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Soil quality assessment using SAS (Soil Assessment System)

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Abstract: The paper proposes a new soil evaluation system using the principle of the Saaty method. The Saaty method has been modified and named Soil Assessment System (SAS). Significance weights are assigned to individual soil characteristics (indicators). This provides a more detailed differentiation of the significance of the indicator on soil quality and a more accurate assessment, especially in marginal cases where the assessment by the methods used so far has not been fully conclusive. In addition to physico-chemical properties, other criteria are taken into account to assess not only productional but also non-productional functions. The possibility of using indicators referring to a broader context (e.g., soil sealing value) is also important, thus enabling a comprehensive assessment of the quality of the land. This results in points for individual sampling locations. Soils are categorized according to the number of points and results are shown on maps.

Keywords: Saaty method; soil ecosystem services; soil protection; soil quality scoring; soil quality indicators

Soil conservation is a pressing challenge today and soil conservation is significantly related to soil assessment. Financially undervalued agricultural land makes it easy to speculate on land and convert it into construction land, where the market value is usually many times higher. There is a need to set up sustainable management of natural resources and to take a holistic approach to land decisions (Herrick 2000; McBratney et al. 2014; Janků et al. 2022).

According to Dominati et al. (2010), who analysed soils as stocks with a focus on their sustainable capacity, soils have different types of characteristics. Some of them can be influenced by human activities, while others cannot. For example, landscape slope, soil depth, cation exchange capacity and clay types can hardly be influenced by humans and are thus "soil-inherent", while soluble phosphate, mineral nitrogen, organic matter content, and others are

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shaped by human management practices and are thus called "soil-manageable properties". Similarly, Greiner et al. (2017), Drobnik et al. (2018), Vogel et al. (2018).

Assessment and evaluation of soil quality

Ecosystem services assessment and trade-off analysis provides new insights into spatial planning and decision-making at different administrative and spatial levels and in different sectoral policies. European and national policies should take into account the benefits provided by the ecosystems concerned and ensure that greater weight is given to the importance of ecosystem services in policy implementation (Veidemane 2019). Unfortunately, many benefits are still neglected since their value is very difficult to quantify in terms of finance (Bastian et al. 2012).

Soil quality frameworks designed for regional planning are rare. According to Drobnik et al. (2018), that concept divides soil quality using scores (the higher the better the soil) based on natural soil functions and anthropogenic soil degradation (landfills). The natural soil functions here are suitability for agriculture and plants, water retention and filter for polluting materials. The author then assigns the availability of soil quality points to municipalities for new urban areas. Many authors agree that several indicators of soil quality are needed if soil quality is to be implemented in decision-making processes in a meaningful way (Drobnik et al. 2018). The SQUID index uses the results of the Delphi survey to identify the contribution of the soil functions to ecosystem services (Drobnik et al. 2018).

The BOKS index was developed for application in the greater Stuttgart region in Southern Germany (Wolff 2006). It is based on a total of six attributes, which are used to characterize soil quality. Unlike many other soil quality indices, the BOKS considers both natural as well as anthropogenic factors that make up the final soil quality index. Four of the six attributes belong to natural factors – suitability for natural vegetation and cultivated crops, regulation of the water cycle, capacity for filtering and buffering contaminants and archiving cultural and natural history. The remaining two anthropogenic attributes include contaminated sites and level of soil sealing.

Soil quality assessment based on indicators has been published (Janků et al. 2022). The data of soil production and non-production functions were used. The specific values of the selected characteristics were then divided into three categories of good, medium and poor. The ranges of values and the respective categories were based on a similar assessment used in the EU URBAN Soil Management Strategy project (Kozák & Galušková 2010). In terms of economically quantifying the value of ecosystem services and the stocks of natural capital that produce them, this has been attempted by Costanza et al. (1997). They noted that the estimate of the economic value of ecosystem services is not complete because many categories of ecosystems and ecosystem services are not included due to data limitations. However, the results are comparable to Constanza et al. (1997), Frélichová et al. (2014).

The evaluation is mainly carried out using Multi-Criteria Analysis (MCA). Multi-Criteria Analysis is a method that is used when deciding between several alternatives, not allowing for multiple resulting alternatives at the same time, and the conclusion of the analysis should always be a single alternative.

Another possibility is using the Saaty method (Saaty 2003; Saaty & Vargas 2006). The Saaty method, also known as the analytic hierarchy process (AHP), is a general measurement theory concerned with the pairwise comparison of specified criteria and prioritization. The application of this method consists in comparing pairs of variables within a single matrix, where they are assigned numerical values from 1 to 9 according to their degree of importance (Saaty 2003; Saaty & Vargas 2006; Kudláč et al. 2017). The weights of each variable are then obtained from the matrix. Saaty's method is also suitable for analysing more complexly structured problems, and in such cases it is the aforementioned hierarchy that is used, which allows the comparison of individual factors within different levels (Saaty 2003; Saaty & Vargas 2006; Kudláč et al. 2017). Saaty's AHP method was also the basis for Šauer (2007), who described the use of multi-criteria analysis for assessing environmental quality. The aim in this case was to aggregate the qualities of individual environmental factors into a single number - an index - that would represent the quality of all of them together. The Delphi method is characterised as a method of dealing with a complex problem by a group of individuals using a structured group communication process. (Linstone & Turoff 1975). Delphi usually goes through four phases. The first phase involves exploring the issue and classifying relevant information. The second phase involves the process of expertly assessing this information, understanding it and commenting on its relevance, appropriateness and feasibility. In the third phase, significant disagreements between expert opinions are discussed and their causes are identified. In the last

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stage, a final assessment is produced in which, after analysing the information gathered, a further assessment is made (Linstone & Turoff 1975).

METHODS

The data of soil characteristics that were analyzed and used for further processing were obtained through the database of the Soil Geographic Information System of the Czech Republic PuGIS (texture, humus content, depth of soil horizon, pH_{H_2O}, pH_{KCl}, $CaCO_3$, P_2O_5, K_2O, base saturation (%) of sorption complex, cation exchange capacity (CEC). Data on soil hydrological groups and water retention capacity and BPEJ (Evaluated soil-ecological unit = Czech system for soil evaluation) data were extracted from the BPEJ code: climatic region, soil type, altitude, skelet content, geographical exposure, annual precipitation. Using the CORINE Land Cover 2012 landscape layer (land.copernicus eu 2018), ecosystem quality was determined. The purpose of the assessment was specified and defined as an assessment of the productive function of the soil, taking into account the basic non-productive functions. For this purpose, it was necessary to select an appropriate representation of physical, chemical, and other indicators of soil quality, which together formed a minimum data set (MDS). For the purpose of further data processing, three basic requirements for the indicators used for the assessment emerged. Data availability: the indicators must be commonly observed in soil sample analysis or in the measurement of other characteristics, or they must be universally detectable in field information systems. Within the dataset for a particular site being assessed, no indicator may be omitted, as this will degrade the result. Indicator relevance: the MDS must select those indicators that best indicate soil quality in line with the purpose of the assessment. Indicators must not be highly correlated with each other in order to avoid unintentionally influencing the result. The production group was further divided into variable (dynamic) and stable (static). Here the criterion was their relative stability in the environment. This division arose from the need for all groups at three hierarchical levels to enter the resulting equations for determining soil value independently: high variability indicators (variable), which are relatively easy to influence in the environment, and low variability indicators (stable), which exhibit high stability in the environment and do not change their values measurably under normal circumstances.

Soil data from two layers, namely 0.0–0.3 and 0.3–0.6 m depth, were selected for evaluation by the Soil Assessment System (SAS) metric. The two layers were evaluated separately. To test the suitability of the method to assess soil quality, indicators were selected and divided into production and non-production indicators. The production group was further divided into variable (dynamic) and stable (static). Here the criterion was their relative stability in the environment. This division resulted from the need for all groups at the three hierarchical levels to enter the resulting equations for determining soil value independently. Indicators with high variability (variable) the relatively easy to be influenced in the environment and Indicators with low variability (stable) thow high stability in the environment. The indicators and their distribution are shown in Figure 1.

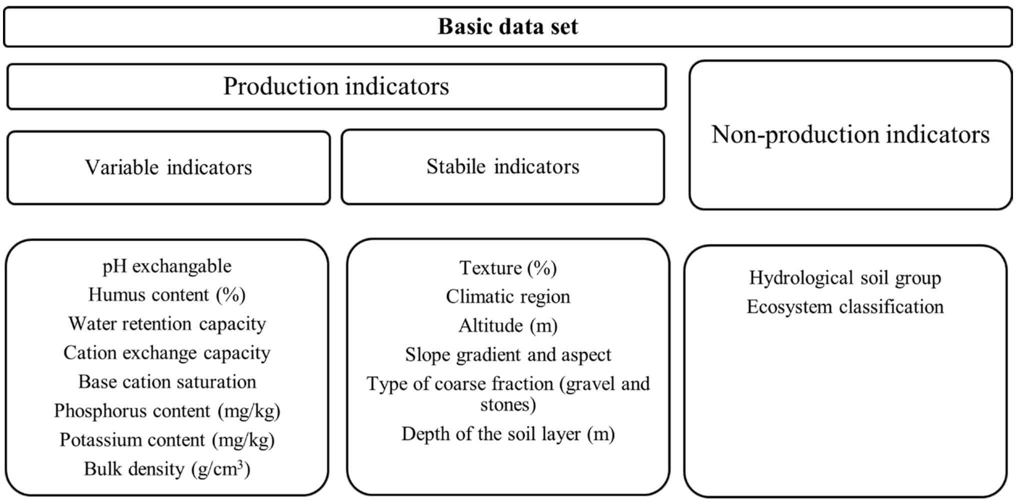

Figure 1. Distribution of indicators

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Subsequently, the measured data of the selected indicators were transferred to the scoring. Determination of reference values was performed according to (Sáňka et al. 2018). Categorization was performed and standardized on a scale of 1–10 points for all monitored indicators, where the value of 1 point always indicates the lowest quality of the indicator and the value of 10 points on the contrary the highest quality of the monitored indicator. The need to increase the rating grid to 10 categories arose during the course of the work in order to minimize value degradation, which is an unwanted part of the process when converting absolute measurement values into a point scale. Degradation is manifested by flattening of values, with a higher number of categories indicating a lower degree of flattening. In the case of exposure assessment, besides the orientation to the cardinal points, another distinguishing condition was the BPEJ affiliation to the climatic region. A so-called AHP matrix was constructed for each group of indicators. In the matrix, each indicator was compared in terms of its significance with each other, and the result of this pairwise comparison, after further calculations, was the determination of the significance value of the element or the weight of the indicator. The significance of the pairwise comparison could be rated by a number from 1 to 9 as shown in Table 1.

In each matrix, outside the cells of the main diagonal, the solver wrote values by expressing the importance of the row attribute before the column attribute as integers from 1 to 9. If the solver preferred the column element to the row element, he wrote the inverted weight value in the cell. A value of 1 was always written on the main diagonal, as this is where the same element is compared. Within the expert group, 4 tables were filled in by different solvers, the final table was created by averaging the resulting weight values of the sub-tables. The total according to the formula:

$$N = \frac{k(k-1)}{2} \quad (1)$$

where:
N – number of pairwise comparisons;
k – No. of criteria (indicators).

Each expert made 28 pairwise comparisons for production variable indicators, 15 pairwise comparisons for production stable indicators, and 1 pairwise comparison for non-production indicators. The developed matrices are included in the results. The weight of the i criterion (v) was then obtained by normalizing this geometric mean:

$$v_i = \frac{w_i}{\sum_{j=1}^{m} wj} \quad (2)$$

where:
w – relative significance (weight);
m – number of measured indicators;
j – j^{th} member.

The same procedure was used to develop two more Saaty matrices comparing the elements of the group of stable indicators and the group of non-stable indi-

Table 1. Basic scale of absolute values of pairwise comparisons

Bond strength	Description	Explanation
1	the same significance	two attributes of equal weight
2	weak significance	the two attributes have slightly different weights
3	middle significance	an attribute is judged as preferential over another
4	greater middle significance	this attribute is preferred over another based on judgment and experience
5	strong significance	the attribute is strongly preferred by judgment and experience over another
6	a bit stronger significance	according to judgment and experience, this attribute is more strongly preferred over another, indicating its dominance in practice
7	very strong or proven significance	the attribute is quite strongly preferred by judgment and experience over another, which gives proof for its dominance in practice
8	a bit more than strong significance	according to judgment and experience, this attribute is more strongly preferred over another, indicating its dominance in practice
9	extreme significance	evidence that favours one attribute over another has the highest possible conclusiveness

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cators. For the purposes of further data processing, three basic requirements for the indicators used for the assessment emerged. Availability of data, completeness of data – no indicator must be omitted within the dataset for a particular assessment site, as this will invalidate the result, significance of indicator. Indicators must not be highly correlated with each other to avoid unintentional bias in the result. Within these options, the criteria were paired in terms of their relevance to the soil value being measured. Pairs of criteria were compared and scored on a scale of 1 to 9 according to their difference in importance, with a value of nine indicating the greatest importance. Each pairwise comparison contains a numerical value assigned to the criterion that was judged to be more important within the soil and its inverse, which in turn was assigned to the criterion with less importance. In this way, a matrix was created that could be used to calculate the weights of each criterion using the geometric mean.

$$\bar{x}_G = \sqrt[n]{x_1.x_2. \ldots .x_n} \quad (3)$$

The geometric mean was calculated separately for each criterion, and the individual means were then added together to obtain the sum. The formula below was used to calculate the weights.

$$\frac{\bar{x}_{Gn}}{\sum \bar{x}_G} \quad (4)$$

The following conditions applied to the calculated weights. The sum of all weights must be equal to 1. The weights of each criterion must correspond to their importance as determined in the previous step. In the next step, the weights determined were expressed as a percentage. The importance of the generally variable and constant criteria was also compared. Variable criteria were assessed as more important and given a weight of 60%, constant criteria a weight of 40%. In the same way, production and non-production functions were compared – 95% production, 5% non-production. The evaluation of the indicators was carried out according to Sáňka et al. (2018). The categorization was carried out and standardized on a scale of 1–10 points for all the monitored indicators, where the value of 1 point always meant the lowest quality of the indicator and the value of 10 points on the contrary the highest quality of the monitored indicator. The need to increase the rating grid to 10 categories arose during the course of the work to minimize value degradation, which is an unintended part of the process when converting absolute measurement values into a point series. Degradation is manifested by flattening of values, with a higher number of categories indicating a lower degree of flattening.

In the case of the phosphorus and potassium assessment, the added condition was the type of agricultural land (arable land/permanent grassland). In the case of the potassium assessment, the soil type (light/medium/heavy) was also taken into account. In the case of the exposure assessment, besides the orientation to the cardinal direction, another distinguishing condition was the affiliation of the evaluated land ecological unit (BPEJ) to the climatic region. Evaluation of indicators in points is shown in Table 2.

The assigned points were then multiplied by the calculated weights of each parameter. The resulting scores for each parameter were summed and multiplied by the weight of either the variable or constant criteria, as well as their total weight and the production function weight. This produced an overall score for a particular soil block.

$$b_s = (v_1 + v_2 + \ \ + v_n) \times n_i \times 0.4 \times 0.95 \quad (5)$$

$$b_p = (v_1 + v_2 + \ \ + v_n) \times n_i \times 0.6 \times 0.95 \quad (6)$$

where:

b_s – productive function for soil block (for constant (stabile) criteria);

b_p – productive function for soil block (for variable criteria).

The same procedure was then applied to assess the non-productive functions of the soil. Two criteria were selected - soil hydrological group and ecosystem quality. These criteria were again evaluated, and their weights were calculated using the geometric mean. Multiplying the weights by the assigned scores of the two criteria then produced a score for the non-productive soil function, which was further multiplied by the weight for the non-productive function. Since two horizons are evaluated in this paper, the score was multiplied by two more for both horizons.

$$b_m = (v_1 + v_2) \times n_i \times 0.05 \times 2 \quad (7)$$

where:

b_m – non-production function for soil block.

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Table 2. Evaluation of indicators in points

		Points									
		1	2	3	4	5	6	7	8	9	10
Variable indicators											
pH exchangeable		< 4.00	4.00–4.49	4.50–4.99	5.00–5.49	5.50–5.99	6.00–6.49	6.50–6.69	6.70–6.79	6.80–6.99	7.00–7.10
pH exchangeable		> 7.99	7.80–7.99	7.70–7.79	7.60–7.69	7.50–7.59	7.40–7.49	7.30–7.39	7.20–7.29	7.11–7.19	–
Humus content		< 0.50	0.50–0.99	1.00–1.49	1.50–1.89	1.90–2.29	2.30–2.69	2.70–2.99	3.00–3.99	4.00–4.99	> 4.99
Water retention capacity				4		3	2				1
Base cation saturation (%)		< 20.00	20.00–29.99	30.00–39.99	40.00–49.99	50.00–59.99	60.00–69.99	70.00–70.99	80.00–89.99	90.00–94.99	95.00–100.00
Cation exchange capacity		< 7.00	7.00–9.99	10.00–12.99	13.00–15.99	16.00–18.99	19.00–20.99	21.00–23.99	24.00–26.99	27.00–29.99	> 29.99
P (P_2O_5)	arable land	< 50.00	50.00–64.99	65.00–79.99	80.00–94.99	110.00–134.99	135.00–144.99	145.00–164.99	165.00–184.99	> 184.99	
	permanent grassland	< 25.00	25.00–36.99	37.00–49.99	50.00–62.99	76.00–89.99	90.00–109.99	110.00–129.99	130.00–149.99	> 149.99	
K (K_2O)	arable land, light soil	< 100.00	100.00–129.99	130.00–159.99	160.99–199.99	200.00–237.99	238.00–274.99	275.00–309.99	310.00–344.99	345.00–379.99	> 379.99
	arable land, medium soil	< 105.00	105.00–137.99	138.00–169.99	170.00–218.99	219.00–264.99	265.00–309.99	310.00–346.99	347.00–382.99	383.00–419.99	> 419.99
	arable land, heavy soil	< 170.00	170.00–214.99	215.00–259.99	260.00–289.99	290.00–319.99	320.00–349.99	350.00–402.99	403.00–455.99	456.00–509.99	> 509.99
	permanent grassland, light soil	< 70.00	70.00–109.99	110.00–149.99	150.00–179.99	180.00–209.99	210.00–239.99	240.00–276.99	277.00–312.99	313.00–349.99	> 349.99
	permanent grassland, medium soil	< 80.00	80.00–119.99	120.00–159.99	160.00–189.99	190.00–219.99	220.00–249.99	250.00–299.99	300.00–349.99	350.00–399.99	> 399.99
	permanent grassland, heavy soil	< 110.00	110.00–159.99	160.00–209.99	210.00–239.99	240.00–269.99	270.00–299.99	300.00–356.99	357.00–413.99	414.00–469.99	> 469.99
Bulk density		> 1.80	1.80–1.61	1.60–1.51	1.50–1.46	1.45–1.41	1.40–1.36	1.35–1.31	1.30–1.26	1.25–1.20	< 1.20
Stabile indicators											
Texture (% of clay < 0.01 mm)			0.00–4.99	5.00–9.99	10.00–14.99		15.00–19.99	20.00–24.99	25.00–29.99		30.00–34.99
Texture (% of clay < 0.01 mm)		75.00–100.00	65.00–74.99	60.00–64.99	55.00–59.99	50.00–54.99	45.00–49.99	40.00–44.99		35.00–39.99	
Climatic region		9	8	7	6	5	4	3	2	1	0
Depth of the soil layer (m)		0.00–1.99	2.00–4.99	5.00–9.99	10.00–14.99	15.00–19.99	20.00–24.99	25.00–29.99	30.00–34.99	35.00–39.99	> 39.99
Coarse fraction			9	8		3, 4, 6			2, 5	1, 7	0
Slope inclination		8, 9		6, 7		4, 5			1, 2, 3		0
Aspect	climatic region 0, 1, 2, 3, 4, 5 (south – negative)	2, 4, 6, 8								0, 1, 3, 5, 7, 9	
	climatic region 6, 7, 8, 9 (north – negative)	3, 5, 7, 9								0, 1, 2, 4, 6, 8	
Non-production indicators											
Ecosystem quality						arable land					permanent grassland
Hydrological soil group		D		C		B					A

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RESULTS

In the district of Příbram, 67 soil pits were selected and the dataset of individual measured properties was complete. Production indicators, both variable and stable, were assessed at two depths 0.0–0.3 and 0.3–0.6 m and their point value was determined; non-production indicators and their point value was determined. Then, the total soil value expressed as a cumulative number of points was calculated. For each section, maps were prepared to show the geographical location of the probes and the number of points divided into five categories. Variable indicators describe properties that are dynamic and relatively easy to change in the soil. The development of the Saaty pairwise comparison matrix resulted in the assignment of weights (importance) to each indicator. As can be seen from Table 3, humus content of the soil received the highest importance among the group of variable indicators, with a weight expressed as 30.8%. The next indicator with a great influence on the evaluation was bulk density with 19.8%. Water holding capacity and base saturation were evaluated as two elements with the same influence of 13.1% on the soil value. 10.6% was obtained for cation exchange capacity. The influence of pH exchange reaction was expressed by 5.5% and less than 4 % by phosphorus and potassium content.

Design of the SAS soil assessment system – description of the process. The data were processed using Microsoft Office Excel (Ver. 64 bit, 2013), which can be used to evaluate the data using the Saaty method including the calculation of weights. For all indicators, a scoring scale from 1 (worst) to 10 (best) was established, as they cannot be added to the Saaty method in their original units but must be established dimensionlessly in order to work with them further. A scale of optimal criterion values was used to score each indicator. As a result, tables for variable and stable indicators of soil production functions and tables for non-productive soil functions are presented (Tables 3–5). Using our SAS (modified Saaty's pairwise comparison matrix), weights for indicators on a scale from 1 to 9 were determined. The larger the number/correlation of the pairs, the more important the indicator. The indicators were compared with each other.

Table 3. Matrix of variable indicators of soil production function

	pH exchangeable	Humus content	Water retention capacity	Base cation saturation	Cation exchange capacity	Bulk density	P	K
pH exchangeable	1	1/5	1/2	1/3	1/5	1/5	3	3
Humus content	5	1	3	4	3	2	5	6
Water retention capacity	2	1/3	1	1	3	1/2	4	3
Base cation saturation	3	1/4	1	1	2	1/2	4	4
Cation exchange capacity	5	1/3	1/3	1/2	1	1/2	4	4
Bulk density	5	1/2	2	2	2	1	4	4
P	1/3	1/5	1/4	1/4	1/4	1/4	1	2
K	1/3	1/6	1/3	1/4	1/4	1/4	1/2	1
Total	21.67	2.98	8.42	9.33	11.70	5.20	25.50	27.00

Table 4. Matrix of stable indicators of soil production function

	Texture	Climatic region	Depth of the soil layer	Coarse fraction	Aspect	Slope gradient
Texture	1	3	3	5	7	7
Climatic region	1/3	1	2	3	5	5
Depth of the soil layer	1/3	1/2	1	2	5	5
Coarse fraction	1/5	1/3	1/2	1	1	3
Aspect	1/7	1/5	1/5	1	1	1
Slope gradient	1/7	1/5	1/5	1/3	1	1
Total	2.15	5.23	6.90	12.33	20.00	22.00

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Table 5. Matrix of soil non-productive function indicator matrix

	Hydrological soil group	Ecosystem quality
Hydrological soil group	1	5
Ecosystem quality	1/5	1
Total	1.2	6.0

For each column of indicators, the sum and geometric mean for each row was calculated (this is not a weight). From the sum of the geometric means of all rows and the individual geometric means, the weights were calculated (Tables 6–8).

Points were assigned for all production indicators of soil function, which were split for values from 0.0 to 0.3 m soil depth and from 0.3 to 0.6 m soil depth, and points were also assigned for non-production values, which were not further split. The indicator variables include soil production functions.

The strength of the 1st and 2nd layer is determined separately in the scoring. The determination of the ratio of variable and stable indicators expresses the production function of the soil. It is important to determine the ratio of the variable and stable indicators to be taken into account. In the case of the work, the indicators are in the ratio of 60% stable to 40% variable and this ratio has been determined by the research team. Determining the ratio of the indicators of the productive and non-productive functions of the soil is an important step in determining the final points of the total value of the soil, the ratio between the indicators of the productive and non-productive functions of the soil needs to be determined. In the case of the work, this is a ratio of 95% of the productive to 5% of the non-productive soil function, which has been established by a team of soil scientists. If the scores for the values and weights for each indicator are established, the overall score can be calculated. The scores are calculated separately for productive and non-productive soil functions. For the soil production function, separate scores are calculated for variable and stable indicators from 0.0 to 0.3 m depth and for indicators from 0.3 to 0.6 m depth. The resulting scores were calculated for the following groups:

– Production variable indicators in depth from 0.0 to 0.3 m
– Production variable indicators in depth from 0.3 to 0.6 m
– Production stable indicators in depth from 0.0 to 0.3 m
– Production stable indicators in depth from 0.3 to 0.6 m
– Total score of production indicators (variable + stable) in depth from 0.0 to 0.3 m
– Total score of production indicators (variable + stable) in depth from 0.3 to 0.6 m
– Total score of non-production indicators
– Total land value (productive + non-productive land functions)

Table 6. Calculation of geometric means and weights for variable indicators of soil production function

	Geometric mean	Weight of variable	%
pH exchangeable	0.575304	0.055435	5.5
Humus content	3.192846	0.307654	30.8
Water retention capacity	1.364262	0.131456	13.1
Base cation saturation	1.364262	0.131456	13.1
Cation exchange capacity	1.104965	0.106471	10.6
Bulk density	2.056571	0.198165	19.8
P	0.388676	0.037452	3.7
K	0.331169	0.031910	3.2
Total	10.378055	1.000000	100.0

Table 7. Calculation of geometric means and weights for stable indicators of soil production function

	Geometric mean	Weight of variable	%
Texture	3.607736	0.429125	42.9
Climatic region	1.919383	0.228303	22.8
Depth of the soil layer	1.423868	0.169363	16.9
Coarse fraction	0.681292	0.081037	8.1
Aspect	0.422825	0.050293	5.0
Slope gradient	0.352079	0.041878	4.2
Total	8.407183	1.000000	100.0

Table 8. Calculation of geometric means of indicators of non-productive soil function

	Geometric mean	Weight of variable	%
Hydrological soil group	2.236068	0.833333	83.3
Ecosystem quality	0.447214	0.166667	16.7
Total	2.683282	1.000000	100.0

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Formulas for calculating the soil production function.

Production variable indicators = ($P_1 \times V_1 + P_2 \times V_2 +$ + ... $P_n \times V_n$) × total number of indicators (production + nonproduction soil functions) × ratio of variable/stable indicators × ratio production soil functions/nonproduction soil functions (8)

where:

P_1 – variable indicator point;

V_1 – weight of variable indicator.

Production stable indicators = ($S_1 \times V_1 + S_2 \times V_2 +$ + ... $S_n \times V_n$) × total number of indicators (Production + nonproduction soil functions) × ratio of stable/variable indicators × ratio of production soil functions/nonproduction soil functions (9)

where:

S_1 – stable indicator point;

V_1 – weight of stable indicator.

Total point score of production soil functions = variable indicators + stable indicators (10)

Formulas for calculating nonproduction soil functions.

Total point score for nonproduction soil functions = ($S_1 \times V_1 + S_2 \times V_2 +$ ... $S_n \times V_n$) × total number of indicators (production + nonproduction soil functions) × ratio of nonproduction soil functions/production soil functions × 2 (11)

At the end, the ratio is multiplied by two because production functions contain two categories – variable and stable indicators.

Formula for calculating total soil values.

Total soil value is total score of production for depth 0.0–0.3 m + total score production for depth 0.3–0.6 m + total score of nonproduction (12)

From the obtained points for production and nonproduction soil functions maps were created. ArcGIS version 10.4 was used to create the maps. Resulting points for both Production and nonproduction functions are shown in the vicinity of the soil probes within a 1 km radius, using intervals of the resulting points and a colour scale. Different intervals were created for each map based on the result points (Table 9).

Table 10 shows the scores for each probe that were calculated for the variable indicators group. The assessment was conducted at two depths, 0.0–0.3 m and 0.3–0.6 m The score variable column represents the total score of the production variable indicators group for both layers. It is not a simple sum of points, the resulting score has been multiplied by the weight of the indicator and the weight of the production variable indicators group within the production indicators group. The

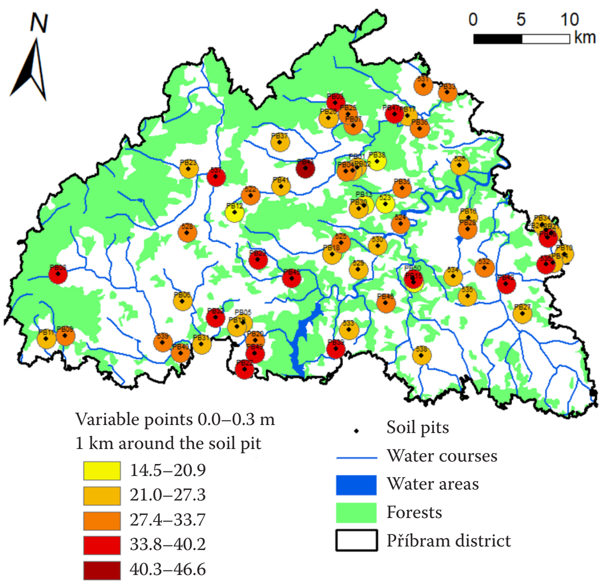

Figure 2. Resulting points for the Production function of the soil (variable indicators)

Table 9. Values for creating result point intervals for map creation

Score non-production	Score variable		Score stabile		Total score		Resulting soil value
	0.0–0.3 m	0.3–0.6 m	0.0–0.3 m	0.3–0.6 m	0.0–0.3 m	0.3–0.6 m	
2.7	14.5	14.8	42.6	37.1	64.9	61.9	141.7
5.3	20.9	20.7	50.5	46.7	75.8	73.4	162.5
8.0	27.3	26.6	58.3	56.3	86.8	84.9	183.3
10.7	33.7	26.7	66.2	65.8	97.7	96.4	204.2
13.3	40.2	26.8	74.0	75.4	108.6	107.8	225.0
16.0	46.6	26.9	81.9	85.0	119.6	119.3	245.8

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Table 10. Evaluation variable indicators (10 examples from 67 of the probes examined; soil layer depth in m)

Probe No.	pH exchangeable		Humus content		P		K		Cation exchange capacity		Base cation saturation		Water retention capacity	Bulk density		Score of variable indicators	
	0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6		0.0–0.3	0.3–0.6	0.0–0.3	0.3–0.6
PB01	7	6	3	2	1	1	1	1	4	5	7	7	3	6	6	26	25
PB02	5	5	3	2	1	1	5	2	5	5	6	7	5	5	5	27	25
PB03	10	10	3	2	7	7	2	2	4	5	8	8	10	5	5	34	33
PB04	8	7	5	3	1	1	5	5	5	5	7	7	6	4	5	32	29
PB05	4	5	4	2	1	1	2	1	4	5	5	6	3	5	6	24	24
PB35	6	6	3	2	1	1	1	1	6	7	7	8	6	6	6	30	29
PB36	5	5	4	3	1	9	3	2	8	7	7	7	6	6	7	33	33
PB37	6	5	3	2	1	1	2	1	4	4	7	8	6	4	5	26	26
PB38	4	5	3	2	1	1	1	1	2	2	4	5	6	2	2	19	18
PB39	10	10	7	4	1	1	1	1	7	6	8	8	5	3	3	35	29

maximum theoretically possible number of points scored in the variable indicators group was 61, the minimum was 6.

The resulting points for the production function of the soil at a depth of 0.0–0.3 m are shown in Figure 2.

Stable indicators represent important soil properties that do not change much over time. A Saaty table pairwise comparison was also developed to determine the significance of stable indicators. The most significant property is texture with a weight of 42.9%. The matrix of stable indicators for determining the weights is presented in Table 11.

Table 12 shows the number of points scored by the stable indicators at the probe site. The evaluation was performed as for the variable indicators at two layers depths. The score stable column expresses the total score of production variable indicators for each depth at a given location. As with the other indicator groups, this is not a simple totalling points; the resulting score was reduced by the indicator weight, the stable indicators group weight, and the production indicators group weight. The maximum theoretically possible number of points obtained in the variable indicators group was 91, the minimum was 9.

The resulting points for stable indicators at 0.0 to 0.3 m depth are shown in Figure 3. Figure 4 shows the resulting points for the soil production function for both variable and stable indicators.

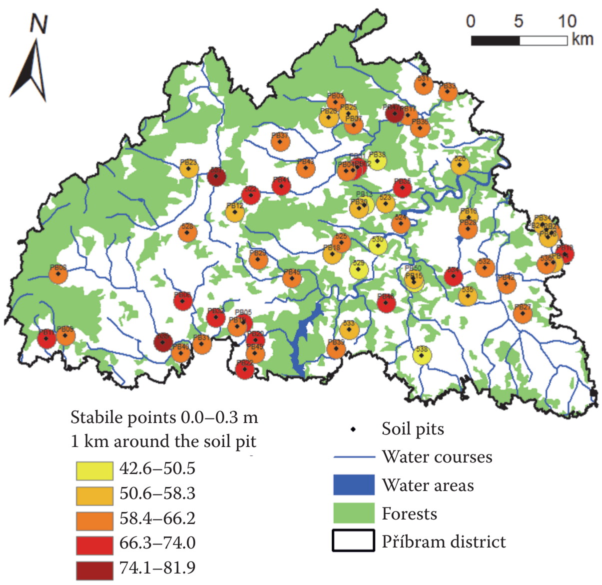

Figure 3. Resulting points for stable indicators at a depth of 0.0–0.3 m

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Table 11. Matrix stable indicators for determining weights

Saaty matrix of pairwise comparison – variable indicators							Calculation of importance evaluation		
Variable indicators	texture	climatic region	depth of the soil layer	coarse fraction	aspect	slope gradient	geometric mean	weight	weight %
Texture	1	3	3	5	7	7	3.608	0.429	42.9
Climatic region	1/3	1	2	3	5	5	1.919	0.228	22.8
Depth of the soil layer	1/3	1/2	1	2	5	5	1.424	0.169	16.9
Coarse fraction	1/5	1/3	1/2	1	1	3	0.681	0.081	8.1
Aspect	1/7	1/5	1/5	1	1	1	0.423	0.050	5.0
Slope gradient	1/7	1/5	1/5	1/3	1	1	0.352	0.042	4.2

Nonproduction indicators extend the evaluation to include ecosystem services of the land that are not related to primary production. The hydrological soil group is the most important with a weight of 83.3% and the importance of ecosystem quality is expressed by the remaining 16.7%. The matrix of nonproduction indicators for determining the weights is presented in Table 13.

Table 14 shows the number of points scored by the stable indicators at the probe site.

For the group of non-production indicators, the indicator score was multiplied by the indicator weight and reduced by the weight of the non-production indicator group. The maximum theoretically possible score obtained in the variable indicator group was 16, the minimum was 2. The non-production score column shows the total score of the non-production indicator group, which averaged 9.1 points. Figure 5 shows the maps with the location of the probes and the scores of the non-production indicators.

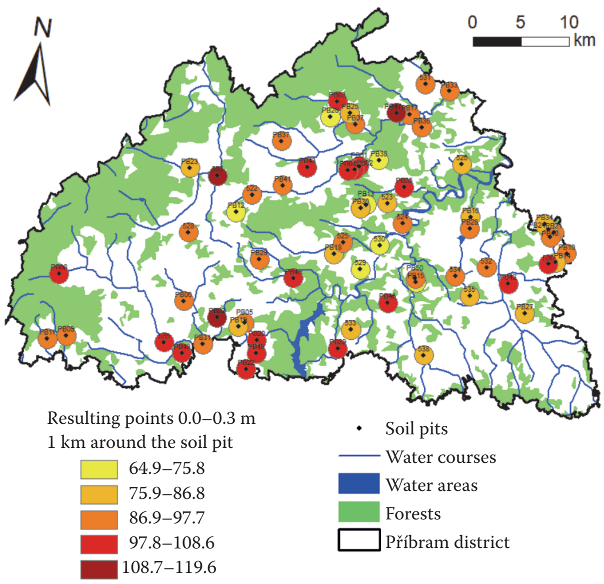

Figure 4. Resulting points for the Production function of the soil (variable and stable indicators)

Table 12. Evaluation stable indicators (10 examples from 67 of probes examined; soil layer depth in m)

Probe code	Texture		Climatic region	Depth of the soil layer		Coarse fraction	Slope gradient	Aspect	Score stabile	
	0.0–0.3	0.3–0.6		0.0–0.3	0.3–0.6				0.0–0.3	0.3–0.6
PB01	10	9	5	6	5	8	8	10	72	67
PB02	10	10	5	6	6	9	8	10	73	73
PB03	8	10	6	6	5	5	8	10	64	71
PB04	8	10	5	6	5	9	10	10	66	72
PB05	9	7	5	6	6	10	10	10	71	63
PB35	9	9	5	6	3	9	10	10	70	65
PB36	7	7	6	4	5	9	8	10	60	62
PB37	8	10	5	6	7	5	8	10	62	72
PB38	4	4	5	6	6	9	8	10	49	49
PB39	8	7	5	6	10	9	10	10	66	68

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Table 13. Soil Assessment System (SAS) matrix of nonproduction indicators for determining weights

Saaty matrix of pairwise comparison – non-production indicators			Calculation of importance evaluation		
Non-production indicators	hydrological soil group	ecosystem quality	geometric mean	weight	weight %
Hydrological soil group	1	5	2.236	0.833	83.3
Ecosystem quality	1/5	1	0.447	0.167	16.7

Table 14. Evaluation of nonproduction indicators (10 examples from 67 of probes examined)

Probe code	Hydrological soil group	Ecosystem quality	Score non-production	Probe code	Hydrological soil group	Ecosystem quality	Score non-production
PB01	3	5	**5**	PB35	10	5	15
PB02	10	5	15	PB36	10	10	16
PB03	10	10	16	PB37	3	5	**5**
PB04	3	5	**5**	PB38	3	5	**5**
PB05	3	5	**5**	PB39	3	5	**5**

Total soil value. The overall soil value represents the hierarchically highest level of assessment, which concentrates the results of the sub-assessments. The total soil value is expressed as the sum of the total scores of the production indicators at both depth layers 0.0–0.3 and 0.3–0.6 m plus the scores of the non-production indicator group. The total soil value is shown by the examples in Table 15. In theory, the maximum possible score is 320, the minimum is 32.

Table 15. Total soil value

Probe code	Resulting soil value	Probe code	Resulting soil value
PB01	195	PB35	209
PB02	212	PB36	204
PB03	217	PB37	191
PB04	204	PB38	142
PB05	187	PB39	204

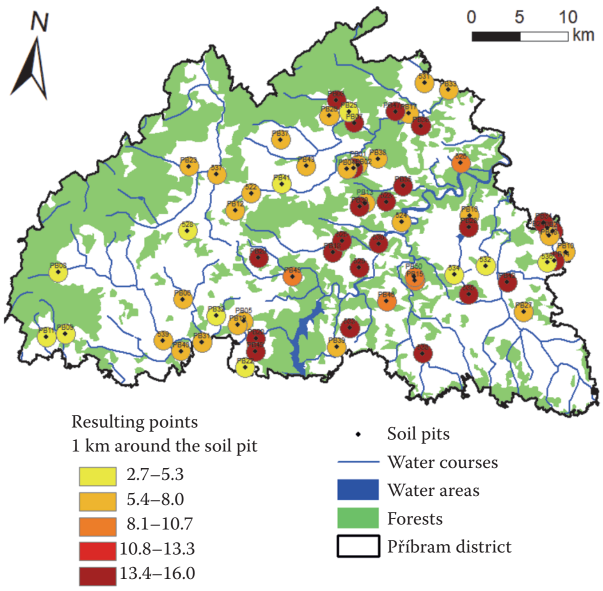

Figure 5. Total score nonproduction indicators

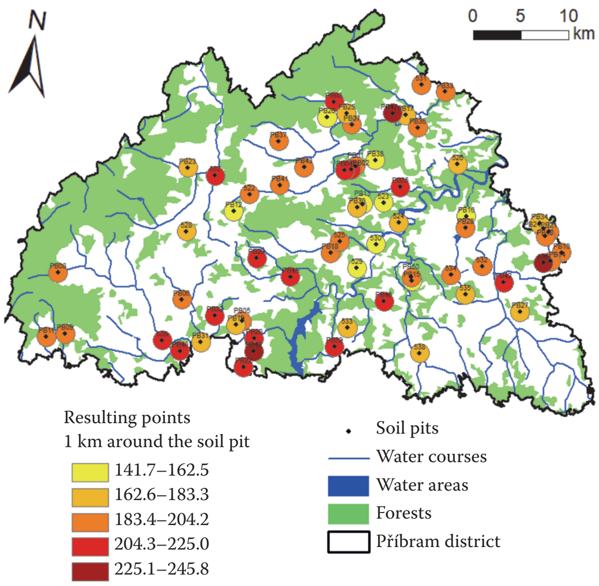

Figure 6. Score total soil values

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DISCUSSION

The aim of the work was to propose a way to assess soil quality as accurately as possible. Saaty's method was selected and modified for soil assessment and called Soil Assessment System (SAS). No similar approach to soil assessment has been proposed in the literature in the past. Methodologically, the closest approach is the one described by Šauer (2007) which combined elements of multi-criteria analysis with a standard procedure for creating indices, as described by, for example, Karlen et al. (2003). In Šauer's case, it combined elements of multi-criteria analysis with a standard procedure for creating indices, as described by, for example, Karlen et al. (2003). In Sauer's case, the goal was to aggregate the qualities of environmental factors into a single number, an index that would represent the quality of all of them together. In our case, several conditions were set to ensure the *y*-wide applicability of the proposed assessment method. This was subject to the selection of soil quality indicators. Indicators that are available were included in the assessment. In the course of the development of the work and on the basis of the results obtained, it was found that the use of the Saaty method brings several major advantages compared to other evaluation methods. First of all, this is a fact defined by the very nature of the pairwise comparison. Its principle lies in simplifying complex decisions. It is difficult to assess the significance of individual soil characteristics (factors) in the context of a complex environment of constantly occurring chemical, physical and biological processes. It is easier to assess the significance of individual characteristics in turn in direct comparison with the significance of all other indicators. Based on the individual pairwise comparisons, it is then possible to mathematically calculate how significant a soil factor is in the whole environment. Solving the problem on this basis greatly simplifies the situation where the determination of the significance of each indicator becomes more difficult as the number of indicators increases, as pointed out by Bünemann et al. (2018). It is evident that the SAS method brings a greater degree of objectivity to the soil assessment process, simplifies decision making on the significance of effects and allows aggregation of properties into a broad index, expressed as an overall soil value. There are critics of broad indices (Sojka & Upchurch 1999) who argue that a clear interpretation of each soil feature is more meaningful than deriving an overall index. Of course, these broad aggregations are only appropriate in the right context. They can inform about the reality of generally high or low quality soil. They could also be a means of assessing the value of soil. This would offer the possibility of a single point value and the sum of these would in effect represent the true value of the land in terms of price. From this, the price of land ecosystem services could then be derived, relative to the area unit of land and time. For such a valuation to be complete, other characteristics, including geographical, topological, cultural or socio-economic, would need to be included in the assessment of the group of non-productive indicators of soil quality. Consideration could be given to developing additional Saaty matrices of pairwise comparisons that would group the added indicators within the purpose of the group. These groups could be added or removed, with no change in the weights within the groups, only in the weights of the groups relative to each other. This flexibility may ultimately determine further development or use. Merrington (2006) points out that there are generally four places in the evaluation (indexing) process where the subjective influence of authors is applied. The first is the selection of the indicators themselves. Here, if appropriate analyses, logical sieves, etc. are performed, influence can be minimized. The second is the setting of indicator benchmarks. It is possible to start from existing generally chargeable reference values established, for example, by national soil assessment programmes, or to base them on the ranges of one's own measurements. Reference values are only valid for the area for which they have been established. The third is a function of the algorithm by which the index value is calculated. Often these values or functions are estimated by expert consensus (Bünemann et al. 2018). In the case of the research, part of Saaty's pairwise comparison method was used, which increases the level of objectivity by simplifying the decision-making process. Last is the interpretation of the results to the stakeholders. The whole evaluation process must be transparent and standardized Merrington (2006). The application of the method was tested in different soil and climate conditions to verify the sensitivity of the approach used. The expected differences were confirmed. In this way, the ability of the method to reflect differences in agricultural soils was verified. The capability of the SAS system was thus confirmed in practice. In the Czech Republic, the soil scoring system was developed by Němeček et al. (1985). The principle of determining soil value

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was to analyse the relationships between the yields of the main agricultural crops from which a point value was derived for the characteristics that entered the equation. The difference is that Němeček took into account the inherent productive capacity of the soil. It was not included in this assessment because the objective was to evaluate soil only on the basis of its primary ability to provide soil ecosystem services. It was not the intention to project the impact of the final ecosystem services already produced back to the means that enable them to be produced. Our approach also took into account essential non-productive functions. The Němeček´s scoring approach was also used by Novák et al. (1995) who modified the methodology for calculating the value of soil by scoring. In the methodology, the basic point values of the soil ecological units were adjusted for special types of areas such as degraded soils, reclaimed soils, erosion-prone soils, protected areas and others. Drobnik et al. (2018) developed a soil quality index (SQUID). Here, a five-level scoring scale was used to assess ecosystem services. The selection of indicators and determination of significance was done by expert Delphi method. In this way, the 10 most important soil functions and 16 linked ecosystem services were identified. The principle of determining the value of the SQUID index is to estimate the soil functions that benefit each ecosystem service. The estimates are multiplied by the weighted values of the factors determined by the experts. The values of the ecosystem services are averaged in the next step and the result is the SQUID index of that service. Janků et al. (2022) assessed the soils of the Central Bohemian Region using the scoring method. Twelve production and non-production characteristics were assessed and scored one to three points based on the quality or quantity achieved. The evaluation was carried out at two levels, firstly as an evaluation of the selected characteristics alone at two different profile depths and secondly as an evaluation of all characteristics together. This was achieved either by averaging the sum of all scores obtained at a site or by adding them together. The limitations of the method used are that both approaches to the overall soil assessment are limited both by the number of 3 categories and by the fact that the importance of each indicator was not distinguished from each other. The obtained soil grain composition (texture) score, which is one of the most important immutable soil properties, has here the same weight as the exchangeable pH, which is also an important property but relatively easy to influence.

CONCLUSION

The Saaty method was used to assess the soil quality, which was modified and named Soil Assessment System (SAS). The transfer of values was done through a scoring table in which the measurements of each indicator were rated in ten grades. The score of the indicator corresponded to the ranking in the scoring table. Sixteen indicators were included in the assessment, indicating the productive and non-productive characteristics of soil ecosystem services. These properties were summed in the result and expressed as a soil score. The indicators were divided into hierarchical groups within which they were paired according to their importance. Subsequently, the groups themselves were assessed in terms of significance. The highest level of assessment is the overall land value. This is the result of combining the scores of all subgroups. Two soil horizons at layers of 0.3 m and 0.3–0.6 m below the surface were considered. The functionality and sensitivity of the assessment was verified by comparing soils in the region with different conditions. It was found that the use of the pairwise comparison method simplifies the decision making on the significance of individual indicators and their groups in the environment. This brings more objectivity to the soil assessment system. The assessment design also allows for aggregation of other indicators or groups of indicators, which opens up possibilities for further development. In its current form, the established procedure already allows for a comprehensive assessment of soils in the Czech Republic in terms of productive and basic non-productive properties. In the future, it may become the basis for the creation of a tool that: monitors the condition of soil; expresses the real value of soil given by the valuation of the whole set of important ecosystem services; and enables adequate protection of the agricultural soil cover.

Agricultural production, its methods and management can in many cases shift the value of land towards a purely economic and agricultural use. However, soil assessment and the proposed methodology approach soil not only from an economic-agricultural perspective but from an environmental perspective. Soil is not only a factor of production, but also provides ecosystem services that must be included in the soil assessment system so that soil is protected in an optimal way.

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