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EXAMINATION OF THE RELATIONSHIP BETWEEN AGRICULTURAL LAND USE AND SOIL CHARACTERISTICS USING SOIL QUALITY INDICES

Doctoral thesis

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The applicant met all of the requirements of the Corvinus University of Budapest PhD regulations. During the revision of the Thesis all remarks and recommendations given by the opponents were taken into consideration, thus the revised Thesis is accepted for the defence process.

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1. SCIENTIFIC BACKGROUND AND AIMS OF THE STUDY

A requirement for the sustainable agriculture is the realization of a land use adaptable to ecological conditions (VÁRALLYAY, 2003; ÁNGYÁN és MENYHÉRT, 2004). A profound knowledge of the relationship between soil and plant is required for choosing the land use, crop rotation and cultivation practice at local level. The environmental adaptation and land management mean the most appropriate land use that the same yield level can be achieved with less artificial energy input, while the environmental load is reducing and the production efficiency is improving (LÓCZY, 1989).

In Hungary, several qualitative (classification) methods were developed to assess the land and soil quality (e.g. BEKE, 1933; KREYBIG, 1956; GÖRÖG, 1954; GÉCZY, 1968). By this time, these results have mostly sunk into oblivion in spite of their valuable informations. Currently, no quantitative soil quality assessment method or soil suitability map exists which could help with land use planning.

The traditional Hungarian economic land evaluation value (aranykorona) indicates the registered net income of landed property but do not evaluate the soil ecologically (DÖMSÖDI, 1999). The tradional quantitative 1-to-100 scale of the Hungarian soil quality value system is based on the genetic soil classification and indicates a general fertility and quality (FÓRIZSNÉ et al., 1972). At the turn of the 2000s, D-e-Meter project undertook to develop a new land evaluation system based on the ecological and economical aspects at the same way (TÓTH et al, 2006). The D-e-Meter is based on the scaling of the genetic soil unit as well, but it is more objective than the traditional soil quality value. It was validated by the national database of yields, soil properties and fertilization. Lack of large-scale soil maps and soil laboratory analyses make impossible to introduce the D-e-Meter land evaluation system.

The Hungarian land evaluation and soil quality assessment methods differ from the international methods in their data processing. The Hungarian methods are based on the units of genetic soil taxonomy, on the other hand, the international methods often interpret and integrate the simple pedological indicators (JUHOS, 2013; 2014). The conception of Hungarian soil quality assessment is that the relationship between measurable edaphic indicators and yields is very complex and it would be difficult to find some usable equation to explain the productivity.

However, the reasons for the yield variability are still poorly understood. According to my hypothesis neither simple pedological indicators nor genetic soil taxonomy categories are suitable to reveal the relationship between soil properties and crop yield. Other kind of derived or complex indicators are necessary to be calculated using multivariate statistical tools. It is necessary to determine (1) the optimal soil conditions for land uses and cultivated plants; (2) soil properties and factors which limite the yields, and theirs weights; (3) adaptation of land management to the soil conditions; and (4) impacts of land use and management on the land properties.

The specific objectives of this study were the examination of the relationship between agricultural land use and soil characteristics in an East Hungarian region; hereby:

- soil survey and mapping relevant to the agricultural land use;
- characterisation of the land management system and expected yields and yield variability under different weather condition using productivity indices;
- to find a suitable multivariate statistical method to explore the relationship between soil properties and crop yield and to develop mathematical soil quality and suitability indices;
- to find a minimum data set which characterize the main limintig combinations of the pedological parameters for cultivated plants;
- to develop a soil suitability classification system based on the soil quality and suitability indices which significant determines in crop yields and level of the land management and helps with land use planning.

2. MATERIALS AND METHODS

2.1. Site description

The research site is located in East Hungary (21º13′ E, 47º17′ N) at an altitude of 86-89.5 m. The total research area covers approximately 300 hectare. Distribution of land use tipes is 24.5% pasture (74 ha), 1.1% forest (3.4 ha) and 74.4% arable (225 ha). Depth of groundwater table is between 50 and 300 cm. Soils were developed on alluvial deposits with loam, loamy clay and clay texture. Soils can be classified as Chernozems, Solonetz and Gleysols. According to the economic land evaluation value (aranykorona), arable lands are divided into 2-7 classes. The mean „aranykorona/hectare" value is 17.5. The agricultural management practice and crop rotation were the same on every plot. The management was characterised by conventional tillage in a nonirrigated system and the fertilization was done by nitrogen only. Plot areas ranged from 1.04 to 31.90 ha.

2.2. Soil survey and analysis

I surveyed the soil conditions concerning crop rotation from 2010 to 2014, and mapped the genetic soil types and properties in the research site (MÉM-FTH-NTF, 1989). Soil samples were collected at 0-100 cm at 20 cm depth increments. The research site was divided into 33 soil units which were characterised by average of properties at 0-100 cm layer, and the 1-to-100 scale of the Hungarian soil quality value system (MÉM-FTH-FFF, 1986). The spatial analysis and soil units mapping were carried out by the software application *QGIS 2.8*. Soil samples composed of 20 subsamples were collected for analysis of potentially available nutrients at 0-30 cm depth from the 28 plots.

Soil pH, $CaCO_3$, soluble salt (MSZ-08-0206-2:1978), soluble and exchangeable sodium (EGNÉR et al., 1960), clay and silt content (MSZ-08-0205-1978) and soil organic matter (MSZ-08-0210-1977) were analysed at 0-100 cm layer at 20 cm depth increments. The hydrolysable nitrogen content (ammonium-, and nitrate-N and some easily available amino-N forms) was determined by oxidative hydrolysis according to Hargitai (HARGITAI, 1970). Available phosphorous and potassium content were determined with acidic ammonium lactate extraction (EGNÉR et al., 1960). Topographical position was determined in order to indicate the average depth of groundwater-table. The means of properties were calculated at parcel level as well.

2.3. Processing of yield data

Winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) were produced on the research site. I developed an evaluation system for characterizing the expected yields and yield variability of parcels. I calculated mean relative yield and relative standard deviation, which standardize the variability of crop rotation and different meteorological conditions of years. Yield data was first standardized using calculated relative yield of each crop as follows:

$$RY_p = \frac{Y_p}{Y_{max}},$$

where: RY_p is relative yield of plot p (a value between 0 and 1), Y_p is yield of parcel p (t ha^{-1}), Y_{max} is maximum yield on the total research site over all parcels (t ha^{-1}). Then mean relative yields between 2004 and 2013 $\overline{RY_p}$ were calculated for each plots p. Yield variability for each plot was expressed as follows:

$$CV(RY_p)[\%] = \frac{SD(RY_p)}{\overline{RY_p}} \cdot 100,$$

where: $CV(RY_p)$ is the yield variability of plot p (%), $SD(RY_p)$ is the standard deviation of relative yield of plot p (2004-2013), $\overline{\mathrm{RY_p}}$ is the mean relative yield of plot p (2004-2013). On the basis of these indices, parcels were divided into 3 productivity classes.

Climatic conditions were characterized by annual precipitation and mean annual temperature of the 10 years studied (2004-2013). The years were separated into two groups according to the Pálfai Drought Index (PDI>5.0: drought; PDI<5.0: no drought) (PÁLFAI, 2002).

2.4. Mathematical and statistical methods

All pedological variables at level of parcel and productivity class were examined using descriptive statistical analyses. Pearson correlation were analysed between soil characteriestics. With dependent variables "mean relative yield" (RY_p) and "yield variability" ($CV(RY_p)$) I applied simple linear and stepwise multivariate linear regression analysis using the simple pedological indicators as predictor variables. All variables were examined as to whether there is any indication for nonlinear analysis but I did not find any reason.

A principal component analysis (PCA) were conducted to simplify the structure of a set of variables by replacing them with fewer uncorrelated linear combinations (principal components, PCs) of original variables. In order to obtain well interpretable PCs, indicator values were first ranked in ascending or descending order using a linear function depending on whether a higher value was considered „beneficial" or „detrimental" in terms of soil function. Namely, indicators were expressed by numerical values between 0 and 1 where 0 means the most adverse condition and 1 means the most suitable values for crop production at research site. PCA were conducted using Varimax (orthogonal) rotation. PCs were interpreted as soil quality indeces based on the rotated component matrix.

Stepwise multiple linear regression processes using the derived PC factors with eigenvalues greater than 1 according to the Kaiser criterion. All PCs were examined as to whether there is any indication for nonlinear analysis but I did not find any reason.

A selected indicator set were interpreted using nonlinear transformation methods: by saturation functions (nutrient contents and soil organic matter indicators) and quadratic inverse functions (all remaining physical and chemical indicators). The interpreted indicators were integrated using multiplicative method as a chemical (Q_{chem}), physical (Q_{phys}) and fertility (Q_{fert}) indices.

With dependent variables "productivity classes" (ordinal variable) I applied discriminant analysis using the soil quality indices (PCs and Qs) as independent variables. Pearson correlation were conducted to analyse the relationship between "mean relative yield" (RY_p) and "yield variability" ($CV(RY_p)$) and soil quality indices as well.

Soil suitability classes were divided based on the soil quality indices which explain the RY_p, $CV(RY_p)$ and productivity classes best of all. Hierarchical cluster analysis (within-groups linkage method) were conducted for the classification of the 33 homogene soil units. Squared Euclidean distance was defined between two sets of observations.

All statistical analysis were conducted using *IBM SPSS Statistics 22*.

3. RESULTS AND CONCLUSION

3.1. Soil conditions

Soils can be classified as Chernozems, Solonetz and Gleysols. Crop rotation is extended on the Chernozems and Gleysols. Land management was characterised by conventional tillage in a nonirrigated system and the fertilization was done by nitrogen only. The research site was divided into 33 soil units which were characterised by average of properties at 0-100 cm layer, and the 1-to-100 scale of the Hungarian soil quality value system. Hungarian soil quality values were between 8 and 100 points. The major limiting factors were potentially the extreme moisture regime resulting from the topographical position and solonetz horizon, and the low soil organic matter content. Arable farming avoids the unfavourable pH and soluble salt content. Available nutrient contents were generally medium and sufficient.

3.2. Expected yields and variability

The plots show striking difference in yields. The mean yield of maize was 6.71 t ha^{-1} on the total arable land area, while the maximum yield was 10 t ha^{-1}. The mean yield of winter wheat was 4.63 t ha^{-1} on the total area while the maximum yield was 7.1 t ha^{-1}. The sunflower produced between 1.4 and 4.5 t ha^{-1}. The mean yield of sunflower was 2.77 t ha^{-1}. Drought did not influence on yields definitely because of the high water capacity of soils. Plots were clearly separated into three productivity classes along the mean relative yield and yield variability:

- Class P1: high yield with low variance; $\overline{RY_p}$ between 0.71 and 0.89 t ha^{-1}, $CV(RY_p)$ between 6.43 and 25.71% (low risk);
- Class P2: medium yield with medium variance; $\overline{RY_p}$ between 0.58 and 0.74 t ha^{-1}, $CV(RY_p)$ between 5.48 and 39.45% (moderate risk);
- Class P3: low yield with high variance; $\overline{RY_p}$ between 0.33 and 0.50 t ha^{-1}, $CV(RY_p)$ between 18.70 and 74.07% (high risk).

Climatic conditions were characterized by annual precipitation and mean annual temperature of the 10 years studied (2004-2013). The years were separated into two groups according to the Pálfai Drought Index (PDI>5.0: drought; PDI<5.0: no drought). Over the 10 years, there were 4 years of drought and 2 years of extreme groundwater recharge. Due to the high water capacity of soils drought did not do a significant damage in yields, while on the other hand, at a specific topographical position the groundwater recharge was capable of causing major crop failure.

The Hungarian economic land evaluation value (aranykorona), which indicates the registered net income of landed property, was highly correlated with the expected yields of the parcels (R^2=0.561; $p<0.001$).

3.3. Linear realtionship between soil characteristics and yield

Simple linear regressions having the simple indicators led to significant models with pH, depth of $CaCO_3$, soil organic matter content, topography and silt + clay content. I did not find any reason for nonlinear analysis. The explained variance were R^2=0.246-0.492 for relative yield ($\overline{RY_p}$) and R^2=0.225-0.504 for yield variability ($CV(RY_p)$). However, having all of the simple indicators as well as the selected non-correlated indicators, multivariate stepwise regressions for $\overline{RY_p}$ and $CV(RY_p)$ were all unsuccessful, i.e. only one or two indices of the variables were selected into the model. The multiple regression models couldn't be reasonably interpreted because of multicollinearity problems.

Variables were analysed using PCA. According to the eigenvalues greater than 1, the analysis yielded three principal components explaining a total of 86.365% of the variance for the entire set of variables (KMO = 0.55; Chi^2 (78) = 569.996; $p < 0.001$). Principal component 1 (PC1) was identified as salinisation, sodification and sodium-enhanced clay translocation at a specific altitude due to the high loadings of the following items: AL-Na^+, EC, clay, pH-H_2O, clay + silt, pH-KCl, topography. The first factor accounted for 56.848% of the total variance. PC2 was labelled as pH-KCl, accumulation of calcium carbonates and humification due to the high loadings of the following variables: pH-KCl, $CaCO_3$ depth, SOM. Namely, this factor expressed the remaining basic capacity, which was not caused by sodium alkalinity but rather by $CaCO_3$. The variance explained by the second factor was 17.789%. PC3 was identified as available nutrient content and topographical position due to the high loadings of the AL-P_2O_5 and AL-K_2O and a moderate loading of the topography. This factor accounted for 11.728% of the total variance. The communalities of the variables included were high (> 0.8) with the exception of one variable (Hargitai-N) having a small amount of variance (49.2%) in common with the other variables in the analysis. So the PC1 discriminated well the *Solonetz* soils from the ones on Chernozems. Furthermore, PC2 can discriminat the Calcic Gleysols with low soil organic matter from the Calcic Chernozems. The first principal component derived from the physical and chemical indicators was highly correlated with the Hungarian soil quality value.

The multiple PCR for mean relative yield ($\overline{RY_p}$) selected all the three PC factors into the linear model, so the explained variance was as high as $R^2 = 0.531$ ($p < 0.001$). The F test resulted in a significant model and the coefficients of the PC1, PC2 and PC3 factors together with the constant were all significant. The minus sign of coefficient of PC3 show that the available nutrients are not the main limiting factors. The stepwise regression analysis for yield variability ($CV(RY_p)$) selected the PC1 and PC2 factors into the linear model, which presented a significant model. The explained variance was lower as $R^2 = 0.442$ ($p < 0.01$) because the variability of yields probably depended on the weather over the years as well. The coefficients of the PC factors together with the constant were all significant. PC3 was excluded from the model. Consequently, the variables can effectively explain the yield and the variability together with other variables as linear combinations.

However, having simple indicators as predictor variables, simple and multivariate stepwise regressions are inadequate for the choice of indicators which have significant influence on yields because of a complex intercorrelation among those. The study of correlation relationships among the variables using PCA showed that some of the variables measured could be grouped to indicate a number of underlying common factors. PCA operates well with even highly correlated indicators and performs a reasonable dimension reduction. Although the derived factors (PCs) do not explain the total variance of the entire set of variables, the PC factors are well interpretable and can be considered as soil quality indices with respect to the specific soil functions. The principal component regression process is a successful method to reveal the site specific relationship between soil properties and yields at local level.

However, the linear methods do not take closer to answer the questions that which soil properties are determining the efficiency of land use and what is their importance? Nonlinear studies are needed to answer these questions.

3.4. Nonlinear transformation of pedological indicators and the derived soil suitability indices

Pedological indicators were selected based on their linear correlation and results of liner regression analyses. Functions were developed so that the nonlinear *q* values express the soil suitablity for crop rotation: 0.8-1: non-limiting; 0.6-0.8: slightly limiting; 0.4-0.6 moderately limiting; 0.2-0.4; strongly limiting; 0-0.2: non-suitable.

The q_{pH} values of homogenous soil units were between 0.400 and 0.947; the q_{salt} values were between 0.181 and 1.000 (*Table 1*). Land use adapted well to the soluble salt content of soil. The multiplicative Q_{chem} index were 0.108 and 0.947 on the total study site. The least Q_{chem} values were on the Solonetz soil. The moisture regime of the soils were the main limiting factor on the research site. Q_{phys} values of homogenous soil units were between 0.318 and 1.000 (*Table 2*). Solonetz and Gleysols had the lowest Q_{phys} values. After the nonlinear transformation of available phosphorus and potassium, the q_{P2O5} and q_{K2O} values were high (>0.870) (*Table 3*). However, the q_{SOM} were between 0.627 and 0.916. Soil organic matter could be a significant limiting factor for crop yields. Because of the high q_{P2O5} and q_{K2O} values, I used the q_{SOM} value as a Q_{fert} index.

Table 1. Nonlinear interpretation of pH and soluble salt and the chemical quality index (Q_{chem})

$\boldsymbol{Q_{chem} = q_{pH} \cdot q_{salt}}$		
$\boldsymbol{q_{pH} = \sum_{i=1}^{n}(y_i \cdot W_i)}$ pH: $x_i \leq 7{,}8$ $y_i = 1$ $x_i > 7{,}8$ $y_i = \frac{1}{1 + 0{,}95 \cdot (x_i - 7{,}8)^2}$	$\boldsymbol{q_{salt} = \sum_{i=1}^{n}(y_i \cdot W_i)}$ soluble salt: $x_i \leq 0{,}1$ $y_i = 1$ $x_i > 0{,}1$ $y_i = \frac{1}{1 + 50 \cdot (x_i - 0{,}1)^2}$	weight of layers

layer i., cm	Wi
0-20	0,36
20-40	0,28
40-60	0,20
60-80	0,12
80-100	0,04

Table 2. Nonlinear interpretation of soil texture and topotgraphical position and the physical quality index, (Q_{phys})

$\boldsymbol{Q_{phys} = q_{text} \cdot q_{topo}}$		
topographical position: $x \geq 88$ $\boldsymbol{q_{topo} = 1}$ $x < 88$ $\boldsymbol{q_{topo} = \frac{1}{1 + 1{,}15 \cdot (x - 88)^2}}$	$\boldsymbol{q_{text} = \sum_{i=1}^{n}(y_i \cdot W_i)}$ clay+silt content: $x_i \leq 40$ $y_i = 1$ $x_i > 40$ $y_i = -0{,}0094 \cdot x_i + 1{,}3771$	weight of layers

layer i., cm	Wi
0-20	0,20
20-40	0,20
40-60	0,20
60-80	0,20
80-100	0,20

Table 3. Nonlinear interpretation of available nutrient and soil organic matter contents and the fertility idex (Q_{fert})

$\boldsymbol{q_{SOM} = \sum_{i=1}^{n}(y_i \cdot W_i)}$ Soil organic m.: $y_i = 1 - 10^{-0{,}2913 \cdot x_i}$ (CSATHÓ 2003a) layer examined: 0-60 cm	$\boldsymbol{q_{P2O5*} = 1 - 10^{-0{,}0141 \cdot x}}$ (CSATHÓ 2003b) layer examined: 0-30 cm	$\boldsymbol{q_{K2O*} = 1 - 10^{-0{,}0083 \cdot x}}$ (CSATHÓ 2005) layer examined: 0-30 cm
* correction of AL-P_2O_5: on parameteres pH-KCl: 7; $CaCO_3$: 1%; K_A: 37 (SARKADI et al 1987; CSATHÓ 2002): $corrP_2O_5 = P \cdot \left[\frac{K^{-0{,}28} \cdot (M + 0{,}22)^{-0{,}15} \cdot H^{0{,}25}}{37^{-0{,}28} \cdot (1 + 0{,}22)^{-0{,}15} \cdot 7^{0{,}25}}\right]^{\frac{1}{0{,}6}}$ P: AL-P_2O_5 (mg/kg); K: texture value (Arany); M: $CaCO_3$ (m/m %); H: pH-KCl ** correction of AL-K_2O: clay+silt > 45%: $x = a \cdot [-0{,}0009 \cdot (b - 45)^2 + 0{,}0017$ a: AL-K_2O (mg/kg); b: clay+silt (m/m %)		
$\boldsymbol{Q_{fert} = q_{SOM}}$		

Although the heavy texture and lower topographical position are the main limiting factors on the study site and these go together the sodification, the land management and land use slighly adapt to topographical position and soil moisture regime. On the other hand, the land use adapt properly to the salinization. The pH value and organic matter content of soils were a slightly limiting factor for crop rotation. Presumably, available phosphorus and potassium do not limite the corop yields.

The nonlinear indices (Qs) explained the productivity classes, expected yields and yield variability better than the linear indices (PCs). These Q values can integrate with additive method:

$$Q = Q_{phys} + Q_{chem} + Q_{fert}$$

The major limiting factors were the extreme moisture regime resulting from the topographical position and solonetz horizon, and the low soil organic matter content. Arable farming avoids the unfavourable pH and soluble salt content. The minimum data set consist of the soil organic matter content at cultivated layer, the thickness of A-horizon, and topographical position.

3.5. Soil suitability classes

Based on nonlinear physical, chemical, and fertility indices, I defined four suitability classes at the research site using hierarchical cluster analysis:

- Class 1: Chemical and physical soil conditions are not or sligly limiting for crop rotation. Expected relative yields are $\overline{RY_p}$ = 0.71-0.89, relative variance of yields are $CV(RY_p)$ = 6.49-25.71%.
- Class 2: The main limiting factor is the unfavourable moisture regime because of the lower topographical position and heavy texture. The soil organic matter content is less than 3%, and the A-horizon is less than 30-60 cm. Expected relative yields are $\overline{RY_p}$ = 0.46-0.63 relative variance of yields are $CV(RY_p)$ = 28.38-62.18%.
- Class 3: The natric horizon appears at depth of 25-50 cm, the moisture regime is unfavourable because of the heavy texture and sodification, but the pH and soluble salt are not a major limiting factors. Depth of A-horizon is typically 60-80 cm. Soil organic matter at cultuvated layer do not limite the yields and it is between 2.4 and 3.53%. Similar to Class 2 expected relative yields are $\overline{RY_p}$ = 0.39-0.66 relative variance of yields are $CV(RY_p)$ = 25.50-74.07%.
- Class 4: Chemical and physical soil conditions are strongly limiting, and it is not suitable for crop rotation. Currently, these soil units are under pasturing.

It is possible to develop a parametric land evaluation system using mathematical and statistical tools. The proper interpretation and integration of those "simple" parameters need specific and highly qualified expertise, due to the fact, that soil qualities can only be evaluated in context of the other qualities and the affecting natural factors. Beside this, their importance in the produced yields can be also different. But these parametric soil quality assessment methods are more suitable to land use planning and evaluation of relationship between soil conditions and yields than the 1-to-100 scale of the Hungarian soil quality value based on genetic soil taxonomy units.

4. NEW SCIENTIFIC RESULTS

1. I surveyed the soil conditions concerning crop rotation, and mapped the genetic soil types and properties in the research site in an East Hungarian region.
2. I developed an evaluation system for characterizing the expected yields and yield variability of parcels. I calculated mean relative yield and relative standard deviation, which standardize the variability of crop rotation and different meteorological conditions of years.
3. I verified that the Hungarian economic land evaluation value (aranykorona), which indicates the registered net income of landed property, was highly correlated with the expected yields of the parcels (R^2=0.561; $p<0.001$).
4. I verified that the relationship between the 1-to-100 scale of the Hungarian soil quality value and expected yield and yield variability is slightly. The reason is that this traditionan Hungarian soil quality evaluation system probably overestimate the importance of the salinization, sodification and chemical conditions.
5. I developed linear soil quality indices based on simple soil indicators by using principal component analysis, which indicate the risks for crop rotation on a relative scale. The first principal component derived from the physical and chemical indicators was highly correlated with the Hungarian soil quality value.
6. Simple pedological indicators can not explain the expected yield and yield variability in themselves, but they can effectively explain the yield together with other indicators as their linear combinations. The principal component regression process is a successful method to reveal the site specific relationship between soil properties and yields at local level.
7. I developed soil suitability indices based on nonlinear interpretation and integration of simple soil indicators, which characterize the physical, chemical and fertility conditions, and their limitation. The integrated soil suitability index explained more than the Hungarian soil quality values and the linear indices (principal components) did.
8. By using the linear and nonlinear indices, I identified the main soil limitation factors, their relative importance, and the minimum data set of indicators at the research site. Based on nonlinear physical, chemical, and fertility indices I defined and mapped four agricultural soil suitability classes at the research site.

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