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Variability of nitrogen and phosphorus load in agricultural areas of the Carpathian Mountains in Poland in relation to production and structural factors

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ABSTRACT

The aim of the study was to determine the relationship between changes in the load of nitrogen and phosphorus of agricultural origin in the catchment area and other structural as well as functional parameters, including mainly agricultural production factors and the overall land use structure. The study area comprised two catchment areas located in the southern part of the Małopolska Province: the upper Dunajec catchment area and the upper Raba catchment area. The study analysed agricultural parameters and land use structure, as well as a multiple analyses of the parameters studied were performed. Structural changes in the upper Dunajec and Raba river catchments in recent years have affected many areas of social and economic life. Among other things, the size and nature of agricultural production have changed dynamically, resulting in long-term changes in land use and spatial distribution. On the basis of Spearman's rank analysis, it was found that among the relationships between the studied factors, the least significant were the relationships between the N and P balance as well as the area of pastures, and, to some extent, the utilisation index. However, a close collinear relationship was noted between the reduction in the N and P balance and a reduction in livestock numbers, as well as a significant reduction in both mineral and natural fertilisation. The dominant importance of these factors in shaping N and P balances also resulted from the regression relationships determined.

Keywords: nitrogen load, phosphorus load, Carpathian regions.

INTRODUCTION

The Carpathian regions have undergone and continue to undergo structural as well as spatial transformations. These are mainly changes in agricultural, infrastructural and environmental factors, covering the entire space, understood as the totality of components that make up the area of human life and activity (Kowalska, 2009). These transformations mainly consist of spatial and functional changes, resulting from a large number of interrelated factors of both natural and anthropogenic origin. They resulted, among other things, from the economic and social changes that took place in Poland after 1989 (Kryza et al., 2011; Pietrzak, 2009). These transformations necessitate the implementation of measures to protect the environment. Humans and their economic, domestic and municipal activities have a negative impact on the quality of ecosystems, which makes pro-ecological measures necessary (Palmeri et al., 2005). The idea of sustainable development is a panacea for this type of dependency. It is therefore necessary to identify the threats to the environment that change over time and the related factors shaping the usable space.

Hence, the aim of this study was to determine the relationship between changes in the load of nitrogen and phosphorus of agricultural origin in the catchment area as well as other structural and functional parameters, including mainly agricultural production factors (livestock numbers, mineral and natural fertilisation levels, crop size and type, yields, etc.) and the overall land use structure.

MATERIALS AND METHODS

The research area covers two river catchments located in the southern part of the Małopolska Voivodeship. Geographically, they are located in the central part of the Polish Carpathians. These are the upper Dunajec river catchment, with a cross-section in Krościenko nad Dunajcem, and the upper Raba river catchment, with a cross-section in Dobczyce.

The upper Dunajec catchment area includes the Czorsztyn-Niedzica dam reservoir, while the upper Raba catchment area includes the dam reservoir in Dobczyce, which serves as a drinking water reservoir for Krakow.

Both studied catchment areas (Figure 1), due to their orographic and spatial characteristics, climate, flora and fauna, as well as hydrography and land use, are representative of the Polish Carpathians, especially their central part (Kowalczyk et al., 2023).

The upper Dunajec river catchment at Krościenko covers an area of 1580 km² and accounts for approximately 23% of the total area of the river catchment, which covers 6804 km² (including the catchment of the large right-bank tributary, the Poprad, covering an area of 2077.3 km²) (Dynowska, 1995; Godlewski, 2003; Starkel and Kundzewicz, 2008). The characteristics of the upper Raba catchment area at the Dobczyce cross-section cover several geomorphological regions, including: the Beskid Sądecki, Wyspowy and Żywiecki ranges, and (within the immediate catchment area of the aforementioned Dobczyce Reservoir). The source part of the upper Raba catchment area is similar to the upper Dunajec catchment area in terms of orography and slope characteristics. Its lower parts are already of a foothill nature, with smaller slopes and varied inclines (Kondracki, 2002).

The study compiled data from, among others, the Central Statistical Office and the Provincial Statistical Office in Krakow. It covered the period 1980–2023 and concerned production parameters, including livestock numbers, mineral fertiliser consumption, sown area and crop yields. It also included basic usage data for similar research years. The data concerned municipalities located in the research catchment areas.

The agricultural parameters were analysed using the MacroBil programme (Institute of Soil Science and Plant Cultivation, State Research Institute, Pulawy, Poland). The structure of land use in the studied catchment areas was also assessed and classified as land use indicators W. This indicator took into account five categories of land use (forests, grasslands, orchards, arable land, buildings and wasteland). The highest values were assigned to the areas with low retention capacity, and the lowest to the areas with high retention capacity. On this basis, the *W* indicator was created according to the formula (Kopacz, 2007):

$$W = \frac{1 \cdot L + 2 \cdot (UZ + S) + 5 \cdot GO + 50 \cdot Z}{60} \quad (1)$$

where: *L, UZ, S, GO, Z* – share of forests, grasslands, orchards, arable land, built-up areas and other areas in the total area of the studied area in [%].

Agricultural and forestry indicators (*Wr*) were also established, covering only agricultural land and forests, excluding built-up areas and other land categories (Kopacz, 2007):

$$Wr = \frac{1 \cdot L + 2 \cdot (UZ + S) + 5 \cdot GO}{60} \quad (2)$$

The statistical analysis examined parameter variability in Spearman's rank correlation analysis (Koronacki and Mielniczuk, 2006; Kowalczyk, 2000; Kowalczyk et al., 2004). The formula

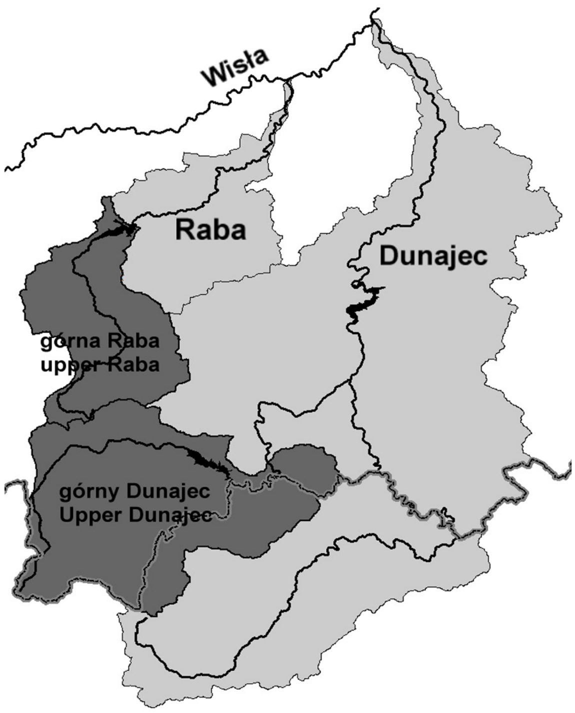

Figure 1. The upper Dunajec and Raba catchments in relation to the whole catchments (own elaboration based on MPHP)

(Juretig, 2019) was used to calculate Spearman's rank correlation coefficients:

$$r = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \quad (3)$$

where: d_i – differences between ranks R corresponding to values of feature x_i and feature y_i; $d_i = R(x_i) - R(y_i)$; (i = 1.23 ..., n); n – number of objects examined.

The interpretation of Spearman's rank correlation coefficient is similar to that of Pearson's classic correlation coefficient, but this coefficient takes into account the aforementioned non-linear relationships and is less sensitive to poor-quality data. It can be applied to any variables, such as values that change over time, which was important in the analysis of the collected material.

Spearman's correlation analysis was performed to identify the most significant relationships between the parameters studied and to select those factors that are statistically significantly correlated with the N and P balance.

The next stage of the relational analysis was to determine, as a result of linear and non-linear estimation, specific regression relationships between the N and P balance as well as the independent factors selected in Spearman's analysis (Kunkel et al., 2008). The functions with the highest coefficient of determination R^2 were selected to describe these relationships. The determined relationships are one-dimensional, therefore, in order to increase the number of influencing factors, multiple regression analysis was used (Juretig, 2019). In this regression, in addition to traditional regression coefficients, standardised partial regression coefficients β, known as path coefficients, as well as partial and semi-partial correlations are determined, which take into account the multifaceted relationships between the variables under study. Standardised path coefficients β make it possible to determine which of the independent variables has the greatest impact on the dependent variable. High partial correlation values and low semi-partial correlation values indicate that a given independent variable is a significant factor influencing the dependent variable and is not significantly disturbed by other factors (Lindeman et al., 1980; Stevens, 1986).

To summarise the research methodology, the overall objective of multiple regression is to quantitatively capture the relationships between multiple independent variables and a dependent variable. Individual factors influencing the dependent variable are assessed in relation to other factors, i.e. the relationship between the independent variable and the dependent variable is considered taking into account the influence of other independent variables and their prediction of the dependent parameter. In addition to traditional regression coefficients, this analysis also determines standardised partial regression coefficients β, known as path coefficients, as well as partial and semi-partial correlations, which take into account the multifaceted relationships between the variables under study. Standardised path coefficients β make it possible to determine which of the independent variables has the greatest impact on the dependent variable. High partial

Table 1. Spearman's rank correlation matrix for selected agricultural parameters

Parameter	Stocking rate	N balance	P balance	W	Wr	Agriculture land	Arable land	Meadows	Pastures	Forests	Built-up areas
Stocking rate		**0.97**	**0.95**	**0.68**	0.28	**0.42**	**0.40**	-0.10	**-0.63**	**-0.88**	**0.59**
N balance	**0.98**		**0.97**	**0.65**	0.31	**0.43**	**0.41**	-0.17	**-0.61**	**-0.86**	**0.55**
P balance	**0.99**	**0.98**		**0.61**	0.34	**0.46**	**0.43**	-0.22	**-0.58**	**-0.85**	**0.51**
W (land use indicator)	**-0.84**	**-0.82**	**-0.83**		-0.34	**-0.18**	**-0.20**	0.33	**-0.63**	**-0.80**	**0.97**
Wr (agriculture and forestry indicator)	**0.96**	**0.95**	**0.95**	**-0.85**		**0.84**	**0.94**	**-0.85**	-0.14	-0.10	**-0.48**
Agriculture land	**0.97**	**0.94**	**0.96**	**-0.87**	**0.98**		**0.82**	**-0.58**	-0.05	-0.35	-0.29
Arable land	**0.96**	**0.95**	**0.95**	**-0.84**	**0.99**	**0.98**		**-0.73**	-0.33	-0.20	-0.32
Meadows	-0.34	-0.37	-0.34	0.25	**-0.40**	**-0.39**	**-0.41**		-0.01	-0.06	**0.47**
Pastures	**-0.46**	**-0.44**	**-0.45**	0.29	**-0.47**	**-0.42**	**-0.46**	**-0.43**		**0.58**	**-0.57**
Forests	**-0.76**	**-0.77**	**-0.74**	**0.56**	**-0.77**	**-0.78**	**-0.77**	0.34	0.27		**-0.75**
Built-up areas	**-0.88**	**-0.86**	**-0.86**	**0.98**	**-0.89**	**-0.91**	**-0.89**	0.29	0.31	**0.61**	

Note: The bold coefficients are statistically significant at probability p-value < 0.05.

correlation values and low semi-partial correlation values indicate that a given independent variable is a significant factor influencing the dependent variable and is not significantly disturbed by other factors (Stevens, 1986).

RESULTS

Selected results of Spearman's rank correlation analysis are presented in the form of a correlation coefficient matrix, in a 'each with each' arrangement. The statistical significance of the coefficients, checked using Student's t-test, was very high (Table 1).

The most statistically significant were the relationships between the parameters directly related to agricultural production, i.e. nitrogen balance and livestock density. Close correlations were also observed between changes in production parameters and the structure of agricultural land use. The coefficients relating to the N and P balance and livestock density to building density were not very reliable.

In all the studied parts of the catchment area, the N and P balances were most closely correlated with livestock density, natural and mineral fertilisation, and crop area.

In the next stage of the analysis, a linear estimation of the impact of selected parameters on the N and P balances was performed. The parameters for linear regression analysis were selected on the basis of the results of Spearman's rank correlation analysis. Thus, the relationships between nitrogen and phosphorus balances and livestock density, mineral as well as natural fertilisation, agricultural land use structure (including agricultural land area, arable land, grassland, as well as *W* and *Wr* indices) and crop area were analysed (Table 2).

In most cases, regression equations were characterised by high coefficients of determination and were statistically significant. Only in the upper Dunajec catchment area, equations were not determined for the relationship between the N and P balance and the utilisation index *W* due to a lack of statistical significance (Table 2).

Using multiple regression, an analysis was performed of the relationship between N and P balances and selected independent parameters of an agricultural and functional nature for both study catchments (Tables 3 and 4). Then, all independent variables were sorted according to the values of standardised partial regression coefficients β (so-called path coefficients), at a specified level of partial correlation and probability p-value, and 7 variables with the most significant

Table 2. Regression correlations ($p < 0.05$) in the upper Dunajec and upper Raba catchments for N and P balance

Parameter	upper Dunajec	upper Raba	upper Dunajec	upper Raba
	N balance		P balance	
Stocking rate	y = 77.31x – 35.74	y = 110.30x – 59.68	y = 20.24x – 13.95	y = 26.07x – 17.96
	R^2 = 0.96	R^2 = 0.95	R^2 = 0.85	R^2 = 0.72
N natural	y = 1.08x – 35.29	y = 1.62x – 59.47	y = 1.98x – 13.30	y = 2.80x – 17.48
	R^2 = 0.96	R^2 = 0.95	R^2 = 0.87	R^2 = 0.75
N mineral	y = 1.45x + 9.49	y = 2.67x – 38.85	y = 1.13x – 3.19	y = 1.47x – 7.90
	R^2 = 0.77	R^2 = 0.89	R^2 = 0.95	R^2 = 0.94
W (land use indicator)	*	y = -9.50x + 144.03	*	y = -2.27x + 30.44
	*	R^2 = 0.88	*	R^2 = 0.68
Wr (agriculture and forestry indicator)	y = 39.03x – 95.49	y = 59.83x – 220.60	y = 9.07x – 25.60	y = 14.34x – 56.86
	R^2 = 0.61	R^2 = 0.90	R^2 = 0.42	R^2 = 0.70
Agriculture land	y = 5.77x – 238.42	y = 5.90x – 260.40	y = 1.34x – 58.59	y = 1.43x – 67.12
	R^2 = 0.48	R^2 = 0.88	R^2 = 0.31	R^2 = 0.70
Arable land	y = 2.37x – 16.01	y = 4.29x – 129.14	y = 0.56x – 7.28	y = 1.03x – 34.88
	R^2 = 0.65	R^2 = 0.89	R^2 = 0.46	R^2 = 0.69
Grassland	y = -3.34x + 121.5	y = -9.44x + 139.30	y = -0.79x + 25.08	y = -2.17x + 28.46
	R^2 = 0.66	R^2 = 0.63	R^2 = 0.47	R^2 = 0.45
Crops	y = 0.0014x – 0.90	y = 0.004x – 64.18	y = 0.0003x – 4.26	y = 0.0008x – 18.76
	R^2 = 0.75	R^2 = 0.71	R^2 = 0.60	R^2 = 0.53

Table 3. Multiple regression analysis in the upper Dunajec (N and P balance in relation to selected agricultural and functional factors

Parameters	β	Correlation		R^2	p-value	Parameters	β	Correlation		R^2	p-value
		Partial	Semipartial					Partial	Semipartial		
N balance						P balance					
Upper Dunajec (Krościenko cross-section)											
N natural	0.78	0.96	0.45	0.67	<0.001	P mineral	0.65	0.95	0.33	0.75	<0.001
N mineral	0.24	0.73	0.14	0.67	<0.001	P natural	0.43	0.81	0.14	0.88	<0.001
W (land use indicator)	-0.05	-0.36	-0.05	0.01	0.080	crops	-0.06	-0.24	-0.03	0.78	0.251
Wr (agriculture and forestry indicator)	0.04	0.10	0.01	0.11	0.655	W	0.00	-0.02	0.00	0.11	0.926
Arable land	0.04	0.12	0.02	0.14	0.593	Wr	0.00	0.01	0.00	0.12	0.957
Grassland	-0.05	-0.18	-0.02	0.18	0.414	GO	0.00	0.01	0.00	0.11	0.947
Crops	-0.02	-0.05	-0.01	0.14	0.813	UZ	-0.01	-0.04	0.00	0.11	0.871

Note: The statistically significant parameters are marked in bold.

Table 4. Multiple regression analysis in respective upper Raba (N and P balance in relation to selected agricultural and functional factors

Parameters	β	Correlation		R^2	p-value	Parameters	β	Correlation		R^2	p-value
		partial	semipartial					partial	semipartial		
N balance						P balance					
Upper Raba (Dobczyce cross-section)											
N natural	0.60	0.84	0.15	0.94	<0.001	P mineral	0.72	0.99	0.48	0.55	<0.001
N mineral	0.42	0.89	0.18	0.81	<0.001	P natural	0.30	0.70	0.06	0.96	<0.001
Grassland	-0.08	-0.38	-0.04	0.76	0.071	crops	-0.04	-0.31	-0.02	0.78	0.147
Crops	-0.06	-0.29	-0.03	0.79	0.187	GO	0.08	0.31	0.02	0.93	0.154
W (land use indicator)	0.03	0.10	0.01	0.04	0.643	W	0.03	0.11	0.01	0.04	0.625
Wr (agriculture and forestry indicator)	0.00	-0.01	0.00	0.04	0.977	Wr	-0.05	-0.06	0.00	0.00	0.801
Arable land	0.01	0.01	0.00	0.04	0.954	UZ	0.00	-0.01	0.00	0.04	0.981

Note: The statistically significant parameters are marked in bold.

regression indicators were selected – natural and mineral fertilisation (nitrogen for N balance, phosphorus for P balance), *W* and *Wr* indices, arable land and grassland area, as well as crop area.

Multiple regression analysis shows that in all parts of the study catchment areas, the level of fertilisation had the greatest impact on the balance of fertiliser components. In the case of the N balance, natural fertilisation was the decisive factor, while in the case of the P balance, mineral fertilisation was the decisive factor. The changing area of arable land and grassland over time also had a significant impact. On the basis of the analysis of residuals (Lindeman et al., 1980), the results of which are not presented, the study found that the residuals were stable, which means that the frequency distribution of the data was correct and the multiple regression analysis is not burdened with statistical error in terms of significance.

As part of the multiple regression analysis, in addition to standardised *β* coefficients, regression coefficients were also determined. This made it possible to determine regression equations that took into account the most important factors determining changes in the N and P surpluses remaining in the environment as a result of agricultural activity:

The upper Dunajec river catchment (Krościenko cross-section):

$$B_N = 0.86 \cdot Nm + 0.40 \cdot Nn - 0.86 \cdot W - 17.16 \quad (4)$$

$$B_P = 0.76 \cdot Pm + 0.90 \cdot Pn + 0.000025 \cdot Z - 8.16 \quad (5)$$

Upper Raba catchment area (Dobczyce section):

$$B_N = 1.19 \cdot Nm + 0.99 \cdot Nn - 0.96 \cdot UZ - 0.0003 \cdot Z - 38.01 \quad (6)$$

$$B_P = 1.09 \cdot Pm + 0.97 \cdot Pn + 0.10 \cdot GO - 0.00005 \cdot Z - 14.83 \quad (7)$$

where: B_N, B_P – N balance, P balance (applied to 1 ha of agricultural land in the catchment area), Nn – level of natural fertilisation in pure N component [kg·ha^{-1} agricultural land], Nm – level of mineral fertilisation in pure N component [kg·ha^{-1} agricultural land], Pn – level of natural fertilisation in pure P component [kg·ha^{-1} agricultural land], Pm – level of mineral fertilisation in pure P component [kg·ha^{-1} of agricultural land], GO – arable land area [% of total area], UZ – grassland area [% of total area], Z – crop area [ha], W – utilisation index [-], Wr – agricultural and forestry indicator [-].

On the basis of Equations 4–7, referring to both study catchment areas, universal formulas were developed for the Polish Carpathian regions, especially their central part:

$$B_N = 0.996 \cdot Nn + 0.564 \cdot Nm + 0.274 \cdot GO + 0.261 \cdot UZ - 52.63 \quad (8)$$

$$B_P = 0.851 \cdot Pn + 0.949 \cdot Pm + 0.098 \cdot GO + 0.164 \cdot UZ - 15.97 \quad (9)$$

where: B_N, B_P – N balance, P balance (applied to 1 ha of agricultural land in the catchment area), Nn – level of natural fertilisation in pure N component [kg·ha^{-1} agricultural land], Nm – level of mineral fertilisation in pure N component [kg·ha^{-1} agricultural land], Pn – level of natural fertilisation in pure P component [kg·ha^{-1} agricultural land], Pm – level of mineral fertilisation in pure P component [kg·ha^{-1} of agricultural land], GO – arable land area [% of total area], UZ – grassland area [% of total area].

The most important factors determining changes in the N and P balance were the levels of natural and mineral fertilisation (Tables 2 and 3). This is evidenced by the high values of β (standardised partial regression coefficient, i.e. the so-called path coefficient), the probability level (<0.001), and thus the high level of the significance index Wi. The combined effect of these factors on the parameter under study was over 90% for the nitrogen balance and 100% for the phosphorus balance.

CONCLUSIONS

Structural transformations in the upper Dunajec and Raba river catchments in recent years have affected many areas of social and economic life, including the natural environment, especially the aquatic environment.

Among other things, the size and nature of agricultural production have changed dynamically, resulting in long-term changes in land use and spatial distribution. Changes in agricultural production were partly determined by natural factors, including extreme meteorological and hydrological phenomena. In recent years, the volatile economic situation on the agricultural market has also had an increasing impact.

A significant reduction in livestock numbers has been observed. Livestock density decreased on average from 1.5 to approximately 0.4 LU·ha^{-1} agricultural land (LU – Livestock Unit). Agricultural nitrogen and phosphorus inputs decreased by approximately 50–57% and 69–73%, respectively. The dynamics of these changes were significant on average during the study period from 1993 to 2023.

On the basis of Spearman's rank correlation analysis, it was found that among the relationships between the studied factors, the least significant were the relationships between the N and P balance and pasture area, and, to some extent, the W utilisation index. However, a close collinear relationship was observed between the reduction in the N and P balance and a reduction in livestock numbers, as well as a significant reduction in both mineral and natural fertilisation. The dominant importance of these factors in shaping N and P balances also resulted from the determined regression relationships.

Multiple regression analysis shows that the level of natural and mineral fertilisation had the greatest impact (on average about 92%) on changes in the nitrogen and phosphorus balance, with natural fertilisation having a greater impact on nitrogen and mineral fertilisation having a greater impact on phosphorus. The remaining few per cent were attributable to other factors, mainly describing the structure of agricultural use or the area under cultivation.

These studies indirectly relate to agroecology activities. Changes in nitrogen and phosphorus loads in the soil profile largely determine the quality of the natural environment. Agroecology assumes that agricultural systems should be assessed not only in terms of productivity, but also in terms of ecological balance, resilience, biodiversity and farm autonomy. The above analyses, which took into account, among other things, ecosystem processes (material cycles as changes in N and P concentrations) and their impact on the condition of the soil profile, water as well as biodiversity of agricultural and forest ecosystems, are consistent with these elements. Summarising the collected measurement and analytical, computational and statistical data, the following key conclusions can be drawn:

1. In recent years, the upper Dunajec and upper Raba river catchment have undergone significant structural and spatial changes, affecting many social, economic and environmental factors.
2. Agricultural production, including livestock numbers, has been reduced, resulting in lesser fertilisation and a reduction in the area of agricultural land, most notably arable land.
3. The most important factors shaping changes in nitrogen surplus in the catchment area were natural fertilisation and, in the case of phosphorus, the use of mineral fertilisers. These two parameters determined more than 90% of the N and P balance.
4. The determined linear regression functions describing the relationships between the excess of fertiliser components remaining in the catchment area and other agricultural and land use factors allow for a better assessment of the structural and spatial changes occurring in the long term.
5. Universal formulas (formulas 8 and 6), obtained from multiple regression analysis, enable the forecasting of changes in the load of excess fertiliser components (N and P) in the Carpathian areas based on the data on land use and fertilisation.
6. The results of the study have guided the principles of active shaping of usable space in terms of its sustainable and multifunctional development, taking into account agricultural and non-agricultural factors and their mutual proportions.

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