Theses of Doctoral (PhD) Dissertation

# Soluble phosphorus content and its change in Hungarian agricultural soils from the regime change (1989) to the present day

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DOI: 10.54598/003530

Keszthely

2023

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The candidate fulfilled all the conditions prescribed in the Doctoral Regulations of the Hungarian University of Agricultural and Life Sciences, the remarks and suggestions made in the workplace debate of the dissertation were taken into account during the revision of the dissertation, therefore the dissertation can be submitted for defense.

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| approval of the head of the doctoral school | approval of the supervisor | approval of the supervisor |

## 1. Antecedents and objectives of the work

Among the various aspects of the sustainability of land use, the preservation of soil fertility is one of the most important tasks. Since the level and availability of nutrients required by plants highly influence the fertility of soils, monitoring and maintaining these nutrients at the right level is crucial, especially in intensively cultivated areas.

Phosphorus is one of the most important nutrients in the soil for plant growth. Its plant-available forms can easily be depleted in intensively cultivated areas because the natural recharge process from less soluble minerals and organic forms is very slow. Artificially replenished (with fertilizing) phosphorus can also be bound within a short time in less soluble forms that cannot be accessible to plants. (Malhotra, 2018).

In fertilization plans, the concentration of soluble phosphorus in soils must be taken into account as well as the specific nutrient requirement of the plant.

Phosphorus recharge/fertilization of Hungarian agricultural soils has undergone major changes since the middle of the last century, and these changes were largely controlled and influenced by broader political/economic events. The increasing use of artificial fertilizers - which began in the 1950s - reached its maximum in the 1970s and 1980s during socialism. The application of fertilizers was exceeding the real needs of crop production at that time.

After the regime change, a drastic decrease in phosphorus fertilizer usage can be observed, which was partly due to economic (changes in the support system) and partly environmental reasons.

As the national phosphorus balances have been permanently negative since the regime change (1989), it is important to analyze the phosphorus concentration of agricultural soils nationally in order to avoid nutrient depletion, as well as to explore other factors that may influence the phosphorus concentration.

In light of the above-mentioned aspects, the goal of my doctoral research was a detailed analysis of the phosphorus concentration of agricultural soils in Hungary. To achieve this goal, I analyzed national and continental scale databases, and created national scale maps about soil soluble phosphorus content using the up-to-date methods of digital soil mapping. During my analyses, I tried to answer the following specific questions:

- Among the environmental parameters, how do climate and the physical/ chemical properties of soils affect the concentration of soluble phosphorus?

- Among the farming characteristics, how do land use, fertilization, and animal density affect the concentration of soluble phosphorus in the soils?
- In Hungary, how close is the correlation between fertilization and concentration of soluble phosphorus in soils at the national level, and can we see any changes in this regard over the last 50 years?
- In Hungary, what other factors played a role in the change (decrease) of phosphorus concentration in the agricultural soils from 1989 to 2009 and 2015 apart from the drastic change in fertilization practice?
- What spatial pattern did the concentration of soluble phosphorus in Hungarian agricultural areas show before the regime change (1989) and what does it show today?
- What is the current phosphorus supply in Hungarian agricultural soils?

# 2. Material and methods

## 2.1 Datasets used in the analyses

During my work, I analyzed the phosphorus concentration data of three different databases (AIIR, TIM and LUCAS). Among the factors affecting the phosphorus concentration of soils, I analyzed the agroclimatic zones - provided by the European Environmental Agency (Ceglar et al. 2019) - and the bioclimatic variables of the WordClim database at the continental level.

I analyzed the relationship between land use and soil-soluble phosphorus using the land use data of the LUCAS database, and the correlation with animal density using the EUROSTAT dataset on the continental scale.

I analyzed the relationship between fertilizer usage and the concentration of soluble phosphorus in agricultural soils at the national scale by using the fertilizing dataset reported by KSH, and I analyzed the effects of other physical/chemical properties of soils on the AIIR and the LUCAS datasets.

## 2.2 Data harmonization

Since the phosphorus data (AIIR, TIM, LUCAS) used in my analyses were measured with different phosphorus extraction methods, I had to harmonize the data for the analyzes in which I compared the databases with each other or analyzed them together. I used the following conversion equation for data harmonization in these cases:

$$\text{OLSEN-P} = 77.75 + 0.412 \times \text{AL-P} - 9.86 \times \text{pH}_{\text{H20}}$$

### 2.3 Main steps of the mapping process

I developed the maps using geostatistical methods (kriging and regression kriging) in five steps building on each other:

1. The AIIR database provided the most reliable basis for creating the national phosphorus concentration map due to its high sample density. During the process of mapping with AIIR data, I did not use auxiliary variables to create the map representing the soil phosphorus concentration before the regime change (1989).
2. In the second step, I calculated the differences in the phosphorus concentrations at the points of the LUCAS datasets using the previous map developed on the AIIR.
3. In the third step, I performed spatial interpolation by using regression kriging (including pH as an auxiliary variable) on the data points containing the differences between AIIR and LUCAS datasets.
4. In the fourth step, I added the raster maps showing the changes in phosphorus concentrations (between 1989 and 2009 and 2015) to the raster map developed on the AIIR database (representing 1989). The resulting maps show the concentration in the years 2009 and 2015.
5. In the final step, I created phosphorus supply category maps from the concentration maps representing the period 1985-89 developed on the AIIR database and from the concentration map representing the year 2015. In this calculation, I used the threshold values of Antal et al (1979).

## 3. Results

### 3.1 The relationship between climate and the soluble phosphorus concentration in soils

Based on the agroclimatic zone map published by the EEA and the phosphorus data of the LUCAS database, statistically significant differences can be observed among the individual climate zones. In summary, the soil phosphorus concentration is higher in climate zones where the climate allows more intensive land use and crop production, while the phosphorus concentration is lower in the soils of zones characterized by more extreme temperatures and rain distribution, which are unfavourable for crop cultivation (Figure 1). The relationship between soil soluble phosphorus concentrations and the bioclimatic variables of the WordClim database describing the climate in more detail was very weak.

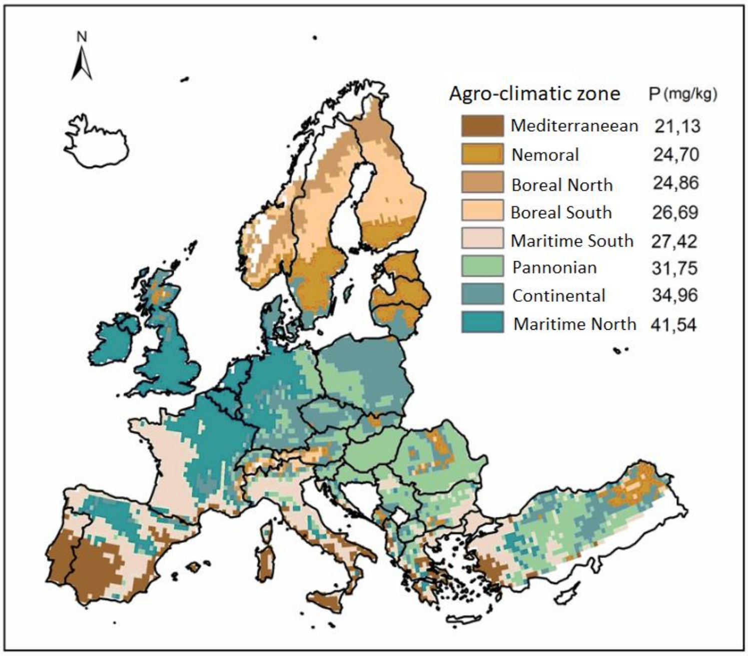

Figure 1. Mean Olsen phosphorus concentrations (mg/kg) in the climate zones of the EEA agroclimatic map

### 3.2 The relationship between the soluble phosphorus content of soils and land use

Overall, it can be established that the average phosphorus values are lower in natural or semi-natural (non-fertilized) areas, while fertilized agricultural areas and artificial (urban, industrial) areas are characterized by significantly higher phosphorus concentrations.

In further analyses of the LUCAS land use categories and sub-categories, interesting correlations were found with soluble phosphorus concentrations of the soils.

The analysis showed that the most phosphorus can be found in the soils of tuber plants (potatoes, sugar beets), which is also surprising because the mentioned plants have a significantly lower specific phosphorus nutrient requirement, such as other field crops (sunflower, cereals). However, the distribution of sample points in the LUCAS database revealed that the representation of these tuber plants is much higher in pedoclimatic zones with more intensive cultivation, where fertilization has already been at a much higher level. In addition, it was also revealed that some plants that require more phosphorus (e.g., sunflower) are more typical in less intensively cultivated areas (in warmer climate zones), and therefore the soils of these plants can be characterized by a lower concentration of phosphorus.

### 3.3 The relationship between the soluble phosphorus content of soils and animal density

The results showed that a positive relationship can be observed between the density of cattle and the soluble phosphorus content of soils. The relationship between pig density and phosphorus level is moderate, while sheep and goat density is not related to the soluble phosphorus concentration of the soils.

### 3.4 The relationship between the soluble phosphorus content of soils and other soil properties

During the analysis of the AIIR database, a significant relationship can be observed between the phosphorus content of the soil and other soil parameters, however, the relationships - in various directions - are mostly very weak.

Soil pH and lime content stand out in terms of the strength of the relationship (Pearson correlation coefficient were r= 0.46 and r=0.33).

Only a weak relationship can be observed between the soil parameters of the LUCAS database and the phosphorus concentration but it is remarkable that the positive relationship with pH and lime content, observed in the case of AIIR, turned into a negative relationship in the case of LUCAS, and although the relationship is weak, it is statistically significant.

### 3.5 The relationship between the fertilizer application data of KSH and the averages values of soil phosphorus concentration at the county level measured in the AIIR and LUCAS databases

Based on the fertilizer application data reported by KSH, the country's use of phosphorus fertilizer after the regime change dropped to 25%. All of this is clearly visible based on the AIIR (before regime change) and LUCAS (after regime change) soil-soluble phosphorus concentration data. I compared the KSH fertilizer application data of 20-year periods (1970-1989 and 1990-2009) with the two databases (AIIR and LUCAS) containing soluble phosphorus data (representing both periods) on average levels calculated on 19 counties in Hungary. The result of the Pearson's correlation test was r=0.68 between the phosphorus data of the AIIR database and the county averages of phosphorus fertilizer application of KSH (1970-1989), and r=-0.31 between the phosphorus data of the LUCAS 2009 database and the county average of phosphorus fertilizer usage (between 1990-2009).

### 3.6 The comparison of the soil soluble phosphorus concentration data of the AIIR, LUCAS and TIM database at the national scale

For a more detailed description and analysis of the phosphorus concentrations in Hungarian agricultural soils, I used phosphorus data from three databases: AIIR, TIM and LUCAS. In the result of the descriptive statistical analysis of these databases, it is noticeable that the phosphorus data of the TIM database (measured every three years from 1992 to 2010) shows phosphorus concentrations very similar to or even higher than in the AIIR database (Table 1). Given the drastic reduction in fertilizer application after 1989 it doesn't seem realistic. Presumably, the TIM phosphorus concentration results overestimate the soluble phosphorus of the soils due to its sampling time (autumn), which takes place at the same time as the basic fertilization in autumn. For this reason, I only used data from the two surveys sampled in the summer (AIIR and LUCAS) to map the phosphorus concentrations.

Table 1: Descriptive statistics of the AIIR, TIM and LUCAS phosphorus data (converted to AL-$P_2O_5$) measured in Hungarian agricultural soils

| Database | minimum | maximum | mean | median | std. |
|---|---|---|---|---|---|
| **AIIR 1985-89** | 2,50 | 550,00 | 190,29 | 175,90 | 91,29 |
| **TIM 1992** | 3,00 | 8890,00 | 270,60 | 161,50 | 555,70 |
| **TIM 1995** | 11,00 | 9073,00 | 300,37 | 160,00 | 652,98 |
| **TIM 1998** | 7,00 | 9433,00 | 286,72 | 161,00 | 562,07 |
| **TIM 2000** | 7,00 | 5705,00 | 260,79 | 147,00 | 470,92 |
| **TIM 2004** | 6,60 | 9540,14 | 290,84 | 154,77 | 646,19 |
| **TIM 2007** | 6,37 | 12636,00 | 314,80 | 174,00 | 639,24 |
| **LUCAS 2009** | 19,41 | 1072,81 | 107,90 | 83,45 | 106,81 |
| **TIM 2010** | 10,20 | 14500,00 | 339,98 | 165,00 | 889,60 |
| **LUCAS 2015** | 17,47 | 517,38 | 105,18 | 79,96 | 81,28 |

### 3.7 The results of the phosphorus mapping at the national scale

The phosphorus concentration maps developed on the AIIR and LUCAS databases and the maps showing the change in phosphorus concentration show that the phosphorus level decreased to the greatest extent in the central part of the country. The mean value of the phosphorus decrease is -82,78 mg/kg between 1989 and 2009 and -82,92 mg/kg between 1989 and 2015. This result is in line with the fact that fertilization usage decreased from an average value of 80 kg/ha (before 1989) to less than 20 kg/ha in the 2010s.

The change can be related to some soil properties, mainly soil pH and lime content. The relationship between the change in phosphorus concentration and some important soil properties can be seen in Table 2.

Table 2. Relationships between the change in soil soluble phosphorus values of the AIIR (1989) and LUCAS (2009 and 2015) databases and some soil properties

| | $P_2O_5$ change 1989-2009 | $P_2O_5$ change 1989-2015 |
|---|---|---|
| **clay (%)** | 0,21** | 0,26** |
| **silt (%)** | 0,00 | 0,00 |
| **sand (%)** | -0,12* | -0,15* |
| **pH** | -0,41** | -0,43** |
| **lime content (%)** | -0,36** | -0,37** |
| **organic carbon (%)** | -0,04 | -0,06 |

The phosphorus supply map of Hungarian agricultural soils representing the period 1985-89 can be seen in Figure 2.

Based on the map, in the period before 1989, 0.03% of the soils in the country were very poor, 0.83% poor, 8.42% moderate, 47.08% good and 43.65% a very good supply of phosphorus. Most of the areas with lower phosphorus supply are located in the northeastern half of the country, in the area between the Danube and Tisza, and along the western border.

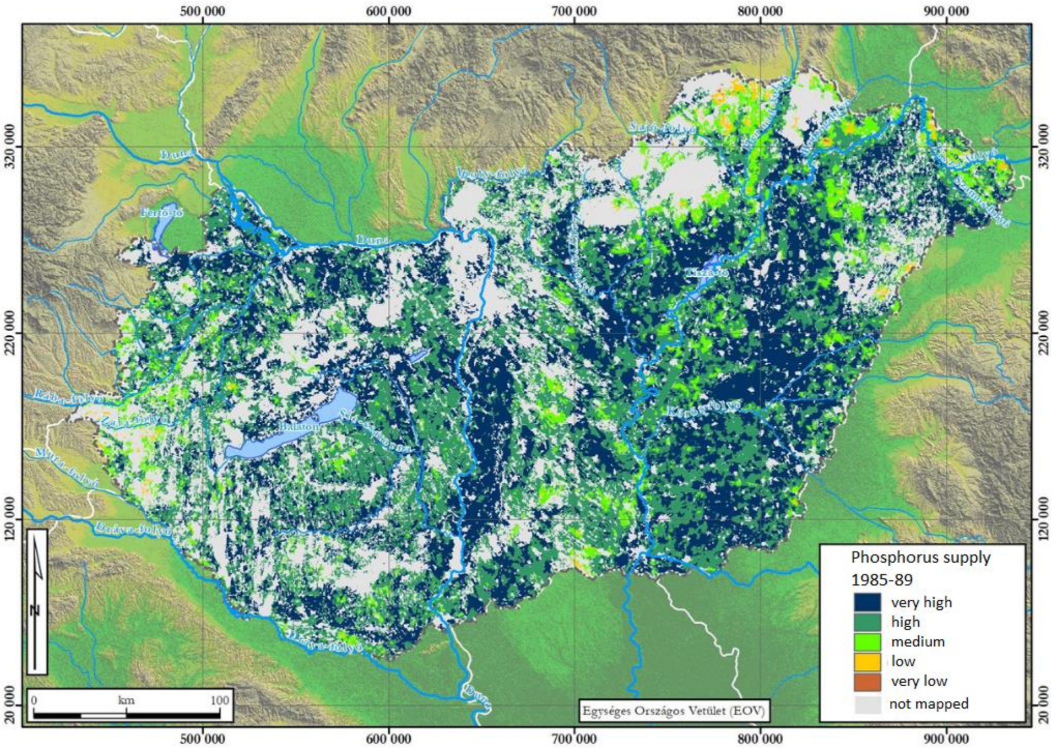


Figure 2: Phosphorus supply of Hungarian agricultural areas between 1985-89.

The phosphorus supply map of Hungarian agricultural soils representing the year 2015 can be seen in Figure 3. Based on this map, in the year 2015, 13.57% of the soils in the country were very poor, 16.01% poor, 30.25% moderate, 19.22% good and 11.94% a very good supply of phosphorus.

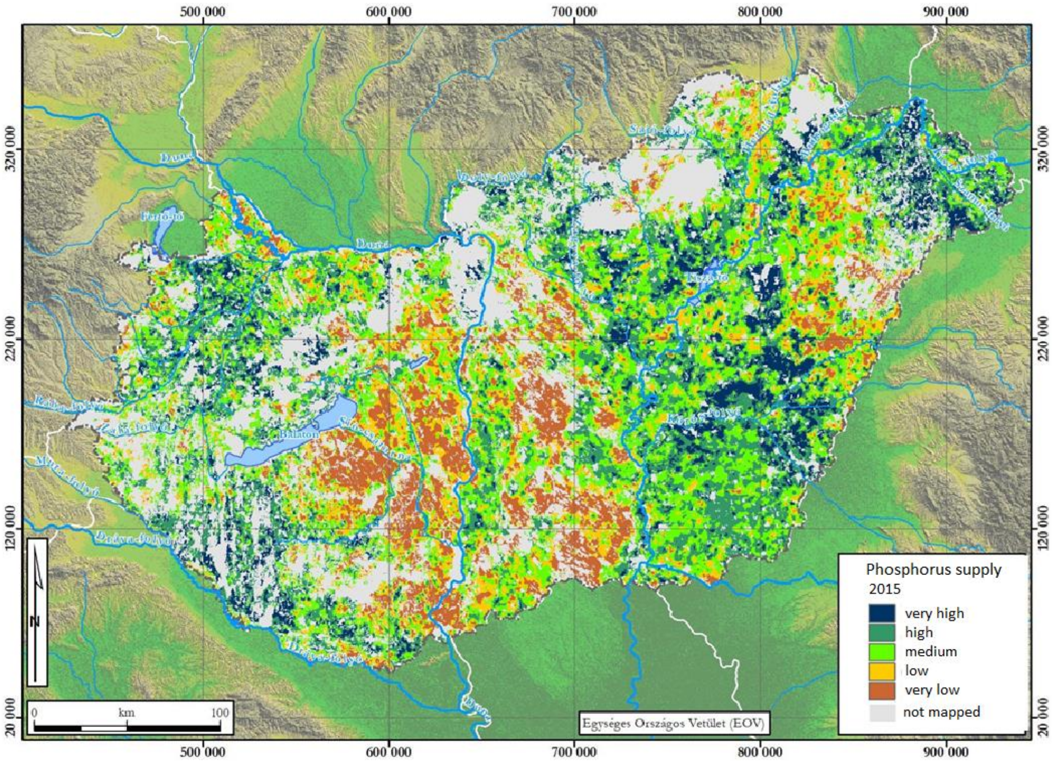


Figure 3: Phosphorus supply of Hungarian agricultural areas in 2015

In summary, 60% of the country is characterized by medium or worse phosphorus supply according to the map representing 2015, while before 1989 medium and worse phosphorus supply was only 10% countrywide.

## 4. Conclusion and suggestions

The actual phosphorus concentrations of the soils are the result of many different factors (which are also related to each other). On the continental scale, climate and land use are influencing the phosphorus content mostly, however, on the national scale, fertilizer usage has the greatest impact on soil phosphorus content. In addition, some soil properties (pH, lime) also have more or less an effect on phosphorus concentration and its change (especially in long term).

The agricultural areas of Hungary can be characterized by a medium phosphorus concentration compared to the mean values of the EU member states. Based on the phosphorus data measured before the regime change (1985-89), more than 90% of the Hungarian agricultural areas had a good or very good phosphorus supply due to over-fertilization during the 70s and 80s. However, after 1989, the level of fertilization decreased to approximately 25% as before, which led to permanently unbalanced nutrient management. It is not surprising that, at the same time, the phosphorus supply of our soils began to decrease significantly.

Currently, only 40% of our soils have a good or very good phosphorus supply, and unfortunately, based on the 2009 and 2015 LUCAS data, the decreasing trend continues.

Based on the data provided by KSH, the phosphorus balance on the national scale has not improved, it is currently negative and the significant increase in fertilizer prices (in 2022) will probably worsen this situation.

Based on the national phosphorus supply map of 2015, we can see that the most sensitive areas (characterized by the lowest supply) are located in the central part of the country. The phosphorus concentration of the soils decreased to the greatest extent in these areas, and the lowest phosphorus values can still be measured here. The decrease can be clearly linked to the pH value and lime content of the soils, which suggests that in areas characterized by higher lime content and basic pH, the previously applied phosphorus could have been bound in the form of various less soluble Ca-minerals. This does not mean that this phosphorus has completely disappeared from our soils, but that it has been transformed into less soluble and accessible forms. In these areas, it would be important to use alternative solutions other than fertilizers that help to improve the phosphorus supply by reactivating the phosphorus bound in the soil.

## 5. New scientific results

1. Significant statistical relationship was found between the agroclimatic zones of the EEA and the soil-soluble phosphorus concentration of the LUCAS database. Among the climate zones, the less intensively cultivated zones with extreme temperatures (Mediterranean, North Boreal, South Boreal) are characterized by lower soil phosphorus content. Higher phosphorus content is experienced in the soils of the more intensively cultivated zones (North Sea, Continental).

2. Based on the analysis of the animal density dataset of EUROSTAT it was found that cattle density shows the strongest correlation (correlation coefficient=0.61) with the concentration of soluble phosphorus in soils (LUCAS).

3. Based on the results of the statistical analysis of the AIIR database and the LUCAS database, it was found that a significant decrease of AL-$P_2O_5$ can be observed in the agricultural soils of Hungary after the regime change in 1989. The average decrease between the AIIR data and the 2009 LUCAS data is -83 mg/kg, while the median value is -91 mg/kg. The average decrease between the AIIR data and the 2015 LUCAS data is also -83 mg/kg, while the median value is -92 mg/kg.

4. The results of the analysis of the AL-$P_2O_5$ change observed in Hungarian agricultural soils between 1989 and 2009 it was found that the soil pH and the lime content show a negative correlation (-0.43 and -0.37) with the change (decrease of AL-$P_2O_5$). It means that the concentration of soluble phosphorus in the soil decreased more in areas where the soil has a higher lime content and basic pH.

5. Based on the soil soluble phosphorus data of the AIIR and LUCAS database, national-scale phosphorus maps were prepared using the regression kriging method in order to represent the spatial pattern of $ALP_2O_5$ concentrations in 1985-89, 2009 and 2015.

6. National scale phosphorus supply maps were created based on soil phosphorus concentration in 1985-89 and 2015. Based on these maps, it was found that in the period before 1989, 0.03% of the soils in the country (Hungary) were characterised by a very poor phosphorus supply, 0.83% were poor, 8.42% were medium, 47.08% were good and 43.65% were very good. In

contrast, the phosphorus supply in 2015 was 13.57% very poor, 16.01% poor, 30.25% moderate, 29.22% good and 11.94% very good in Hungarian agricultural soils.

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# Publications related to the topic of the dissertation

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Tóth Gergely - Kismányoky Tamás - Kassai Piroska*- Hermann, Tamás - Fernandez-Ugalde Oihane - Szabó, Brigitta (2020): Farming by soil in Europe: status and outlook of cropping systems under different pedoclimatic conditions. PeerJ 8 :5 Paper: 8984, 18 p (Q1)

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