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ECONOMIC AND ENVIRONMENTAL FACTORS DETERMINING SPATIAL VARIATION IN SOIL LIMING IN POLAND

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ABSTRACT: The aim of this research was to identify the key factors determining the level of soil liming in Poland. Spatial analyses were conducted using data from the 2020 National Agricultural Census. The study presents regional variations in selected parameters that characterise agricultural production quality and structural features, including the market connections of farms. The Classification and Regression Trees (C&RT) method was employed to identify the factors that most significantly influence the intensity of liming in the examined districts. These factors include the share of permanent grasslands, labour inputs, the percentage of farms engaged in commercial production, farm size, and the level of mineral fertilisation (NPK). The results indicate that regions with larger farms and higher NPK fertilisation tend to apply more lime. In contrast, areas with a higher share of permanent grasslands and labour-intensive activities show lower levels of liming. These findings suggest that improving agricultural practices, particularly in regions with small farms and limited fertilisation, could enhance soil liming efforts and align them with the European Green Deal's goals for sustainable agriculture.

KEYWORDS: soil pH, production costs, classification and regression trees (C&RT), agricultural structure, European Green Deal

Introduction

In light of the systematic increase in the global population, it has become necessary to explore ways to ensure an adequate supply of safe food. The technologies utilised in intensive farming require significant industrial production inputs, which can impact the quality of products and the natural environment. The European Green Deal (EGD), implemented in European Union countries, is considered a partial response to these negative consequences. It requires farmers, researchers, and advisors to seek agrotechnical solutions that enable high yields of field crops while simultaneously reducing the use of production inputs such as mineral fertilisers, plant protection products, or antibiotics.

To ensure the smooth implementation of the EGD, it is crucial to optimise the properties of arable soils, which constitute a fundamental element of agricultural production areas. This is particularly important in Poland, where acidic and very acidic soils dominate in most regions. Soil acidification reduces the efficiency of nutrients applied as part of NPK fertilisation, increases production inputs, and can negatively affect the environment. To counteract this phenomenon, it is necessary to regulate soil pH, which can be achieved through an appropriate level of soil liming.

Therefore, this study aims to identify the key factors influencing the spatial variation of soil liming levels in Poland. Particular attention is paid to local natural conditions, agrarian structure, the market integration of farms, and production intensity.

The hypotheses tested in the study are as follows:

- H1: The level of soil liming in a given area depends more on the specifics of the agrarian structure than on natural conditions.
- H2: An increase in production intensity and farm size promotes an increase in the level of liming.

Verification of these hypotheses will deepen our understanding of the impact of regional and structural factors on liming practices and soil management in Poland. By analysing data from the Agricultural Census and conducting our own recalculations and reinterpretations, the study provides an original scientific contribution, leading to new conclusions based on fresh interpretations of the data.

Literature Review

The success in agricultural production over the last several decades has been made possible thanks to technological, biological, and organisational advances. Unfortunately, it has also had negative environmental effects, primarily on the environment, climate, biodiversity, soil quality and food quality (Poczta, 2023). Global issues related to the state of the natural environment have prompted an international initiative aimed at preventing undesirable changes occurring in ecosystems used for agricultural purposes. In 2019, the European Commission introduced the European Green Deal strategy (EDG). The idea was to establish a modern economy based on resource conservation and to create the appropriate conditions to ensure economic competitiveness (European Commission, 2019). The main principles of the EGD strategy regarding agriculture include reducing the use of chemical pesticides and fertilisers, as well as decreasing the risks associated with their use. For instance, the strategy aims to reduce the use of mineral fertilisers and pesticides by 20% and 50%, respectively, by 2030. The strategy also aims to mitigate soil acidification and increase biodiversity in rural areas (European Commission, 2020). According to the European Commission, this resulting "healthy soil" will be a key solution in addressing the significant challenges of achieving climate neutrality, resisting climate change, reversing the process of biodiversity loss, protecting human health, preventing desertification, and reversing the process of land degradation.

One of the primary methods for reducing the use of plant protection products in agriculture is to optimise the properties of soils used for agricultural purposes through pH regulation (Nicia et al., 2023). Acidic pH can reduce the capacity of the soil's sorptive complex to retain micro- and macroelements that are supplied through mineral fertilisers. This can lead to the leaching of these fertilising substances into ground and surface waters while also increasing the plant's ability to uptake heavy metals. (Szeląg-Sikora et al., 2019). Soil pH is one of the key factors determining plants' efficient uptake of nutrients, including macronutrients, secondary nutrients, and micronutrients. Several factors, both natural and anthropogenic, can contribute to soil acidification, reduced nutrient availability, and suboptimal plant growth. This, in turn, affects the quantity and quality of agricultural crops,

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as well as the overall health of other plants growing in the environment, including forests and other wild plants (Witkowska-Dąbrowska, 2018). Liming is a technique that helps regulate soil pH, creating a safe and appropriate environment. It is not only essential for environmental protection but also for improving the economic efficiency of farms. In the case of acidic soils, both the quantity and quality of agricultural crops significantly decrease, which can be a concern, especially for plants sensitive to soil acidification that is grown to ensure food safety for a country (Nicia et al., 2023).

The economic performance of farms in agricultural markets heavily depends on soil quality (Zabochnicka-Świątek & Kocela, 2019). Soil serves as the foundation for agricultural production areas and directly influences the quality and quantity of agricultural crops. Soil properties, including productivity and fertility, are primarily determined by the process of soil formation and factors such as parent material, time, climate, the presence of living organisms, topography, and human activity (Hillel et al., 2008). Among the most significant soil properties are particle size distribution, which indicates the composition of soil types, humus content, and pH (Nicia et al., 2023). In Poland, the most critical period for the formation of the parent material of most soils was the Quaternary period, specifically the Pleistocene, when over 90.0% of the country's surface became covered by heavily eroded glacial sediments (Hołubowicz-Kliza et al., 2021). The carbonate-free soils formed from these sediments fall into the agronomical category of light and very light soils, which have a low content of floatable fractions that significantly affect the sorptive complex's capacity and physical properties (Bartmiński et al., 2022). The particle size distribution of such soils makes them susceptible to the leaching of alkaline cations, primarily calcium and magnesium ions, leading to soil acidification. The majority of soils in Poland (58.2%) are very acidic and acidic (Pietr & Krysztoforski, 2022).

Soil acidification is also a result of human agricultural activities. Factors that contribute to cation leaching (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and soil decalcification include the use of fertilisers containing nitrates, chlorides, and sulphates, as well as the decomposition of organic matter from crop residues and organic fertilisers into humic acids. Moreover, calcium and magnesium uptake by crops and the combustion of fuels that release acidogenic sulfur and nitrogen oxides into the soil exacerbate soil acidification (Dong et al., 2022; Bolan et al., 2023).

Although the liming of acidic soils contributes to an increased yield of most arable crops, the relationship between yield and soil pH depends on the specific arable crop species and soil type (Fageria, 2009; Fageria et al., 2011; Farhoodi & Coventry, 2008; Goulding, 2016; Liu et al., 2004). There are significant variations in pH tolerance and the extent of yield decline beyond the optimal range across and within arable crop species (Fageria, 2009; George et al., 2012). As it is not feasible to match the entire pH range to each individual species in a crop rotation, it is recommended to maintain soil pH levels at the optimal range of 6.5 for arable land (5.8 in peat soils) and 6.0 for grassland (5.3 in peat soils) (Hołubowicz-Kliza, 2006). The nature of the relationship between yield and soil pH has significant implications for sustainable development and plant production efficiency and quality. Liming permanent grassland positively impacts the amount of biomass produced for pasture purposes and grass production (pickled products). The response of grassland to liming is visible over a period of 3-5 years (Kopeć & Gondek, 2013). These production benefits of liming can be attributed to the exhaustion of easily mineralised organic nitrogen reserves in the soil during that time.

The influence of climate on agriculture is evident on a global scale, as reflected in the zonal distribution of crops worldwide. Poland's location in the transition zone between maritime and continental climates provides highly diverse and generally favourable conditions for extensive agricultural activity (Bański, 2007; Dmuchowski et al., 2022). Climatic factors that determine the type and effectiveness of agricultural production include insolation, precipitation, and temperature (Nantongo et al., 2023). The development and specialisation of agriculture also depend on topographical relief, which influences natural conditions and determines fieldwork and the selection of appropriate tools, machinery, and crop species (Everest et al., 2021). Varied topography can, on the one hand, bring additional benefits, such as the cultivation of southern slopes with higher insolation and longer vegetation periods. On the other hand, it can hinder and increase the costs of agricultural activities, particularly in mountainous and foothill areas (Wójcik-Leń, 2022). Furthermore, topographical relief is associated with detrimental phenomena like erosion and the formation of isolated bodies of standing water, which significantly impact agrarian conditions, including nutrient leaching (Nicia et al., 2023).

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Research methods

Spatial analyses were conducted based on the results of the 2020 National Agricultural Census. Information about the valorisation of the agricultural production area was gathered from the resources of the Institute of Soil Science and Plant Cultivation in Puławy. The land district (NUTS 4) was used as the basic unit of study. Cities with county rights were excluded from the analyses due to their specific characteristics. While seeking to determine the causes of variations in the levels of soil liming in Poland, the research focused on the basic characteristics of the agrarian structure, agricultural production intensity, as well as natural conditions, including soil quality, water conditions, topography, and agroclimate.

The research employed the method of Classification and Regression Trees (C&RT), which is one of the tools in Data Mining (Statistica®) (Łapczyński, 2005; Dacko & Kurczyna, 2023). When developing a classification tree model (C&RT), the following assumptions were made:

- the costs of incorrect classifications will be considered equal,
- the goodness of model fitness will be assessed based on the Gini coefficient,
- the rule for stopping the algorithm will be to trim at an incorrect classification error,
- terminal nodes will include a minimum of 10 observations,
- the quality control of the obtained results will be conducted using V-fold cross-validation for V=10.

Both the dependent variable and the selected independent continuous variables were converted into categorical variables, with one of three categories: low (A), medium (B), and high (C). The conversion of quantitative variables into qualitative assessments was carried out using quartile division of the analysed datasets. Counties with a low value of a given characteristic (1st quartile) were categorised as 'low', counties with a high value of a given characteristic (4th quartile) were categorised as 'high', while the remaining counties, where the values of a given characteristic fell within the 2nd and 3rd quartiles, were categorised as 'medium' (see Table 1).

Table 1. Basic features of the variables analysed (year 2020)

Name of variable and measurement unit			Average value	Rating scale		
				low (A)	medium (B)	high (C)
Dependent variable						
Calcium fertilization level		kg CaO/ha of agricultural land	86.8	<52.9	52.9-109.8	>109.8
Independent variable						
Agricultural structure (AS)	Farm's average surface area	ha of agricultural land	14.9	<7.3	7.3-27.0	>27.0
	Farms' possession of agricultural tractors	units/farm	1.1	<0.9	0.9-1.3	>1.3
	Share of farms with the surface area exceeding 15 ha of agricultural land	%	20.6	<8.5	8.5-31.2	>31.2
	Proportion of farms with the economic size up to 8000 euro of standard production	%	61.5	<49.1	49.1-72.4	>72.4
	Labor inputs	AWU/100 ha of agricultural land	10.4	<5.7	5.7-13.1	>13.1
Production intensity (PI)	Stocking density (cattle, pigs, hens)	LSU/100 ha of agricultural land	46.8	<20.3	20.3-62.0	>62.0
	Share of permanent grassland in the surface area of agricultural land	%	23.2	<10.6	10.6-31.7	>31.7
	NPK fertilization level	kg/ha of agricultural land	126.0	<95.2	95.2-162.8	>162.8
Connections to the market (MC)	Proportion of farms selling agricultural products	%	71.1	<63.8	63.8-75.2	>75.2
	Proportion of farms receiving incomes from hired labor	%	42.4	<36.9	36.0-47.5	>47.5
	Proportion of farms receiving incomes from non-agricultural economic activities	%	15.4	<12.8	12.8-17.5	>17.5

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Name of variable and measurement unit			Average value	Rating scale		
				low (A)	medium (B)	high (C)
Natural conditions (NC)	Soil quality	points	49.6	<41.5	41.5-55.8	>55.8
	Agroclimate	points	10.1	<8.8	8.8-11.7	>11.7
	Topography	points	3.8	<3.5	3.5-4.4	>4.4
	Water conditions	points	3.3	<2.7	2.7-3.9	>3.9
	Agricultural Production Area Quality	points	66.7	<59.2	59.1-73.5	>73.5

AWU – Annual Work Unit, LSU – Livestock Unit[1].
Source: authors' work based on FADN (n.d.).

Results of the research

The Institute of Soil Science and Plant Cultivation in Puławy developed a method for valorising agricultural production areas to comprehensively assess the natural conditions and their impact on agricultural activity in Poland. This valorisation is represented by a special index called the Agricultural Production Area Quality (Pol: JRPP), and it reveals significant regional variations across Poland. High values of the JRPP index are observed in the Lesser Poland Upland, Lubelska Upland, Silesian Lowlands, Przemyśl Foothills, eastern Mazovia, Pyrzyce Land (Ziemia Przyrzycka), and Vistula Fens (Żuławy Wiślane). In contrast, low values of the JRPP index are found in the northern and western parts of Poland, as well as in the Świętokrzyskie Mountains, Carpathian Mountains, and the Sudetes (IUNG, 2023). Poland also exhibits significant regional variations in soil pH; however, the issue of soil acidification affects a substantial portion of the country overall (see Figure 1).

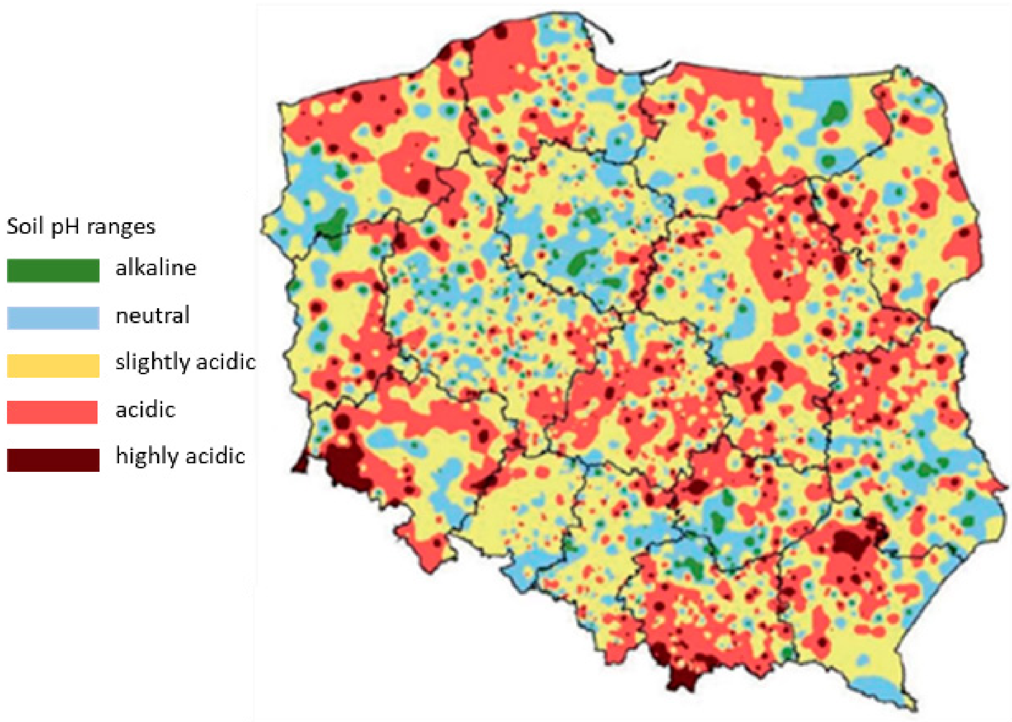

Figure 1. Division of Poland based on soil pH
Source: authors' work based on Pietr and Krysztoforski (2022).

1 AWU – Annual Work Unit: A conventional unit of labor measuring labor input in agriculture, representing the equivalent of one full-time job. LSU – Livestock Unit: A conventional unit representing the number of livestock on a farm, corresponding to one cow weighing 500 kg according to Polish standards. It is used, among other things, to estimate the farm's feed requirements.

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The use of mineral fertilisers in Poland varies across regions and is closely related to agricultural production intensity. The largest quantity of mineral fertilisers is used in western and northwestern Poland, while the smallest amount is used in eastern and central Poland. According to data from Statistics Poland (CDR, 2023), Greater Poland Voivodeship has the highest level of NPK fertiliser use in Poland, with nearly half of its counties exhibiting a high level of NPK fertiliser use, exceeding 1628 kg/ha. In contrast, the lowest level of fertilisation usage in agricultural production is found in counties in Lesser Poland and Subcarpathian Voivodeships, with an average usage at around 74 kg.

Spatial patterns at the regional level reveal the importance of comprehensive agrotechnical measures. In counties with higher levels of NPK fertiliser usage, the level of calcium fertilisation is typically higher. Unfortunately, the use of calcium fertilisers in Poland remains insufficient. From 2006 to 2020, the annual average usage of CaO/ha of agricultural land was below 49 kg (Artyszak, 2022). Although it nearly doubled during the years 2010-2020 compared to the economic year 2009/2010, it still falls short of meeting the actual needs (Hołubowicz-Kliza et al., 2021). The demand for lime in domestic agriculture is around 31 million tonnes of CaO, averaging around 2 tonnes of CaO/ha of agricultural land. Analysis of the fertilisation data from the period 2010-2020 indicates that the quantities of calcium fertilisers used by farmers in Poland are many times lower than the optimum (Nicia et al., 2023). The highest usage of lime was recorded in 2020 in Opole Voivodeship (14.3 kg of CaO/ha of agricultural land), Lower Silesia Voivodeship (141.2 kg of CaO/ha of agricultural land), and West Pomeranian Voivodeship (115.9 kg of CaO/ha of agricultural land). In these voivodeships, 60% of the counties were characterised by high usage of calcium fertilisers, exceeding 109.8 kg of CaO/ha of agricultural land (see Figure 2).

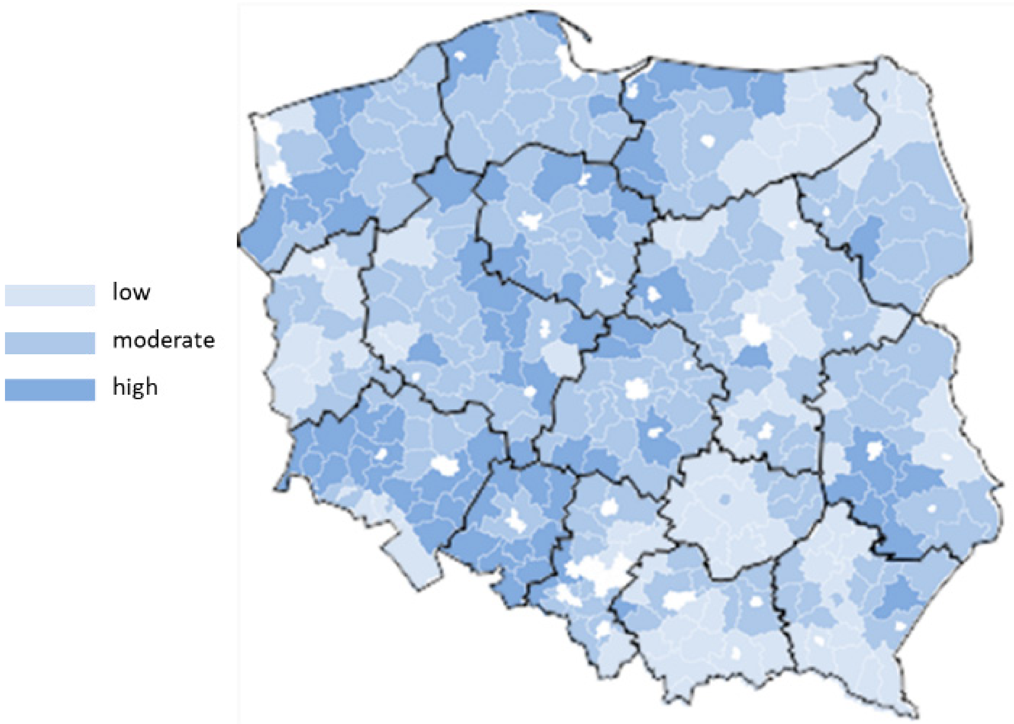

Figure 2. Levels of soil fertilisation with calcium fertilisers in Poland by county in 2020
Source: authors' work based on GUS (2021).

A different situation was observed in Świętokrzyskie Voivodeship, Lesser Poland Voivodeship, and Podlaskie Voivodeship, where 52.8% of soils require urgent liming (Hołubowicz-Kliza et al., 2021). The levels of calcium fertilisation in these areas were 52.0 kg of CaO/ha of agricultural land, 53.9 kg of CaO/ha of agricultural land, and 68.6 kg of CaO/ha of agricultural land, respectively (GUS, 2021). The lowest usage level of calcium fertilisers was 1.0 kg of CaO/ha of agricultural land (Lesko county in Subcarpathian Voivodeship).

Agricultural productivity is primarily determined by acreage, meaning that the larger it is, the more effective the utilisation of intensive, technically and technologically advanced plant cultivation

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methods. However, such methods require increasingly high expenses, which is why the economic potential of farms (measured by the acreage of utilised agricultural land) plays such a crucial role. According to the results of the 2020 National Agricultural Census, there were over 1.3 million agricultural farms in Poland operating on a total agricultural land area of over 13.5 million hectares. The average size of an agricultural farm was 10.4 hectares of agricultural land. The current state of the Polish agricultural structure indicates that in terms of farm size, production scale, concentration, and field size and distribution, agricultural farms in southeastern regions deviate unfavourably from the structure of farms located in the western and northern parts of the country.

Another feature that characterises the agricultural structure is the way agricultural land is used. Permanent grassland (Polish: TUZ) represents one type of agricultural land. Due to its specific nature, it requires a different approach to liming compared to arable land. Pastures and meadows are crucial for providing essential feed for farm animals. The appropriate quantity of good-quality basic feed can mainly be produced in soils that have been provided with the most favourable conditions, including the right pH. However, it is estimated that around 50.0% of the soils in the grasslands of Poland are acidic and very acidic, which creates unfavourable conditions for sward growth and development (Pietrzak et al., 2019). The share of permanent grassland in agricultural land varies significantly in Poland. A relatively high proportion of meadows and pastures is found in counties located in the northeastern part of the country, known as the 'milk region,' and in the southern part. This is due, in part, to the specific topography of these areas, which makes plough tillage challenging (Gabryszuk et al., 2021). In Poland, mountainous counties in the southern part of the country have the largest share of permanent grassland in the structure of agricultural land. In contrast, counties situated in central and western Poland, where natural conditions favour intensive plant production, have a significantly smaller share of meadows and pastures.

One of the conditions for the development of farms is strengthening their connections to the market, which often compels them to increase production scale and the sale of agricultural products. In 2020, the lowest percentage of farms selling agricultural products was observed in the voivodeships located in southeastern Poland. Conversely, regions with the highest proportion of farms selling agricultural products at the national level were those located in the central part of the country, primarily in Greater Poland Voivodeship and Kuyavian-Pomeranian Voivodeship (see Figure 3).

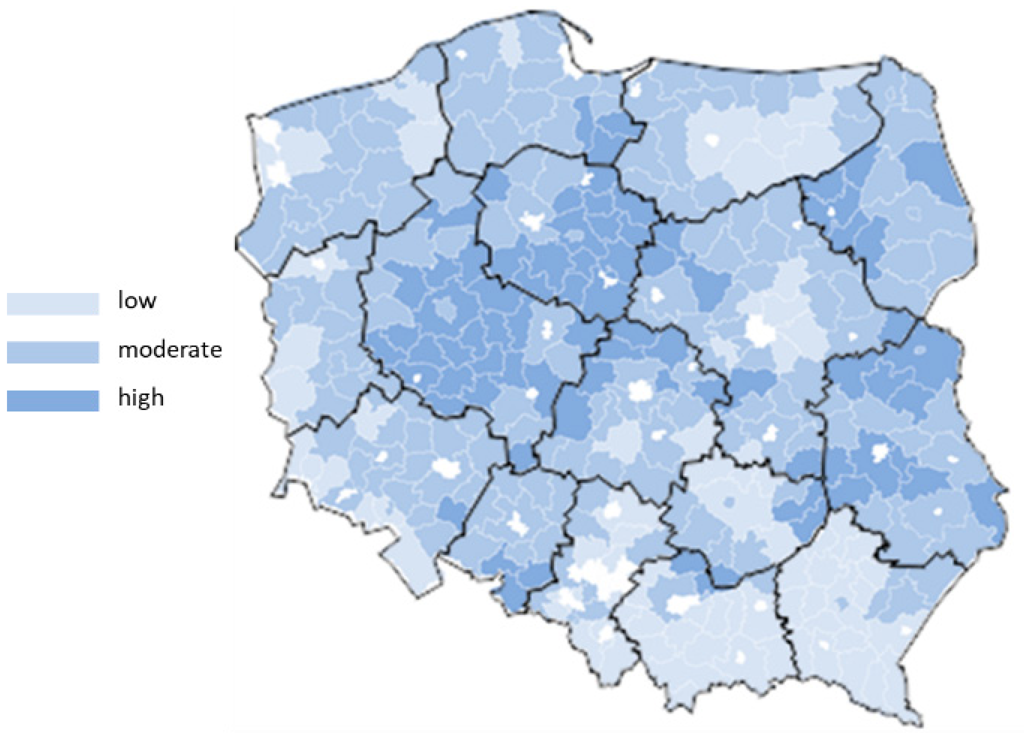

Figure 3. The proportion of farms in Poland selling agricultural products [%]
Source: authors' work based on GUS (2022).

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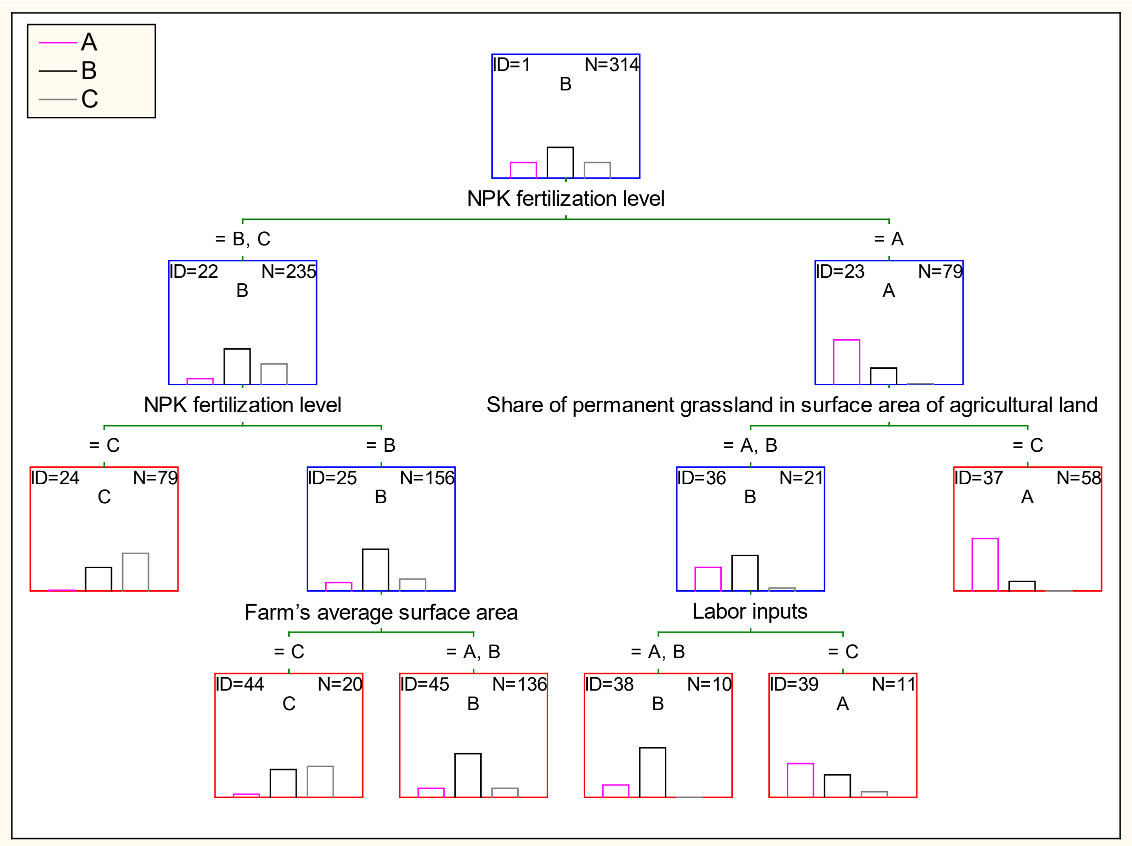
Significant variations in the levels of soil fertilisation using calcium fertilisers and a very low overall level of soil fertilisation in most areas of the country raise the following question: What is the reason? This question is particularly relevant in the context of the arguments provided above concerning the influence and effects of liming on the production process in agriculture, which is becoming particularly important in light of the efforts to institutionally limit NPK fertilisation levels. To provide an answer to this question, the Classification and Regression Tree method (C&RT) was utilised. The results of the studies are presented in Figure 4.



Labels as in Table 1: where A – low; B – moderate; C – high.

Figure 4. A C&RT model for the variable calcium fertilisation level

The developed model consists of 5 split nodes and 6 terminal nodes (Fig. 4). The percentage of incorrect classifications was 31%, which was considered a satisfactory result, suitable for exploratory purposes. The first (node 1) and second (node 22) splitting criterion was the NPK fertilisation level. The NPK fertilisation level in the individual counties consistently corresponded to the level of calcium fertilisation, confirming the comprehensiveness of the agrotechnical measures undertaken. Interestingly, in the case of 156 counties with a moderate NPK fertilisation level and a prevailing moderate level of liming (node 25), an additional explanatory factor was the average surface area of farms. It was observed that as the average farm size in counties increased, the average level of liming also increased. Given that this division pertained to counties with a moderate level of NPK fertilisation usage, the use of larger quantities of calcium fertilisers in larger farms appears to be the correct approach. A more intensive application of deacidifying fertilisers in these entities not only better compensates for the losses resulting from CaO leaching during the vegetation period but also allows for the optimisation of soil pH levels and their adjustment to the requirements of specific plant species. This enhances plants' assimilation of mineral substances supplied to the soil with fertilisers and increases the soil's sorptive capacity, consequently reducing the leaching of fertilising substances into water bodies. These factors contribute to a reduction in agricultural production costs and have a positive impact on both crop quantity and quality.

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While the left-hand side of the diagram (node 22) consisted of 235 counties with predominantly moderate and high levels of liming, 79 counties with a low level of liming were grouped on the right-hand side (node 23) (Figure 4). In the latter case, the most significant predictor for liming application was the share of permanent grassland in the surface area of agricultural land. Farms with a low proportion of meadows and pastures in their agricultural structure exhibited a higher level of soil liming (node 36). This confirms a well-documented pattern in the literature, namely that farmers use calcium fertilisers more frequently in arable fields compared to meadows and pastures. Kasperczyk and Szewczyk (2006) demonstrated that in the case of permanent grassland, the desired effects of liming are significantly lower compared to other types of land. Grass vegetation growing in acidic soils can absorb a sufficient amount of nutrients to ensure high yields, provided that the content of such substances in the soil is high. This is why farmers often refrain from liming. The consequence of such an approach can be excessive soil acidification in grassland, which can lead to its degradation (Kopeć & Gondek, 2013). In counties with a small or medium share of permanent grassland, the level of liming was associated with unit labour inputs. In counties with low or medium labour inputs (node 38), moderate usage of calcium fertilisers prevailed. Conversely, in counties with high labour inputs (node 39), a predominantly low level of calcium fertilisation was observed. This can be attributed to differences in production structure. The observed pattern is a result of the higher labour intensity of certain crops and milk production. These types of agricultural activities include a significant share of crops that are more tolerant to low soil pH, such as potatoes and permanent grassland, which provides the basis for milk production. Consequently, counties with a relatively higher share of labour-intensive agricultural activities and, consequently, higher labour inputs more frequently exhibited a low level of calcium fertilisation.

An additional functionality of classification trees (C&RT) is that they allow for the generation of a ranking of predictors in terms of their importance. This is essential since there were numerous predictors that did not appear in the diagram, but they may have a strong connection to the liming level. For the purpose of this study, the ranking generated in the Statistica software was expanded to include information about the predictor category. It can be observed that two of the five most important predictors of liming described a county's agricultural structure, while two others related to production intensity (Table 2). One predictor pertained to farms' connections to the market.

Table 2. Ranking of the importance of predictors

Predictor	Category	Importance	Ranking	Predictor	Category	Importance	Ranking
Share of permanent grassland in surface area of agricultural land	PI	1.00	1	Farms' possession of agricultural tractors	AS	0.46	9
Labor inputs	AS	0.77	2	Proportion of farms with the economic size up to 8000 euro of standard production		0.44	10
Proportion of farms selling agricultural products	CM	0.75	3	Topography	WP	0.42	11
Farm's average surface area	AS	0.72	4	Agroclimate		0.32	12
NPK fertilization level	PI	0.70	5	Proportion of farms receiving incomes from hired labor	CM	0.31	13
Soil quality	NC	0.62	6	Water conditions	WP	0.29	14
Share of farms with surface area exceeding 15 ha of agricultural land	AS	0.50	7	Stocking density (cattle, pigs, hens)	PI	0.26	15
Agricultural Production Area Quality index (JRPP)	NC	0.47	8	Proportion of farms receiving incomes from non-agricultural economic activities	CM	0.12	16

* Predictor categories: AS – agricultural structure; PI – production intensity; CM – connections to the market; NC – natural conditions.

Source: authors' work based on FADN (n.d.).

However, stating that natural conditions did not play an important role in liming practice would not be an accurate conclusion, as soil quality was ranked sixth, whereas agricultural production area quality was eighth. The factors examined in the research do not exist in isolation but constitute a web of interconnections. However, of the 17 examined determinants of liming, economic factors, especially those closely related to production economics, appeared to be the most significant.

Discussion

Agricultural structure is a defining feature of agriculture and significantly influences the performance of this economic sector. It refers to the organisation and distribution of land, resources, and knowledge within an agricultural system. This includes aspects such as land ownership, land rental systems, land use patterns, farm size distribution, and the social and economic relationships among different stakeholders (Frolova et al., 2020). It is also a critical factor in determining the production capacity of agricultural farms (Czudec et al., 2017). Agriculture is inseparably linked to the natural environment, and its current state is a result of the evolutionary development of technology, production methods, and farming practices, all strongly influenced by local environmental conditions. Therefore, agriculture is a complex economic activity that shapes the unique conditions of rural areas (Bański, 2007). It interacts with the natural environment and adapts natural conditions to its requirements (Saboori et al., 2023; Tan et al., 2022).

The results of the conducted studies clearly indicate significant regional variations in soil liming practices in Poland. Moreover, it was demonstrated that the characteristics of the agrarian structure of a given area had a greater influence on the level of liming than natural conditions (as indicated by the decision tree diagram and the predictor importance ranking), which allowed us to positively verify Hypothesis 1.

An element of agro-technology that largely determines the quantity and quality of crops is the application of fertilisers. In the context of Polish soil and climate conditions, fertilisation accounts for 40-50% of plant productivity (Konieczny, 2023). Optimising fertilisation has the potential to bring benefits in terms of improving food security. By precisely adjusting the quantities of applied fertilisers to the requirements of plants, one can enhance their growth, yields, and quality (Ahmed et al., 2021). Nitrogen fertilisers, particularly nitrogen such as nitrogen fertilisers, play a significant role here. Nitrogen has a strong effect on the modification of the morphological and biological features of plants that are essential for high yields (Zielewicz et al., 2019). However, in the case of most plants cultivated in Poland, fertilisation with a single substance does not yield good production results, as the soil usually lacks sufficient amounts of other necessary substances for plant growth (Dyśko et al., 2014).

Soil liming has long been used to maintain the optimal pH for plant production (Goulding, 2015). Most arable crops respond positively to liming; however, individual plant species have specific requirements in this regard. Significant differences in yield due to lime application can be observed among arable crop species (Cifu et al., 2004). Additionally, arable crop species differ in terms of their tolerance to acidic soil conditions (Slattery & Coventry, 1993). In soils with low aluminium content, the beneficial effects of liming often result from improved nutrient availability. Liming not only impacts crop yield but can also enhance the nutritional quality of crops by increasing mineral concentrations and reducing the phytotoxicity of heavy metals (Soltani et al., 2016; White et al., 2012). It also helps reduce physiological disorders and yield losses resulting from insufficient lime concentration in plant tissues (Jemrić et al., 2017; White, 2017). It should be emphasised that the current level of deacidifying fertilisation does not even partially compensate for the losses of lime leached from the soil during the growing season. Calcium oxide (CaO) loss per hectare of agricultural land is estimated at 350-450 kg per hectare per year. These losses should be replenished through appropriate deacidifying fertilisation to maintain the optimal soil pH for crops (Pietr & Krysztoforski, 2022).

The analyses conducted clearly indicate a higher level of living in regions with greater agricultural production intensity (decision tree diagram, node no. 36) and in regions characterised by a larger average farm area (decision tree diagram, split at node 25). Conversely, a significantly lower level of liming was found in areas where the level of NPK fertilisation was low (decision tree diagram, split at node no. 22) and where there was a large share of permanent grasslands (decision tree diagram, split at node no. 23). These observations allowed us to positively verify Hypothesis 2.

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The spatial variation in the agricultural structure of Polish agriculture results from the interaction between various past and present socio-economic processes. The strategy for redesigning the agricultural structure should consider the dual nature of agriculture. On the one hand, this model is based on modern family farms that are capable of developing and competing in both domestic and international markets. On the other hand, it encompasses small-scale farms that primarily produce subsistence crops and are closely linked to local markets (Wojewodzic, 2017). However, regardless of which model of agriculture is chosen, solutions related to fertilisation, including liming, will be essential for enhancing the potential of agricultural soils.

It is, therefore, necessary to conduct further research on the long-term economic benefits resulting from liming and on how various policy interventions can support smaller farms in improving soil management practices.

Conclusions

The conducted research indicates significant regional variations in the level of soil liming in Poland, which do not fully reflect the actual needs of agriculture. It is important to emphasise that increasing the level of soil liming requires actions focused on educating farmers in both the technological and economic aspects of production. Raising farmers' awareness regarding liming, particularly in the context of its environmental and economic benefits, could contribute to improving agricultural efficiency.

The analysis revealed that the factors with the greatest impact on the level of liming were farm size, NPK fertilisation levels, and the share of permanent grassland in the agricultural area. The results suggest that larger farms that use higher levels of NPK fertilisation tend to lime their soils more frequently, resulting from their greater financial and technological capacities. In contrast, regions with a higher share of permanent grasslands and more labour-intensive practices exhibited lower levels of liming, which may be related to the lower intensity of agricultural production and the specific land-use practices in these areas.

The implementation of the European Green Deal concept requires raising environmental awareness among farmers, especially in regions with acidic and highly acidic soils, which dominate most areas of Poland. In these regions, particularly in southeastern Poland, promoting liming as an effective tool for soil pH management is essential for optimising cultivation conditions and achieving sustainable agriculture.

The study also highlighted the need for further analyses of the long-term effects of liming, particularly in the context of climate change and increasing restrictions on the use of mineral fertilisers. Agricultural policies should support smaller farms, which may face difficulties in accessing adequate financial resources for investments in liming.

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The contribution of the authors

Conceptualisation, T.W., P.N., P.Z., M.D. and A.P.; literature review, J.B.-C., A.K., T.W., Ł.P., A.O. and S.M.; methodology, T.W., M.D. and J.B.-C.; formal analysis, M.D. and A.K.; writing, T.W., A.P., Ł.P., A.O., P.Z., P.N. and S.M.; conclusions and discussion, J.B.-C., M.D., T.W. and S.M.

The authors have read and agreed to the published version of the manuscript.

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EKONOMICZNE I ŚRODOWISKOWE CZYNNIKI DETERMINUJĄCE PRZESTRZENNE ZRÓŻNICOWANIE WAPNOWANIA GLEB W POLSCE

STRESZCZENIE: Celem badań było określenie cech decydujących o poziomie wapnowania gleb w Polsce. Analizy przestrzenne przeprowadzono w oparciu o wyniki Narodowego Spisu Rolnego 2020. W pracy przedstawiono zróżnicowanie regionalne Polski w zakresie wybranych parametrów charakteryzujących jakość rolniczej przestrzeni produkcyjnej oraz niektórych cech struktury rolniczej, w tym powiązań gospodarstw z rynkiem. Podjęto próbę identyfikacji cech strukturalnych rolnictwa mających największy wpływ na ilość stosowanego wapna (CaO). Zastosowana metoda drzew klasyfikacyjnych (C&RT) pozwoliła na identyfikację czynników najbardziej różnicujących intensywność wapnowania w badanych gminach, m.in.: udział trwałych użytków zielonych w użytkach rolnych, nakłady pracy, odsetek gospodarstw prowadzących produkcję towarową, wielkość gospodarstw i poziom nawożenia mineralnego (NPK). Analiza wykazała, że regiony z większymi gospodarstwami i wyższym poziomem nawożenia NPK stosują więcej wapna. Natomiast obszary o większym udziale trwałych użytków zielonych i intensywnych nakładach pracy wykazują niższy poziom wapnowania. Wyniki te sugerują, że wprowadzenie ulepszonych praktyk rolniczych, zwłaszcza w regionach z małymi gospodarstwami i ograniczonym nawożeniem, mogłoby poprawić efektywność wapnowania gleb i wspierać cele Europejskiego Zielonego Ładu w zakresie zrównoważonego rolnictwa.

SŁOWA KLUCZOWE: pH gleby, koszty produkcji, metoda drzew klasyfikacyjnych C&RT, struktura rolnicza, Europejski Zielony Ład

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