Integrated index of agricultural soil quality in Slovakia

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\textbf{ABSTRACT}

On the basis of existing spatial databases and maps of soil parameters relating to production, environmental parameters and soil threats, indices of agricultural soil quality in Slovakia were developed and their distribution shown on maps. Existing maps of agricultural soil properties in vector format developed at the Soil Science and Conservation Research Institute in Bratislava were used. Unlike many quality evaluations of agricultural soils, the indices developed here take into account other parameters, not only production but also environmental and risk factors. The results show that in Slovakia 1.0\% of agricultural soils are of very high quality, 30.3\% are of high quality, 37.9\% are of medium quality, 30.5\% are of low quality and 0.3\% are of very low quality.

\textbf{1. Introduction}

An evaluation of soil quality in terms of its benefits to society is the basis for the formulation of land use strategies, especially for agriculture land, and regional development (Wytrzens, 1996), because soil can be included among capability factors for development (Robert, 1982). The issue of evaluating soil quality, including its functions and evaluation indicators, is the subject of extensive research, especially in the USA (Karlen, Ditzler, & Andrews, 2003).

Soil quality is the capacity to function within natural or managed ecosystem boundaries and to sustain plant productivity while reducing soil degradation (Doran, Coleman, Bezdicek, & Stewart, 1994; Karlen et al., 1997). Soil quality is a complex functional concept, and therefore cannot be measured directly in the field or laboratory (Stocking, 2003). The estimation of soil quality is based on derivations from soil characteristics (Diack & Stott, 2001).

Various mathematical and statistical methods are used for calculating the soil quality index (SQI) (Doran et al., 1994; Karlen et al., 1997). The estimation of SQI is a complex and complicated process (Bhardwaj, Jasrotia, Hamilton, & Robertson, 2011), especially when linked with several functional goals. Yet considerable progress has been made towards estimating SQI across a number of soil types and management practices (Andrews & Carroll, 2001; Andrews, Karlen, & Cambardella, 2004; Andrews, Karlen, & Mitchell, 2002; Andrews, Mitchell, Mancinelli, Karlen, & Hartz, 2002; Bhardwaj et al., 2011; Fernandes, Gamero, Rodrigues, & Mirás-Avalos, 2011; Mandal et al., 2011). Most studies have indexed soil quality using only one method, with a few exceptions (Andrews, Karlen & Mitchell, 2002; Zobeck, Halvorson, Wienhold, Acosta-Martinez, & Karlen, 2008). As the computation of SQI is complicated, it is important to develop a user-friendly and credible SQI using a combination of various available methods.

Until recently, the capacity to produce phytomass was the main indicator in assessing the quality of soils, and especially agricultural soils. The level of yields per hectare was one of the decisive factors in the evaluation of the agricultural landscape and a tool for economic stimulus. For this reason, the issue of production potential and influence of each soil parameter on yield is reviewed in some detail (Mukherjee & Lal, 2014). A range of scientific and vocational publications exist for conditions in the Slovak Republic in the fields of agriculture (e.g. Kováč et al., 2003; Kudrna, 1985; Špaldon, 1982), soil science (e.g. Bielek, 2008; Džatko, 1981; Hraško, 1985; Vilček & Bedrna, 2007), and geography (e.g. Bielek, 2008; Džatko, 1981; Hraško, 1985; Vilček & Bedrna, 2007).

We consider the soil, including agricultural soils, not only as a means of production (food, biomass and bioenergy) but also as a part of the natural environment where the pedosphere has functions other than food production (e.g. environmental filter, hydrological stabiliser, chemical reagent, accumulation of nutrients, pollutant transformation and environment for organisms) (e.g. Acton & Gregorich, 1995; Andrews et al.,...
2004; Blum, 1990; Karlen & Stott, 1994; Larson & Pierce, 1994; Yaalon and Arnold, 2000). In Slovakia, Jurán (2005), Bujnovský, Balkovič, Barančíková, Makovníková, and Vilček (2009), Vilček, Bujnovský, and Koco (2010), Vilček and Bujnovský (2014) and Barančíková, Koco, Makovníková, and Torma (2010) have also dealt with this issue. These authors define a minimum collection of soil indicators for sufficient assessment soil quality.

The goal of this contribution is to create a spatially identifiable integrated quality index of agricultural soils in Slovakia using geographic information systems (GISs) and based on available maps and spatial databases, productive and non-productive soil parameters and their potential threat.

2. Study area

Agricultural soils, which occupy 49.3% of the Slovak Republic (Figure 1), were assessed. The Slovak Republic is in a temperate climatic zone with regular seasons and a relatively even distribution of rainfall during the year. Altitude varies between 94 m a.s.l. and 2654 m a.s.l.

There is a high diversity of soil types, which is the result of varying geological, topographical and climatic conditions (Table 1).

Bielek (2014) divided soil types in Slovakia into nine groups based on a combination of information about average yields, slope and its exposition, stone content, depth of soil, soil texture and climate region coefficient. According to an assigned point value from 3 to 100, 9.2% is highly productive, 19.6% very productive, 20.0% productive, 7.9% medium productive, 13.0% less productive, 13.5% low productive, 9.6% very low productive soils, 5.2% is less suitable for agriculture and 2.0% is unsuitable soil.

Using an index of agricultural soils that assesses their ability to maintain environmental functions, Vilček and Bujnovský (2014) reported that in Slovakia 5.0% of soils have a very high index, 26.6% are high, 37.4% are medium, 27.2% are low and 3.8% are very low.

In Slovakia, 45% of agricultural soils are at risk by water erosion and more than 30% by compaction (Vilček & Zverková, 2015).

3. Data and methods

When generating indices and agricultural soil quality maps, we assessed their production, non-production (environmental) parameters and parameters threatening their stability. These parameters were derived from the databases and vector maps of the Soil Science and Conservation Research Institute in Bratislava and integrated according to the flow chart in Figure 2.

The vector layers used for this analysis come from databases of soil-ecological units (Džatko, 1996) that contain information about soil parameters (soil type and texture, slope and aspect, stone content, climatic

Figure 1. Location of Slovak Republic.
region and soil depth). Data about environmental parameters contain additional information such as bulk density, organic matter, average precipitation and temperature, and pH (Bujnovský et al., 2009). The smallest spatial unit is a polygon with an area of 1 hectare. Tiny sliver polygons resulting from the spatial intersection approach were found and fixed using tools of check and repair geometry in GIS.

3.1. Soil parameters related to production

Soil parameters related to production were obtained from maps and databases and each agricultural soil type was assigned a value within a range of 0–100 points (Džatko, 2002), where 100 points indicate the most productive soils. Point value is the sum of points assigned to the average yield of crop production according to soil type (0–60 point), slope and its aspect (0–15 points), stone content and soil depth (0–15 points) and soil texture (0–10). Values were categorised into five groups (range of 20 points) and a value index was assigned as follows (min = 3 and max = 100 points):

Table 1. Soil types in Slovakia (Vilček & Zverková, 2015).

| Location and soil types | Percent of agricultural land |
|-------------------------|------------------------------|
| Lowlands and hilly lands|                              |
| Chernozems              | 11.3                         |
| Mollic Fluvisols        | 7.4                          |
| Fluvisols               | 14.3                         |
| Gleysols                | 19                           |
| Hills lands             |                              |
| Cutanic Luvisols        | 9.9                          |
| Regosols                | 5.4                          |
| Planosols               | 7.4                          |
| Foothill lands          |                              |
| Cambisols               | 34.2                         |
| Rendzic Leptosols       | 4.1                          |
| Mountains               |                              |
| Podzols                 | 0.1                          |
| Lithic and Haplic Leptosols | 0.3               |
| Others                  |                              |

| Andosols                | Minor areas                  |
| Solonchaks              | Minor areas                  |
| Solonetzs               | Minor areas                  |
| Vertisols               | Minor areas                  |

Figure 2. Flow chart for integrating indices and compiling agricultural soil quality maps.
3.2. Environmental parameters of soils

For non-productive (environmental) parameters of soils, the following were used:

Potential accumulation of water in soil was obtained from maps and databases (Vilček & Bujnovský, 2014). The database was divided into five groups as follows (min = 57.2 mm and max = 683.28 mm):

- very high ability to accumulate water (water capacity more than 400 mm) – index 1
- high ability to accumulate water (water capacity 300–400 mm) – index 2
- medium ability to accumulate water (water capacity 200–300 mm) – index 3
- low ability to accumulate water (water capacity 100–200 mm) – index 4
- very low ability to accumulate water (water capacity less than 100 mm) – index 5

Data on the potential soil immobilising risk elements were created from maps and databases based on the fusion of digital layers of the risk potential element concentration and a layer of sorption potential (Makovníková, Barančíková, Dlapa, & Dercová, 2006). This gives the possibility of risk elements (for example, heavy metals) penetrating the food chain or groundwater. This parameter has also been differentiated into five groups as follows:

- very high ability of soils to immobilise risk elements – index 1
- high ability of soils to immobilise risk elements – index 2
- medium ability of soils to immobilise risk elements – index 3
- low ability of soils to immobilise risk elements – index 4
- very low ability of soils to immobilise risk elements – index 5

We used a database of immobilisation indexes based on maps and databases of organic pollutants immobilising potential (Barančíková et al., 2010). This was categorised into five groups as follows (min = 1.87 and max = 18.78):

- very high ability of soils to immobilise organic pollutants (more than 14.36) – index 1
- high ability of soils to immobilise organic pollutants (10.12–14.35) – index 2
- medium ability of soils to immobilise organic pollutants (6.75–10.11) – index 3
- low ability of soils to immobilise organic pollutants (4.17–6.74) – index 4
- very low ability of soils to immobilise organic pollutants (less than 4.16) – index 5

The potential for soil to transform organic pollutants was derived from maps and databases. The transformation index for this parameter, calculated as the sum of biotransformation and abiotic transformation (Barančíková et al., 2010), was categorised into five groups (min = 18.66 and max = 79.87):

- very high ability of soils to transform organic pollutants (more than 46.36) – index 1
- high ability of soils to transform organic pollutants (38.40–46.35) – index 2
- medium ability of soils to transform organic pollutants (32.62–38.39) – index 3
- low ability of soils to transform organic pollutants (27.48–32.61) – index 4

Potential production of phytomass harvested on agricultural soils was derived from maps and databases (Vilček, 2006). Potential is expressed in dry mass per hectare and was divided into five groups as follows (min = 2.45 t ha⁻¹ and max = 14.83 t ha⁻¹):

- very high phytomass production (more than 14.00 t ha⁻¹) – index 1
- high phytomass production (12.01–14.00 t ha⁻¹) – index 2
- medium phytomass production (10.01–12.00 t ha⁻¹) – index 3
- low phytomass production (8.01–10.00 t ha⁻¹) – index 4
- very low phytomass production (less than 8.01 t ha⁻¹) – index 5

Potential production of bioenergy on agricultural soils was derived from maps and databases (Vilček, 2006, 2013, 2014). We divided the soil potential for bioenergy produce in GJ ha⁻¹ into five groups (min = 40.45 GJ ha⁻¹ and max = 300.00 GJ ha⁻¹):

- very high bioenergy production (more than 250 t GJ ha⁻¹) – index 1
- high bioenergy production (200.01–250.00 GJ ha⁻¹) – index 2
- medium bioenergy production (150.01–200.00 GJ ha⁻¹) – index 3
- low bioenergy production (50.01–150.00 GJ ha⁻¹) – index 4
- very low bioenergy production (less than 50.00 GJ ha⁻¹) – index 5
• very low ability of soils to transform organic pollutants (less than 27.47) – index 5

3.3. Parameters of soil threats

For soil threat parameters, the following were used:

Potential erosion threat of agricultural soils in Slovakia was derived from maps and databases based on USLE equation. Based on soil erosion hazard indicators, a database of spatial differentiation of threats by water soil erosion was created and was categorised into five groups as follows (min = 0.14 t ha\(^{-1}\) yr\(^{-1}\) and max = 92.98 t ha\(^{-1}\) yr\(^{-1}\)):

- soils without water erosion risk – index 1
- soils with low water erosion risk – index 2
- soils with medium water erosion risk – index 3
- soils with high water erosion risk – index 4
- soils with very high water erosion risk – index 5

Potential threats of agricultural soils in Slovakia by compaction were assessed from maps and databases. These maps were created on the basis of a combination of soil texture, depth of soil and content of stones. The primary basis for the categorisation of soils in this respect is the fact that the light soils (sandy and loamy sand), which are deep and without stones, are not threatened by compaction. However, very heavy soils (clayey and clay) are greatly threatened by compaction. As in the previous cases, this parameter was divided into the following five groups:

- soils not threatened by compaction – index 1
- soils with low threat by compaction – index 2
- soils with medium threat by compaction – index 3
- soils very strongly threatened by compaction – index 4
- soils with very high water erosion risk – index 5

Maps and databases of spatial differentiation of soil organic matter content were used. This parameter, represented by depth of humus horizon, has a big influence on soil stability. It is another sorting factor in the formation of the sum of the soil vulnerability index. For the purpose of this project, the depth of the soil humus horizon was differentiated into five groups as follows (min = 2 cm and max = 56 cm):

- soils with very deep humus horizon (more than 30 cm) – index 1
- soils with deep humus horizon (24–30 cm) – index 2
- soils with medium deep humus horizon (18–24 cm) – index 3
- soils with shallow humus horizon (12–18 cm) – index 4
- soils with very shallow humus horizon (less than 12 cm) – index 5

4. Mapping results and discussion

Identification and mapping of agricultural soil quality was carried out, based on categorisation of soil parameters contained in the databases and the map outputs, which constituted sources for the compilation of the final SQI map.

For the purposes of creating an integrated SQI, the following indices were created:

4.1. Index of production potential of agricultural soils in Slovakia

This parameter was created as an intersection of map layers identifying agricultural soils in terms of their point value indicating production ability of agricultural soils the potential production of phytomass and potential bioenergy production.

We obtained new layers using the following procedure:

We generated a layer of indices expressing the production potential of the soil in the form of a three-digit code. For example, code 132 identifies soils with a very high point value, medium potential for phytomass production and high potential for bioenergy production. Within Slovakia, 33 combinations of these parameters (different three-digit combinations) were created.

The production potential layer, expressed by integrated index, which was derived from the average of the point values, phytomass and energy production indices, is shown in Figure 3.

The proportion of individual categories from the total agricultural soils is as follows:

- very highly productive agricultural soils (index 1) – 15.3%
- highly productive agricultural soils (index 2) – 22.2%
- medium productive agricultural soils (index 3) – 24.0%
- low productive agricultural soils (index 4) – 15.0%
- very low productive agricultural soils (index 5) – 23.5%

4.2. Index of non-production potential of agricultural soils in Slovakia

This parameter was created as an intersection of map layers identifying agricultural soils in terms of their water accumulation potential, immobilisation of risk elements, immobilisation of organic pollutants and transformation of organic pollutants.

We obtained new layers using this procedure:

A layer of indices expressing the non-production potential of soils in the form of a four-digit code. For example, code 1235 identifies soils with a very high ability to accumulate water, high ability of soils to
Figure 3. Input data and resulting map of the spatial differentiation and variability of production potential of agricultural soils of Slovakia.

Figure 4. Input data and resulting map of the spatial differentiation and variability of non-production potential of agricultural soils of Slovakia.
immobilise risk elements, medium ability of soils to organic pollutants and very low ability of soils to transform organic pollutants. Within Slovakia, 493 combinations of these parameters (different four-digit combinations) were created.

The layer of non-production potential, expressed by the numerical integrated index, which was derived from the average of the partial indexes, is shown in Figure 4.

The resulting map expresses the spatial differentiation and variability of non-production potential of agricultural soils of Slovakia. The proportion of individual categories from the total agricultural soils is as follows:

- very high environmental potential of soils (index 1) – 1.0%
- high environmental potential of soils (index 2) – 22.9%
- medium environmental potential of soils (index 3) – 45.3%
- low environmental potential of soils (index 4) – 29.8%
- very low environmental potential of soils (index 5) – 23.5%

4.3. Index of the threat potential of agricultural soils in Slovakia

This parameter was created as an intersection of map layers identifying agricultural soils in terms of their potential water erosion threat, compaction and humus horizon stability.

We obtained new layers using this procedure:

A layer of indices expresses the potential threat of soil in the form of a three-digit code. For example, code 142 identifies the soil without water erosion risk, strongly threatened by compaction and with deep humus horizon.

The layer of potential threat of the soils is expressed by a numerical integrated index, derived from the average of soil risk indexes by erosion, compaction and organic matter content, is shown in Figure 5.

The resulting map expresses the spatial differentiation and variability of threat potential of agricultural soils of Slovakia. The proportion of individual categories from the total agricultural soils is as follows:

- soils with very low threat potential (index 1) – 4.0%
- soils with low threat potential (index 2) – 31.7%
- soils with medium threat potential (index 3) – 48.6%
- soils with high threat potential (index 4) – 15.4%
- soils with very high threat potential (index 5) – 0.3%

4.4. Index of agricultural soils quality

The final index of soil quality was created in the GIS environment by the intersection of the indices described above, while preserving an equivalence rule – that is, all rated parameters had the same weight.
The result is the following layers:

- Units are labelled with a three-digit code characterising the given unit in terms of production, non-production (environmental) potential and potential threat. For example, code 132 identifies very high productive soils with medium environmental potential and low threat potential.
- The integrated index was created as the average of values from the three-digit index while preserving the equivalence rule. The indices are as follows:
  - very high quality soils – index 1
  - high quality soils – index 2
  - medium quality soils – index 3
  - low quality soils – index 4
  - very low quality soils – index 5

Details of a particular area are presented in Figure 6 and the spatial identification of the integrated index of agricultural soil quality for the whole territory of Slovakia is documented in the main map.

Our resulting map of agricultural soil quality shows that only a very small proportion of soil in Slovakia can be considered to be of high quality (1.0%), and poor quality soil is in equally a small proportion (0.3%). Almost all soils fulfil either production or non-productive stabilising functions. Most (37.9%) are represented by soils classified as medium quality. High quality is 30.3% and low quality is 30.5% of agricultural soils.

Most high quality soils are in the lowlands and basins, which are mostly in the south of Slovakia.

The practical output from this project is the ability to obtain information about the quality of each agricultural soil in Slovakia.

5. Conclusions

A map of an integrated index of agricultural soil quality in the Slovak Republic was compiled from an analysis of soil parameters and map overlays. In addition to soil quality assessment for agricultural use, our approach also takes into account other functions of soils.

The methodological approach used here made it possible to reach these conclusions:

- In terms of agricultural production potential, 15.3% of soils in Slovakia are very high, 22.2% are high, 24.0% are medium, 15.0% are low and 23.5% are very low productive agricultural soils.
- In terms of environmental potential, 1.0% soils in Slovakia are very high, 22.9% are high, 45.3% are medium, 29.8% are low and 2.5% are very low.
- In terms of the potential for soil threat, 0.3% soils in Slovakia are very high, 15.4% are high, 48.6% are medium, 31.7% are low and 4.0% are very low.
- The resulting integrated index of agricultural soils quality in Slovakia indicates 1.0% very high quality, 30.3% high quality, 37.9% medium quality, 30.5% low quality and 0.3% very low quality of soils.

The maps allow the identification of the presented indices as well as the resulting SQI for each agricultural soil. The results are useful for agrarian landscape planning at specific sites as well as for the creation and optimisation of land use.

Software

The maps were compiled and edited using Esri ArcGIS 10.3. Calculations and statistical analyses of raster data sets were also performed in ArcGIS 10.3. The main graphics were created using Inkscape 0.92.1.

Disclosure statement

No potential conflict of interest was reported by the authors.

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