contributes to structural stability, water retention, cation exchange capacity, and nutrient availability to plants (Lal, 2015; Githongo et al., 2023; Xing et al., 2025). At the same time, the organic matter reserve represents the main source of nitrogen for extensively exploited grassland ecosystems, being closely correlated with mineralization processes and nitrogen availability for plants (Doran and Parkin, 1994).

In recent decades, the concept of soil quality has become a central tool for assessing the sustainability of agricultural systems. Doran and Parkin (1994) defined soil quality as its ability to function within natural and managed ecosystems to support biological productivity, maintain environmental quality, and promote plant and animal health. Subsequently, numerous studies have developed methods based on synthetic indicators for assessing soil quality and on the simultaneous integration of physical, chemical and biological properties. (Bünemann et al., 2018).

The development of precision agriculture and the concept of site-specific management has allowed the identification of spatial variability of agrochemical properties and the delimitation of areas of differentiated management. This approach aims to optimize the use of agricultural inputs and increase the efficiency of interventions on soil fertility (Mulla, 2013; Herbei and Sala, 2014; Govedarica et al., 2015; Sala et al., 2020).

In Romania, studies on the fertility of permanent grasslands have highlighted the existence of significant variability in agrochemical properties, but the application of integrated approaches based on synthetic indicators of quality and agrochemical zoning is still limited. In this context, the objective of the present study was to assess the agrochemical status of permanent grasslands in Fârdea commune (Timiș county), analyze the relationships between the main soil fertility indicators and develop a differentiated management model based on synthetic indicators of soil quality.

MATERIAL AND METHODS

Study area and database

The study was conducted on permanent grasslands in Fârdea ATU, Timis County, Romania, Figure 1. The dataset included 72 cadastral plots totaling 772.06 ha. For each plot, information was available on soil reaction (pH), available phosphorus (P-AL) and potassium (K-AL), humus content (H, %) and nitrogen index (NI).

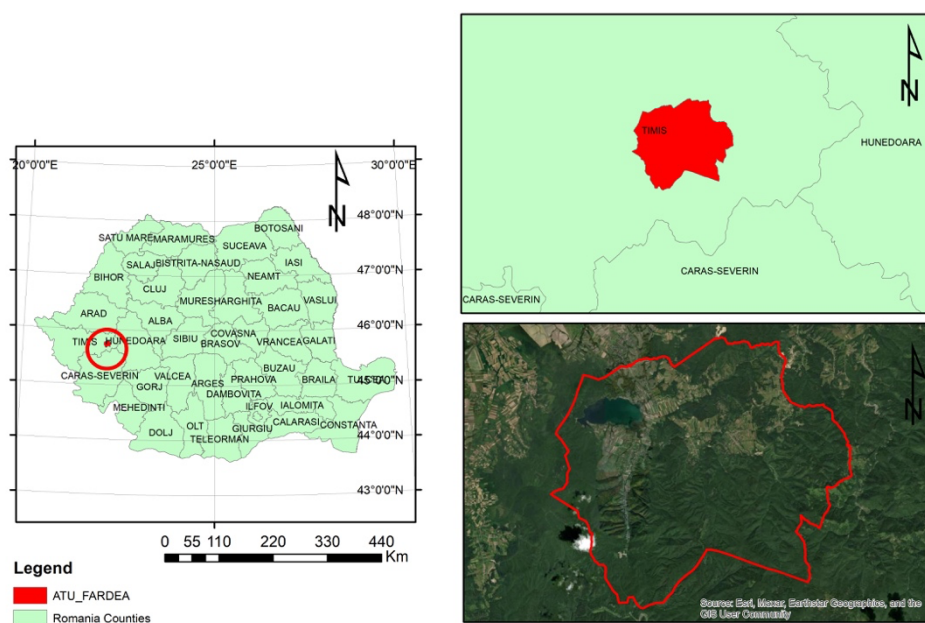


Figure 1. Fardea ATU, Timis County, Romania

Descriptive statistical analysis

For each agrochemical indicator, the arithmetic mean, median, minimum and maximum values, standard deviation and coefficient of variation (CV) were calculated. The variability of the parameters was evaluated according to the classification proposed by Wilding (1985). The coefficient of variation was calculated according to Equation (1).

$$CV = \left(\frac{SD}{\bar{X}} \right) \times 100 \quad (1)$$

where: SD represents the standard deviation, and $\bar{X}$ represents the arithmetic mean.

Area-weighted averages

For the agrochemical characterization of the entire analyzed area, weighted averages were calculated using the area of each plot, according to Equation (2).

$$WA = \sum (X_i \times A_i) / \sum A_i \quad (2)$$

where: WA - Weighted average; X_i = indicator value for plot i ; A_i = area of plot i .

Standardization of indicators

To integrate variables expressed in different units, z-score standardization was used, Equation (3).

$$z = (x - \mu) / \sigma \quad (3)$$

where: x = observed value; μ = mean of the variable; σ = standard deviation.

Nutrient Balance Index (NBI)

To assess the general state of nutrient supply, the Nutrient Balance Index, Equation (4), was calculated.

$$NBI = (zP + zK + zNI) / 3 \quad (4)$$

Positive values indicate fertility above the average of the data set, and negative values signal the existence of nutritional limitations.

Soil Quality Index (SQI)

The overall agrochemical quality was assessed using the Soil Quality Index, Equation (5).

$$SQI = (z_{pH} + zP + zK + zH + zNI) / 5 \quad (5)$$

The interpretation classes used were: $SQI > 0.50$ – high quality; $-0.50 \leq SQI \leq 0.50$ – medium quality; $SQI < -0.50$ – low quality.

Correlation analysis

The relationships between agrochemical indicators were evaluated using the Pearson correlation coefficient (r). The statistical significance of the relationships was assessed at the thresholds $p < 0.05$, $p < 0.01$ and $p < 0.001$.

Principal component analysis (PCA)

Principal Component Analysis (PCA) was applied to identify the dominant factors explaining soil fertility variability. Components with eigenvalues greater than 1 were retained, according to the Kaiser criterion.

Cluster analysis and management zoning

To delimit homogeneous management areas, hierarchical cluster analysis was applied using Euclidean distance and the Ward method. Based on the Soil Quality Index values, three management classes were delimited: Class I – intensive intervention; Class II – maintenance and optimization; Class III – conservation.

Differentiated recommendations were formulated for each class regarding fertilization, amendment and management of the vegetative cover.

In relation to the purpose of the study, the PAST software v.4.14 (Hammer et al., 2001) was used.

RESULTS AND DISCUSSIONS

The statistical evaluation of the agrochemical indices for the 72 permanent grassland plots, which totaled 772.06 ha, revealed agrochemical variability sufficiently pronounced to justify the application of differentiated soil fertility management, Table 1.

Table 1. Results of Descriptive Statistical Analysis for agrochemical indices in the studied area, Fardea ATU

Statistical Parameters	pH	P	K	H	NI
N	72	72	72	72	72
Min	5.68	6.43	136.00	1.59	1.28
Max	8.32	71.70	719.00	4.42	4.42
Mean	6.28	29.78	245.92	3.11	2.59
Std. error	0.06	1.72	11.36	0.11	0.09
Stand. dev	0.54	14.55	96.40	0.92	0.79
Median	6.14	26.70	216.00	3.32	2.56
25 prentil	5.95	19.64	183.00	2.36	2.02
75 prentil	6.45	39.58	285.75	3.74	3.07
Kurtosis	5.53	0.31	7.39	-1.04	-0.34
Coeff. var	8.57	48.87	39.20	29.48	30.61

The unweighted average values were 6.28 for pH, 29.78 ppm for mobile phosphorus, 245.92 ppm for mobile potassium, 3.11% for humus and 2.59 for nitrogen index, while the area-weighted values were 6.31 for pH, 26.54 ppm for P-AL, 218.82 ppm for K-AL, 3.23% for humus and 2.74 for NI. The differences between simple and weighted averages indicated that interpretation at the territorial level must be carried out by reference to the area, since large plots can substantially influence the general characterization of the soil resource.

The soil reaction showed an average of 6.28, with values ranging between 5.68 and 8.32, which indicated the predominance of weakly acidic conditions, favorable for most forage species specific to permanent grasslands. The coefficient of variation of pH, $CV = 8.57\%$, revealed a low variability, suggesting that the soil reaction is relatively uniform across most of the analyzed plots. However, the maximum values in the alkaline range of the soil reaction showed the existence of distinct local situations, which must be treated separately in the development of management recommendations.

Mobile phosphorus was the indicator with the highest variability, having a coefficient of variation $CV = 48.87\%$, which confirmed the very heterogeneous nature of the supply of this nutrient. This high variability was explainable by the reduced mobility of phosphorus in the soil, by the influence of soil reaction on the available phosphorus forms, and by possible historical differences in fertilization between plots. From an agronomic perspective, this result is essential, as it showed that uniform phosphate fertilization across the entire surface would be less effective than a differentiated fertilization strategy, applied primarily in areas with deficiency.

Mobile potassium recorded an average of 245.92 ppm and a coefficient of variation $CV = 39.20\%$, indicating high variability, but, unlike phosphorus, the overall level of potassium supply was favorable. The high and very high values observed in some plots suggested that potassium fertilization should be applied with caution, as unjustified additional inputs can lead to nutrient imbalances and reduce the economic efficiency of management.

The humus content and nitrogen index showed moderate variability, with CV values = 29.48% and $CV = 30.61\%$, respectively. This result indicated a relatively good state of organic matter in the analyzed meadows, but also the existence of local differences associated with the intensity of use, the accumulation of plant residues, the grazing regime and the micro-pedological conditions. The relationship between humus and nitrogen index has thus become a central element in the interpretation of the biological fertility of the soil.

Agrochemical distribution of grassland areas

The distribution of areas by soil reaction classes showed that permanent grasslands in the study area (Fârdea ATU) are dominated by weakly acidic soils, this class representing 58.09% of the total analyzed area. Moderately acidic areas represented 27.17%, while neutral soils occupied only 4.48%, and alkaline ones 10.26%. This agrochemical structure indicated that the soil reaction is, overall, close to the range favorable for the development of forage species, but the existence of over a quarter of the surface with pH below 6.0 justified the application of acidity correction measures on vulnerable plots. The distribution is presented in Figure 2.

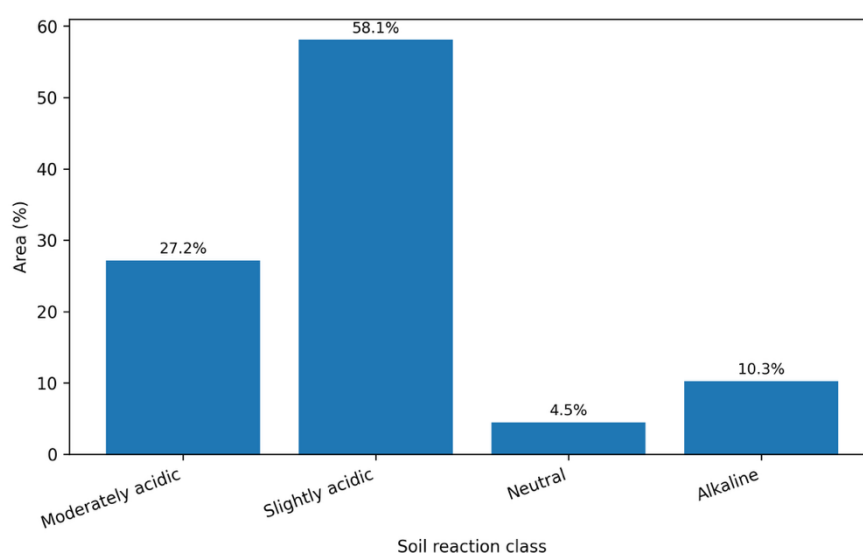


Figure 2. Graphic representation of soil reaction classes in the study area

From the point of view of mobile phosphorus, the analyzed area was characterized by a predominance of the middle class, which represented 53.83% of the total, but the deficient classes, respectively with very low and

low phosphorus content, amounted to 26.10% of the area. This proportion is agronomically important, as phosphorus is an element with a major role in the development of the root system, in the vegetative growth and in the competitiveness of valuable species in the vegetation cover. Consequently, Figure 3 represents one of the central figures of the study, as it justifies the need for differentiated and prioritized phosphate fertilization.

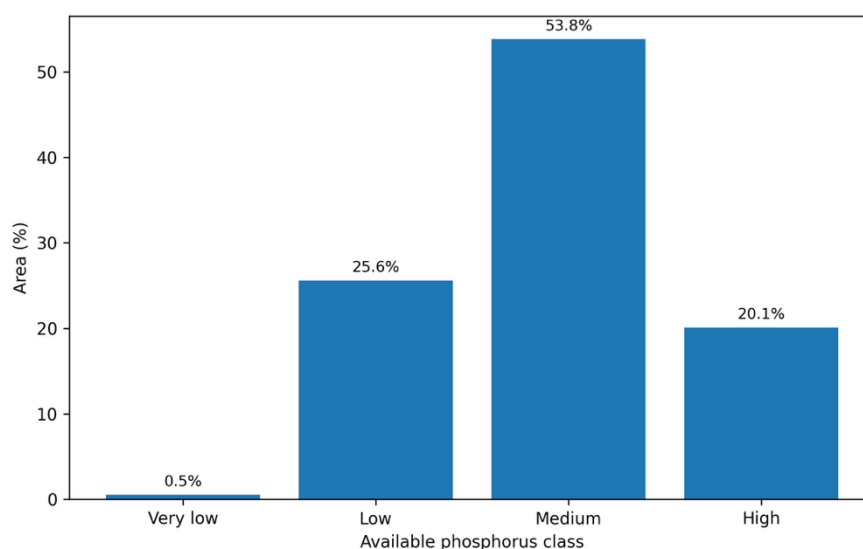


Figure 3. Graphic representation of soil phosphorus supply classes in the study area

The distribution of mobile potassium revealed a different situation compared to phosphorus. No plot fell into K-AL deficient classes, and the analyzed area was distributed between medium (59.20%), high (26.68%) and very high (14.11%) supply classes. This structure showed that potassium was not the main limiting factor of grassland fertility in the study area (Fârdea ATU), and potassium fertilization should be treated mainly as a maintenance measure, not as a priority intervention. The data are summarized in Figure 4.

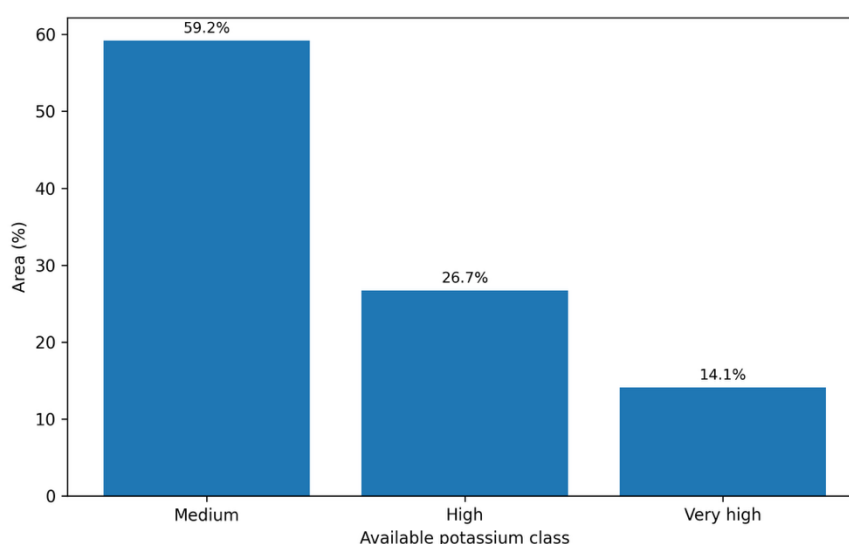


Figure 4. Graphic representation of soil potassium supply classes in the study area

Relationships between soil fertility indicators

The Pearson correlation matrix highlighted important relationships between agrochemical indicators, providing an integrated picture of the processes controlling soil fertility, Figure 5. The strongest correlation was identified between humus content and nitrogen index, with $r = 0.96$ and $p < 0.001$, which confirmed that the relative availability of nitrogen is closely dependent on the organic matter reserve and mineralization processes.

This association supported the interpretation that maintaining or increasing soil organic matter content is an essential condition for the stability of nitrogen fertility in permanent grasslands.

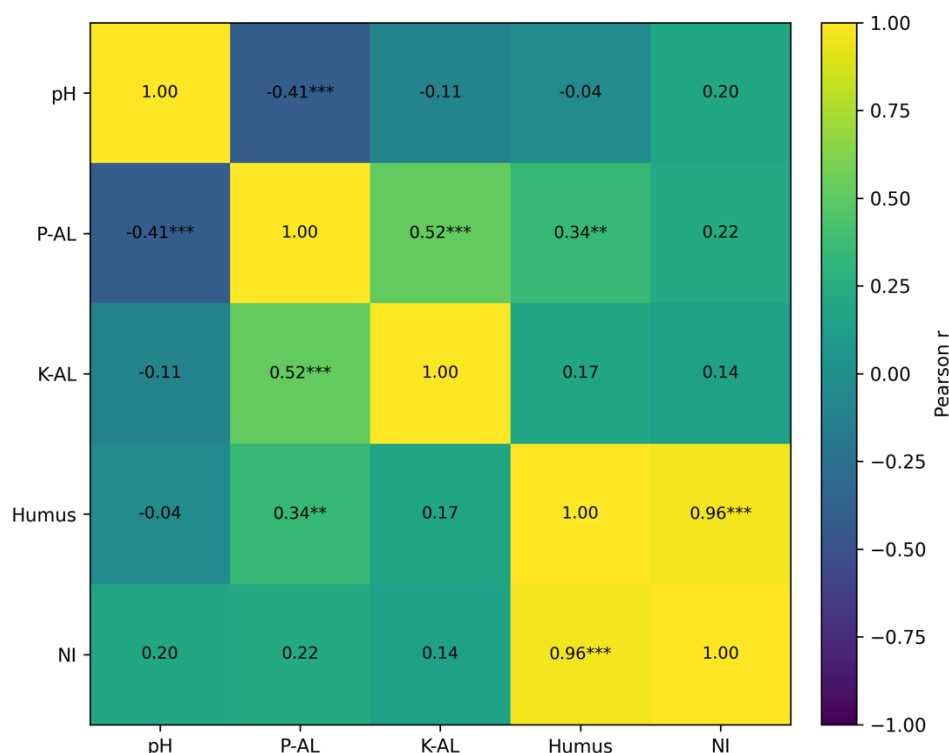


Figure 5. Graphic representation of the correlation matrix between soil agrochemical indices in the study area

A moderate and statistically significant positive correlation was observed between mobile phosphorus and mobile potassium, with $r = 0.52$ and $p < 0.001$. This relationship may reflect either a common history of fertilization interventions or local soil conditions favorable to the simultaneous accumulation of these two mineral elements. Phosphorus also showed a positive correlation with humus ($r = 0.34$, $p = 0.0036$), which suggested that organic matter may contribute to maintaining more accessible forms of phosphorus, or to improving the overall supply capacity of the soil.

The correlation between pH and phosphorus was negative and significant ($r = -0.41$, $p = 0.0004$), which represented an important result for the agrochemical interpretation of the territory. Although, theoretically, phosphorus availability is favored by a weakly acid-neutral range, data from the study area (Fârdea ATU) showed that higher phosphorus values occur more frequently in plots with a more acidic reaction, which may indicate the influence of previous fertilizations, local phosphorus accumulation or some pedological and agrochemical particularities regarding its fixation and mobilization.

Figure 6 presented the correlation matrix, and Figure 7 details the pH-P relationship through a scatter plot with linear regression.

Synthetic fertility indices: NBI and SQI

For the integrated assessment of soil fertility, the analyzed indicators were standardized, and based on them the Nutrient Balance Index (NBI) and the Soil Quality Index (SQI) were calculated. In the case of SQI, the pH component was treated as an index of adequacy to the optimal range, not as a simple linear increase in the pH value, since both excessive acidity and alkalinity can reduce phosphorus availability and fertilization efficiency. This approach is more appropriate for agrochemical interpretation of grasslands because it avoids the automatic classification of alkaline soils as superior solely based on a higher numerical pH value.

The SQI distribution indicated the existence of three functional categories of agrochemical quality. Class I, corresponding to intensive intervention, included 16 plots, with an area of 114.10 ha, and represented 14.78% of the total area. Class II, for maintenance and optimization, included 38 plots, with an area of 547.75 ha, and represented 70.95% of the total area. Class III, for conservation, included 18 plots, with an area of 110.21 ha, and represented 14.27% of the analyzed area.

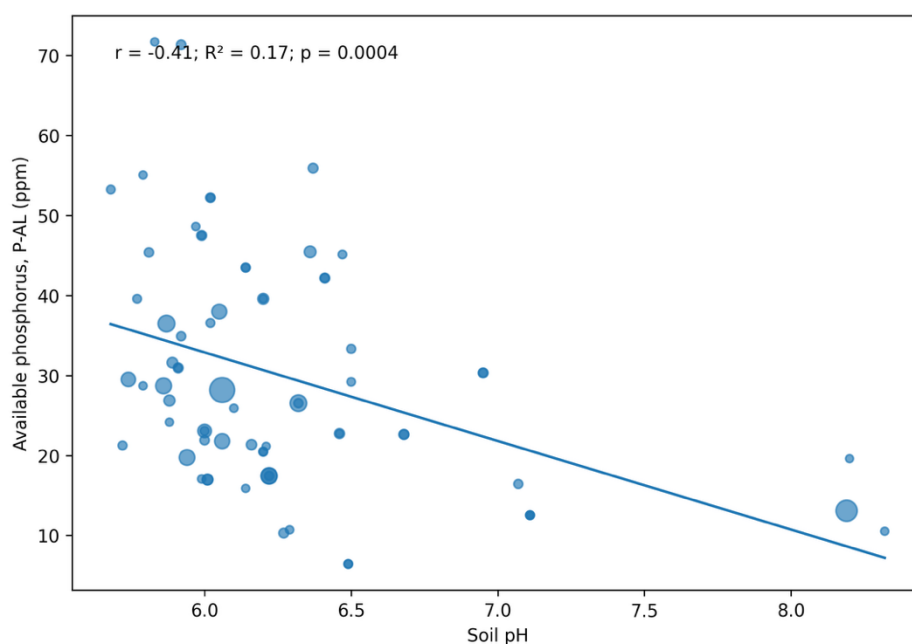


Figure 6. pH – P relationship through a scatter plot with linear regression

The results showed that most of the area falls into the maintenance and optimization class, which indicated an average general agrochemical condition, but with the need for some punctual corrections. The intensive intervention class was characterized by lower values of humus and nitrogen index, as well as lower levels of SQI, while the conservation class presented higher values for humus, NI, phosphorus and potassium. Figure 7 illustrates the distribution of SQI, and Figure 8 presents the share of areas by management class.

The relationship between NBI and SQI was strongly positive (Figure 9), indicating that nutrient supply balance was an essential component of overall agrochemical quality. However, the fact that SQI also includes pH adequacy and humus content allows for a more complete interpretation than NBI, which focuses on P, K and NI. This difference is important for management, as a plot with good nutrient levels may still require interventions if the soil reaction is unfavorable, or if the organic matter reserve is reduced.

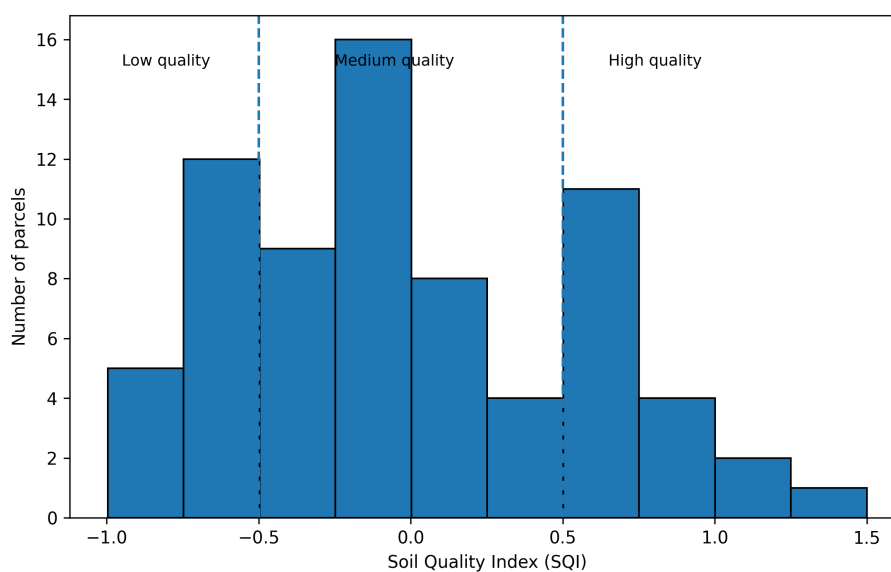


Figure 7. Soil Quality index (SQI)

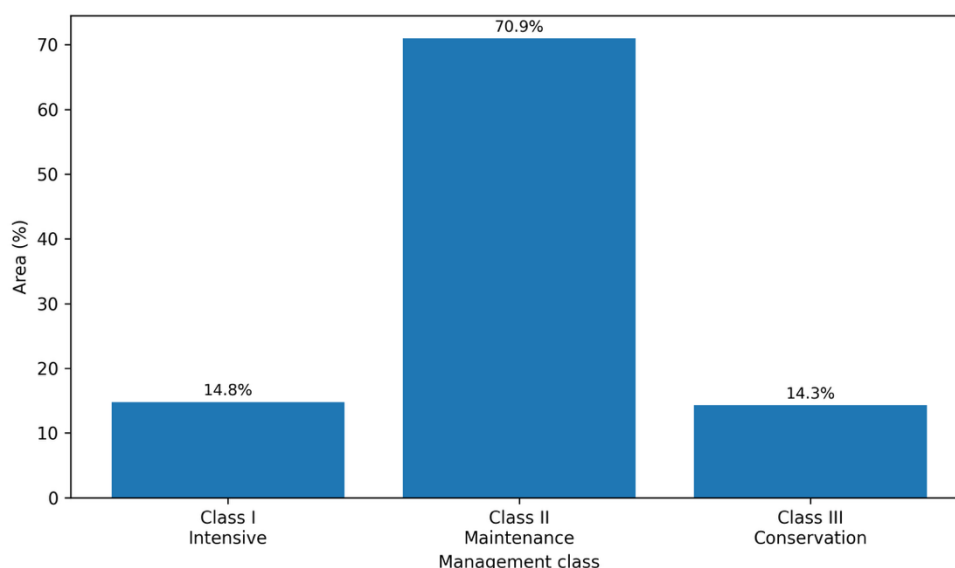


Figure 8. Management classes based on SQI

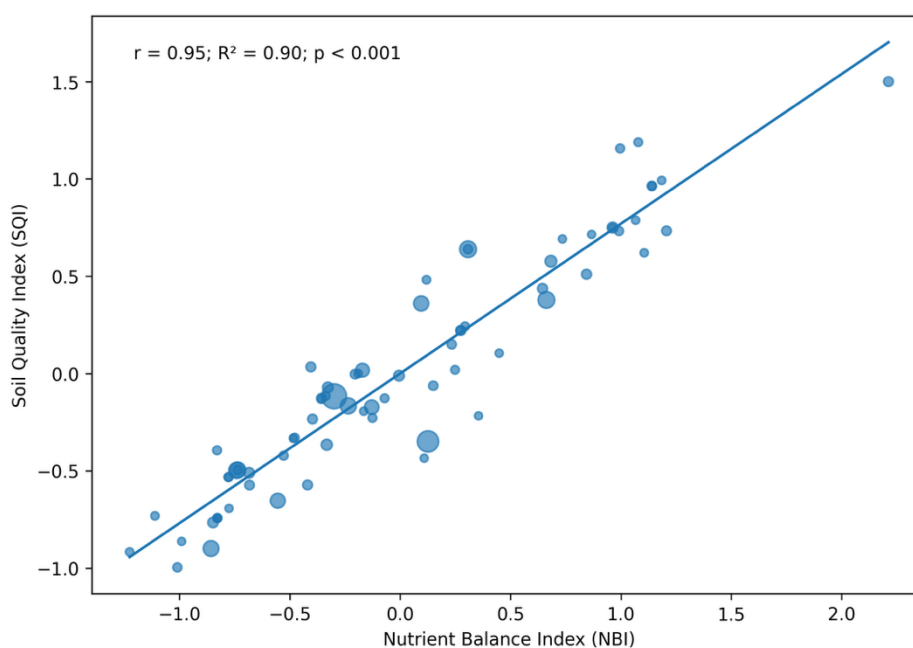


Figure 9. Graphical representation of the SQI vs NBI relationship

Principal component analysis and plot clustering

Principal component analysis (PCA) was used to identify the dominant directions of agrochemical variability. The first two principal components together explained 78.29% of the total variance of the data set, of which PC1 explained 47.11% and PC2 explained 31.18%. Interpretation of the PCA biplot, Figure 10, suggested that the first component is mainly associated with the general fertility gradient, reflected by the humus input, nitrogen index and mobile nutrients, while the second component separates the plots according to soil reaction and differences in phosphorus and potassium availability.

Figure 10 shows that humus and NI are oriented in the same direction, confirming the very strong correlation between these indicators, while the P and K vectors are relatively close, which supports the idea of a partially common accumulation or similar pedological control. The positioning of the plots in the PCA space allowed the identification of distinct agrochemical groups and supported the application of a differentiated

approach in establishing fertilization and improvement interventions.

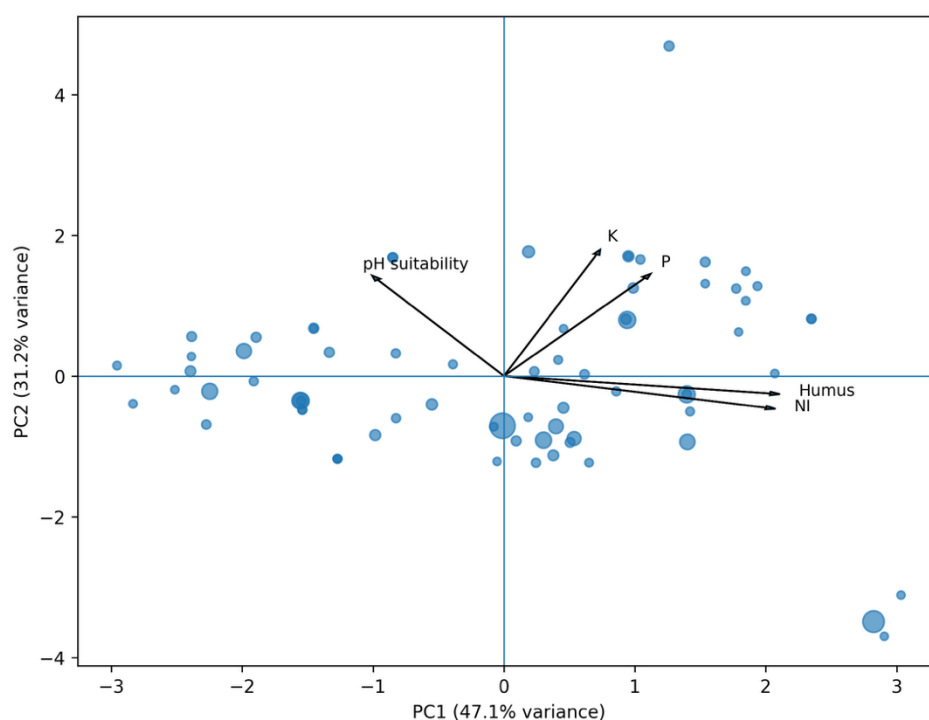


Figure 10. PCA diagram

The hierarchical cluster analysis, based on standardized variables and the Ward method, confirmed the existence of natural groupings of plots according to their agrochemical profile. The dendrogram presented in Figure 11 indicated that the plots did not form a uniform continuum, but could be grouped into relatively homogeneous units, which justifies the zoning of management. From a practical point of view, this approach allowed the transition from general recommendations to differentiated recommendations for groups of plots with similar agrochemical behavior.

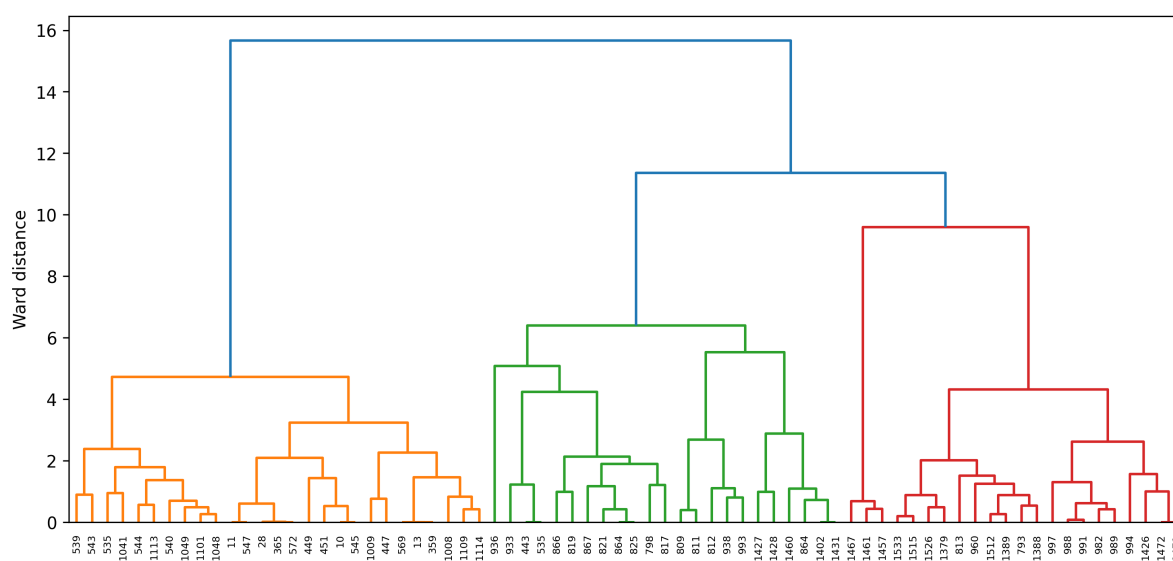


Figure 11. Cluster dendrogram

Three-dimensional representation of agrochemical relationships

To simultaneously highlight the relationship between soil reaction, mobile phosphorus and mobile potassium, a three-dimensional representation was made (Figure 12). The plot showed that the plots were not randomly distributed in the pH-P-K space, but tended to form distinct zones, where high potassium levels did not always coincide with high phosphorus levels, or with optimal soil reactions. This observation confirmed that soil fertility cannot be correctly assessed on the basis of a single indicator, but requires a multivariate approach.

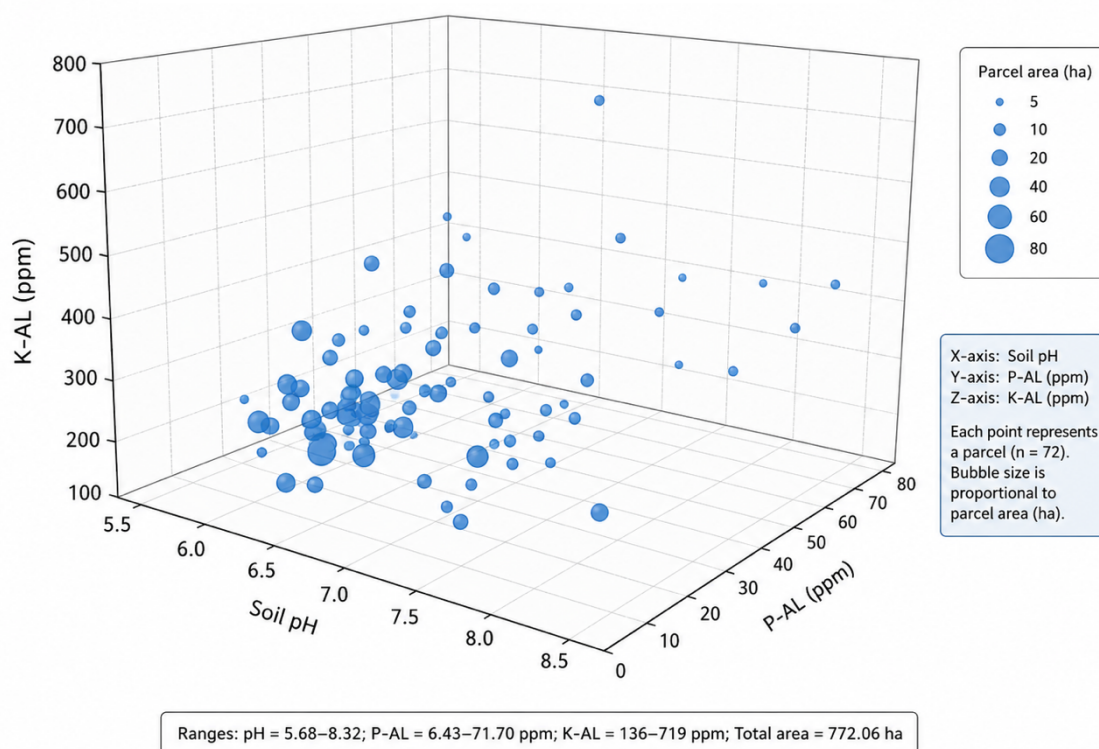


Figure 12. 3D relationship among pH, P and K

The results obtained support the need for a differentiated management of permanent grasslands in the study area, Fârdea ATU. The first intervention direction targets areas with pH below 6.0, where calcareous amendment, applied based on the real neutralization need, can improve phosphorus availability and fertilization efficiency. The second direction targets plots with low mobile phosphorus, for which priority phosphate fertilization is recommended, applied in moderate doses and adapted to the initial supply level.

On the other hand, potash fertilization should not be considered a general priority, since all the analyzed areas fall at least in the middle class of K-AL supply. For plots with very high potassium values, the main recommendation is to avoid unnecessary inputs and monitor the nutrient balance, especially in relation to phosphorus and nitrogen. Maintaining humus content should be treated as a cross-cutting objective, since organic matter supports nitrogen fertility, water retention capacity and the resilience of the vegetation cover.

Overall, the study demonstrates that the combined use of classical agrochemical indicators, synthetic fertility indices, correlation matrix, multivariate analysis (PCA) and cluster analysis allows a more robust substantiation of permanent grassland management than the individual interpretation of each indicator. This approach can support the reduction of fertilization costs, the increase of input use efficiency and the preservation of the ecological functions of grasslands in the study area (Fârdea ATU).

CONCLUSIONS

The agrochemical evaluation of the 72 permanent grassland plots in the study area, Fârdea ATU, totaling 772.06 ha, highlighted the existence of significant variability in the main fertility indicators, confirming the need to apply differentiated soil management at the level of the analyzed territory.

The soil reaction was mainly characterized by weakly acidic values, considered favorable for the development of most forage species. However, approximately a quarter of the analyzed area presented pH values below the optimal limit, which may negatively influence phosphorus availability and fertilization efficiency.

Mobile phosphorus presented the highest variability among the analyzed indicators, highlighting the existence of important differences between plots and identifying phosphate fertilization as one of the main measures necessary to improve the productivity of permanent grasslands.

Mobile potassium recorded generally favorable levels, without the appearance of areas classified in deficient classes, which indicated that this nutrient did not represent the main limiting factor for vegetation development in the studied area.

Correlation analysis revealed a very strong relationship between humus content and nitrogen index, demonstrating the essential role of organic matter in supporting soil biological fertility and maintaining available nitrogen reserves.

The integration of agrochemical indicators through the Nutrient Balance Index (NBI) and Soil Quality Index (SQI) allowed for the synthetic assessment of fertility and the delimitation of distinct management classes, providing an objective basis for planning fertilization and improvement measures.

Principal component analysis (PCA) and cluster analysis confirmed the existence of distinct agrochemical groupings of the plots, demonstrating that fertility variability can be efficiently described by multivariate statistical methods and used for the development of modern site-specific management strategies.

The results obtained demonstrate that the integrated use of classical agrochemical indicators, multivariate statistical analyses and synthetic soil quality indices can contribute to increasing the efficiency of agricultural input use, reducing fertilization costs and improving the sustainability of permanent grassland ecosystems.

STUDY LIMITATIONS

The present study was conducted based on an agrochemical dataset available at plot level, without information on the exact geographical positioning of soil sampling points and without additional data on soil physical characteristics, topographic conditions or history of technological interventions.

The analysis was limited to the main agrochemical indicators used in soil fertility monitoring practice, namely soil reaction, mobile phosphorus, mobile potassium, humus content and nitrogen index. Consequently, the influences of additional parameters such as soil texture, cation exchange capacity, bulk density, biological activity or total organic carbon content could not be assessed.

Also, the data used represents an assessment carried out at a single point in time, without the existence of a time series that would allow the analysis of fertility evolution and the quantification of the effects of management applied in the past.

PCA and cluster analyses were performed based on available agrochemical indicators and should be interpreted as exploratory tools for identifying patterns of variability and not as predictive models of plant productivity.

In the future, the inclusion of detailed geospatial data, information on biomass production and soil biological indicators could lead to the development of more complex models for assessing the quality and sustainability of permanent grasslands.

FUTURE RESEARCH DIRECTIONS

Future research should aim to integrate agrochemical indicators with geospatial data and information on grassland productivity, to develop predictive models capable of estimating vegetation response to different management scenarios.

The application of GIS technologies, remote sensing and multispectral satellite imagery could allow detailed mapping of spatial variability in fertility and the development of site-specific management maps.

An important research direction is the evaluation of the relationship between soil agrochemical indicators and the floristic composition of permanent grasslands, in order to identify fertility thresholds associated with maintaining biodiversity and high forage value.

At the same time, long-term monitoring of fertility indicators and the implementation of differentiated fertilization experiments could contribute to the practical validation of the proposed management classes and the optimization of agricultural input use strategies.

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