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Pedo-climatic predictions and reality of sunflower (*Helianthus annuus* L.) growing in Slovakia

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Abstract: This work aims to differentiate the rural land of Slovakia in view of the possibility of effective sunflower growing. The differentiation is based on pedo-climatic and production-economic parameters. Soil categorisation took into account the correlation between the site properties (soil and climatic conditions) and the biological and agrotechnical requirements of the crops. Sunflower requirements were included in yield databases using software filters such that a given site property excluded or limited sunflower growing, which was reflected in predicted production. The prediction was subsequently interpolated into four suitability categories: soils unsuitable for sunflower growing, less suitable soils, suitable soils and very suitable soils. A map of categories of soil suitability for sunflower growing was created using a Geographic Information System on the distribution of soil parameters in Slovakia. According to our calculation in Slovakia, 18.8% of farmland is very suitable for sunflower growing, 24.9% is suitable, 16.6% is less suitable, and 39.7% is unsuitable for sunflower growing. These categories are characterised and specified in detail in the paper in terms of geographical, soil, climatic, production and economic parameters. The analysis of the actual sowing of sunflowers between 2018 and 2021 showed that 51% of the areas were located in very suitable soils, 32% in suitable, 10% in less suitable soils and 7% in unsuitable soils for cultivation.

Keywords: oil crops; land potential; agricultural landscape categorisation

The sunflower (*Helianthus annuus* L.) has been used by American Indians since 3 000 B.C. Seiler and Gulya (2016) report that Ukraine is currently the largest producer of sunflower, followed by the Russian Federation, Argentina, China, France, etc. In the context of the ongoing situation in Ukraine, apart from the political aspects, the concern about the sufficiency of basic agricultural commodities on the world market is emerging as an issue. This undoubtedly includes the production and market for sunflowers. For this reason, individual countries are adopting strategies to compensate for a possible shortfall of this commodity. One possibility is to increase sowing and, therefore, the production of sunflowers on their land. Slovakia is no exception in this regard. What is important, however, is whether Slovakia has sufficient land suitable for efficiently growing sunflowers.

Annual sunflower has, especially since the beginning of the 1980s, seen a rapid increase in the area

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of crops sown in Slovakia. Currently, the crop is represented in the structure of agricultural land use in Slovakia in almost all regions. This fact is linked to its high adaptability to the environment and good implementation in the commodity market.

The Guinness Book of World Records lists the world's tallest sunflower, which grew to a height of 9.17 m in Germany in 2014. In Slovakia, the record was set in 2004 with a height of 5.1 m. This figure also shows that soil and climate conditions significantly influence successful sunflower cultivation. Merava (2021) states that yields of sunflowers in Slovakia per hectare are 10% to 15% above the EU average in the long term. According to her, sunflower production in Slovakia in 2021 reached 135 720 t; in the EU, it is around 8 863 000 t. In the world, about 57 130 000 t of sunflowers are produced. Our calculations show 7 kg of sunflower production per capita globally. In Bulgaria, it is 273 kg, in Ukraine up to 335 kg, but only 2 kg in China, for example. In Slovakia, there is 25 kg of sunflower per capita, which creates the preconditions for sunflower exports.

The suitability of the environment for sunflower cultivation is the subject of many publications with different perspectives. According to Hraško and Bedrna (1988), sunflower is drought-resistant and an important oilseed, especially in the drier areas of Slovakia. It is not very soil-demanding. In dry areas, it requires deep soils. Almost all the soils of Rye Island and adjacent parts of the Danube Plain are suitable for it. The optimum soil reaction range is 5.7–6.5 pH. Vilček and Bedrna (2007) state that sunflowers do not tolerate waterlogged soils, especially if they have reduced gley horizons in the lower parts of the soil profile, which the root system cannot grow through. According to Kandel et al. (2020), sunflower is adapted to different soil conditions but grows best on well-drained soils with high water holding capacity and near-neutral pH (pH 6.5–7.5). Sunflower can use a large rooting volume for soil water. Fields for sunflower cultivation should be selected from those with a higher water-holding capacity and from soils without layers that could restrict the roots. Water-holding capacity depends mainly on soil texture and soil depth. The loam, silt loam, clay loam and silty clay loam soils have the highest water-holding capacity.

Demo et al. (1998) argue that sunflower has no particular soil requirements. It thrives best on Chernozems, Mollic Fluvisols and Fluvisols. Waterlogged and very sandy soils are not suitable. Optimum pH is 6.0–6.8. Values of pH 4.7 to 5.3 reduce yield by more than 10% (Sutradhar et al. 2014). It does not tolerate high concentrations of salts well (Zeng et al. 2016), which is particularly evident during seed germination.

Similar characteristics are also reported by Kováč et al. (2003). The most suitable soils are considered to be loamy-sand and sandy-loam soils, black-earth and brown-earth types. Sunflower is a crop in arid regions. It is relatively thermophilic with a required total temperature range of 1 600–2 000 °C. It is considered a drought-tolerant crop.

Recently, there have been publications on the influence of soil physical parameters on sunflower biomass yield. Both Silva et al. (2021) and de Sousa Linhares et al. (2020) report that sunflower is particularly sensitive to soil compaction.

Despite a good knowledge base regarding the possibility of sunflower cultivation in Slovakia, the comprehensive characterisation of the pedological regionalisation of this crop has not yet been elaborated. This paper aims to correct this handicap at least partially and to try categorising agricultural soils according to their suitability for growing this interesting crop. The aim is also to highlight the current practice (reality) in selecting soils for sunflower cultivation.

Similar studies on the suitability and use of Slovak soils have been carried out for other crops described in this study (Vilček 2013, Vilček and Torma 2016, Koco et al. 2020).

MATERIAL AND METHODS

In categorising soils into areas suitable for sunflower cultivation, we have checked sentence our analysis on both exact and potential data on this crop. Since suitability for cultivation is assessed primarily by the actual production achieved, this factor played a decisive role in creating the categories. Specific data on yields and economic parameters of sunflower cultivation were obtained from more than 200 agricultural entities and data from the Statistical Office of the Slovak Republic.

Since successful sunflower cultivation's production and economic parameters are directly related to soil and climatic conditions, we analysed and specifically applied data on climatic regions of Slovakia, slopes, gravel content, soil depth, soil types or subtypes, soil point value and soil typology and production categories. These data were obtained from the information database of Soil Science and Conservation Research Institute (SSCRI) Bratislava on soils of Slovakia in

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vector form. The database characterises the categories and areal distribution of the mapped parameters of agricultural soils in the form of special-purpose soil units – the so-called bonited soil-ecological units (Džatko and Sobocká 1996, Džatko 2002).

The analysis of hectare yields, costs, revenues, and profits of selected farmers in the period 2000–2020 in Slovakia was carried out based on data from 205 farms that grew sunflowers and were able to provide us with the requested data.

In the next step, the data collected directly from the farmers was assigned a point value that reflects the production potential of the land of a specific subject (farm). The point value of the land of individual farms was calculated based on the average point values of individual soil units (based on the soil ecological evaluation – (Džatko 2002)) as follows:

$$PV = (ST + SE + GD + ST) \times TP \quad (1)$$

where: PV – point value of the soil units; ST – point value of soil type (interval 1–60 points); SE – point value of slopes and exposure of the landscape (interval 1–15 points); GD – point value of gravel contents in the soil and soil depth (interval 1–15 points); ST – point value of soil texture (interval 1–10 points); TP – coefficient of the climatic region (interval 1.00–0.59).

Characteristics and categorisation of analysed soil parameters (Džatko and Sobocká 2009):

Slopes: plains (0–3°), slight slope (3–7°), middle slope (7–12°), significant slope (12–17°);

Gravel contents: non or sporadic gravely (particles > 0.2 mm less than 10%), slightly gravely (particles > 0.2 mm in the interval 10–25%), gravely (particles > 0.2 mm in the interval 25 – 50%), very gravely (particles > 0.2 mm more than 50%);

Depth: deep (more than 0.6 m), medium depth (0.3–0.6 m), shallow (less than 0.3 m);

Texture: light soils (sandy and loamy sand), medium heavy soils (sandy loam and loam), heavy soils (clayey loam), and very heavy soils (clayey and clay).

The values of the climatic region (TP) were determined according to the long-term average sum of the temperature in respective climatic regions (Table 1).

The specification of soil suitability for sunflower cultivation (from very suitable to unsuitable) was determined by dividing the point scale of the soil production potential (one-hundred-point scale) into four categories as follows:

- unsuitable soils: 40 points and less;
- suitable soils: 41–60 points;
- less suitable soils: 61–80 points;
- very suitable soils: more than 80 points.

We tested the dependence of the real yields of sunflowers in the years 2000–2020 on the potential production capacity of the soils of the analysed farms, represented by the average score on a 100-point scale, with a non-linear polynomial regression analysis. Based on this dependence, we established a regression equation for sunflowers, using which we assigned to each soil unit the crop's potential yield.

Table 1. Chosen parameters of soil and climatic regions in Slovakia

Code	TP	Characteristics	TS > 10 °C	CMI (mm)	T veget °C
00	1.00	very warm, very dry, flat	> 3 000	> 200	16–17
01	0.95	warm, very dry, flat	3 000–2800	200–150	15–17
02	0.88	sufficiently warm, dry, hilly	2 800–2500	150–100	15–16
03	0.95	warm, very dry, flat, continental	3 160–2800	200–150	15–17
04	0.94	warm, very dry, basin-like, continental	3 030–2800	200–100	15–16
05	0.87	relatively warm, dry, basin-like, continental	2 800–2500	150–100	14–15
06	0.86	relatively warm, moderately dry, highland-like continental	2 800–2500	100–50	14–15
07	0.79	moderately warm, moderately moist	2 500–2200	100–0	13–15
08	0.73	moderately cold, moderately moist	2 200–2000	100–0	12–14
09	0.68	cold, moist	2 000–1800	60–50	12–13
10	0.59	very cold, moist	< 1 800	< 50	10–11

TP – coefficient for the climatic region for soil point value calculation; TS > 10 °C – sum of average daily air temperatures more than 10°C; CMI (mm) – climatic moisture indicator (difference of potential evaporation and precipitation) according to Budyko (Tomlain 1980, Škvarenina et al. 2004, Džatko and Sobocká 2009); T veget °C – average air temperature during the vegetation period

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$$y = 0.001x^2 - 0.0817x + 2.9013 \quad (r = 0.692;\ n = 205) \qquad (2)$$

where: y – yield; x – soil point value; *r* – coefficient of correlation; *n* – number of paired values.

Potential profit is the difference between revenues and costs (provisional data provided by individual farms). The rate of profitability is the ratio of profit to costs expressed as a percentage.

The productive categorisation of cultivated soils (Table 2) divides the agricultural soils of Slovakia into types of their rational use (type O – typical arable soils, type OT – arable land or grassland, type T – typical permanent grassland, while type T does not occur in potato cultivation).

The final map of the spatial distribution of each category was created using ArcGIS software based on vector maps in scale 1:5 000, which graphically identify soil point diffusions (database of the Research Institute of Soil Science and Soil Conservation in Bratislava, Slovakia). The analytical overlay of this map layer with layers representing data on soil type, soil texture, climatic region or geomorphological parameters enabled the creation of soil-ecological characteristics of individual categories (regions). Their characteristics are presented in the results and discussion section.

Real identification of sunflower cultivation areas in 2018–2021 was based on information from farmers who applied for subsidies through the land parcel identification system (LPIS). LPIS is a system based on aerial or satellite photographs that record all agricultural parcels in the Member States of the European Union. Each parcel is assigned a unique number, providing unique identification in space and time. Using this unique identification, we linked the cultivation statistics to the spatial data and selected all plots where sunflower was cultivated from 2018–2021. Descriptions of soil properties in the selected LPIS plots where sunflower was cultivated were obtained using analytical overlays with relevant spatial databases and spatial identifications of different soil parameters. These databases for the whole territory of Slovakia are operated by the Research Institute of Soil Science and Soil Protection in Bratislava. Spatial analyses were performed using the ArcGIS 10.3 software (ESRI, Redlands, USA) environment.

The geographic terminology of the geomorphological subdivision of the territory of Slovakia was adopted according to Mazúr and Lukniš (1986).

RESULTS

The cultivation of sunflowers in Slovakia has over 170 years of tradition. Larger sowing areas were established after the First World War. Subsequently, cultivation stagnated, which lasted until 1949. After the Second World War, the area gradually increased until 1953, when it reached 13 000 ha. This was followed by a further decline (to 4 000 ha). Since the 1970s, the area under sunflower cultivation has gradually increased again. The highest sunflower area to date was 131 000 ha in 2003 (Figure 1).

The potential of agricultural land and soils for sunflower cultivation

Based on the knowledge and identification of soil parameters (their spatial distribution) and sunflowers' environmental requirements, we classified Slovakia's agricultural land into four areas according to their suitability for sunflower cultivation (Figure 2).

Table 2. Productive categories of arable soils in Slovakia

Code	Characteristics	Point value*
O1	the most productive arable soils	90–100
O2	highly productive arable soils	81–89
O3	very productive arable soils	72–80
O4	productive arable soils	63–71
O5	medium productive arable soils	54–62
O6	less productive arable soils	45–53
O7	low productive arable soils	36–44
OT1	moderately productive arable soils and very productive grassland	28–35
OT2	medium productive arable soils and medium productive grassland	20–27
OT3	low productive arable soils and less productive grassland	< 20

*on a 100-point scale

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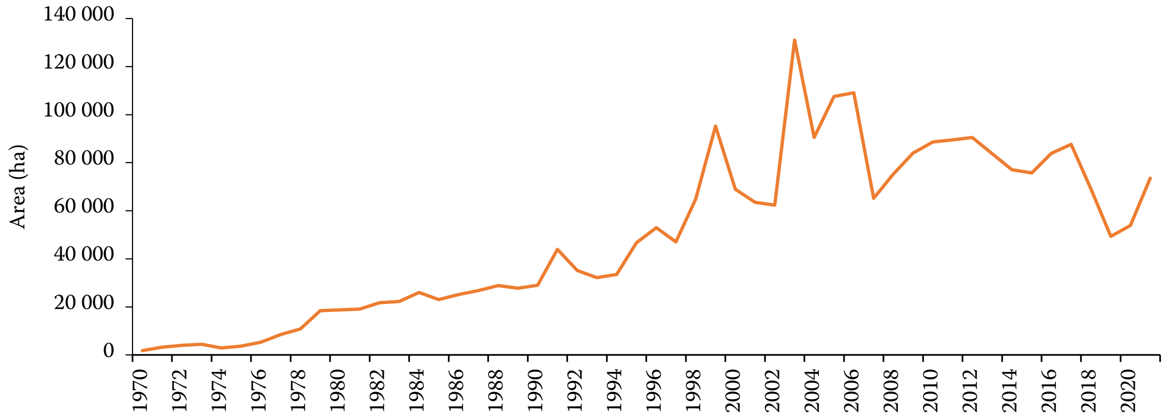

Figure 1. Development of sunflower area sown in Slovak Republic

Area of very suitable soils. Of the total agricultural land, this area covers 18.8%. It mainly includes the soils of the Danube Plain and the Chvojnica Upland. The soil types are Chernozems, Mollic Fluvisols, Haplic Luvisols and Fluvisols, which are medium textured, deep, and skeleton-free. They are located in a warm to very warm, very dry climatic region.

This area included highly productive to productive arable soils with a sunflower production potential greater than 3.0 t/ha. According to the typological and production categorisation of agricultural soils, these are the first two productive categories of soils (O1–O2). Sunflower cultivation on these soils can achieve a profit of more than EUR 170/ha and a more than 30% profitability rate.

Area of suitable soils. It covers 24.9% of the agricultural land in Slovakia. Geographically, it is mainly represented by the higher (peripheral) parts of the Chvojnica Upland and the Danube Lowland, the higher quality soils of the East Slovak Lowland, the South Slovak Basin, the Považské Podolie and the Košice Basin. The dominant soil types are Fluvisols, Haplic Luvisols, and Regosols. The predominant soils are medium to heavy, skeleton-free, deep, and located on flat to gentle slopes. The area covers climatic regions 00 to 04 (very warm and very dry to warm and very

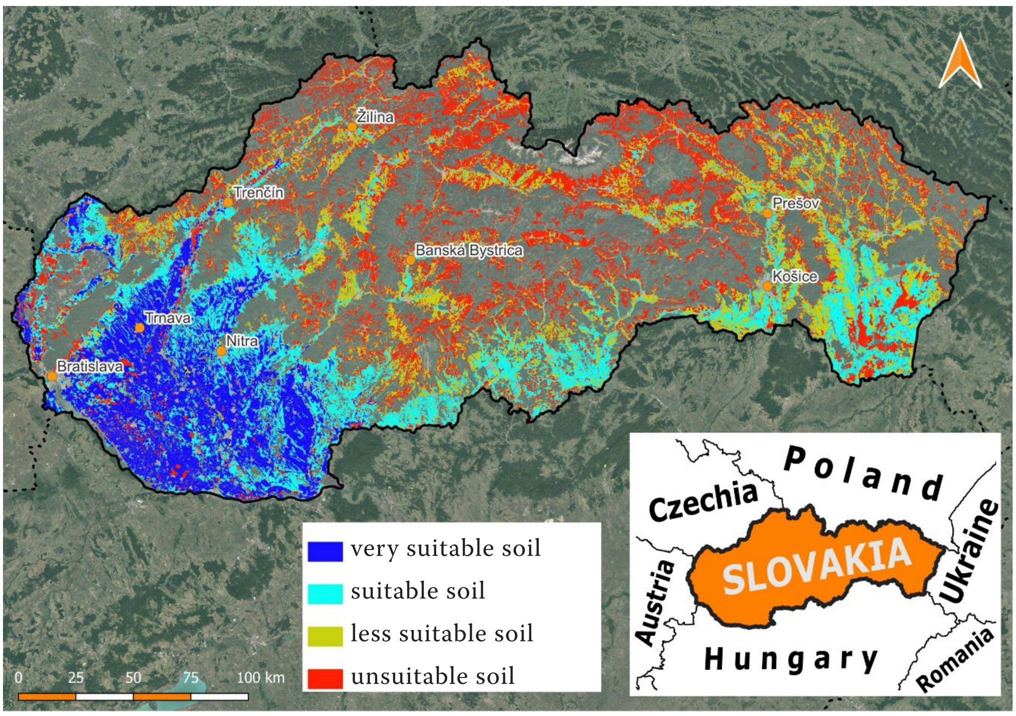

Figure 2. Suitability of agricultural soils in Slovakia for sunflower cultivation

dry, basin, continental), the most widespread being region 01 with warm and very dry weather.

The potential sunflower yields in this area are 2.41–3.00 t/ha. According to the typological and production classification of Slovak soils, this includes very to medium productive arable soils (O3 to O5). Sunflower cultivation profits can reach up to EUR 150/ha, and the profitability rate is up to 27%.

Area of less suitable soils. This area covers 16.6% of the agricultural land in Slovakia. It includes the heavier-grained soils of the Eastern Slovak Plain, the Eastern Slovak Upland, the Ondavská and Laborecka Uplands, the Myjava Upland, the Podtatranská, Hornádská, Košická, Turčianská and Zvolenská basins. Cambisols dominate among the soil representatives, especially Stagnic Cambisols. Pseudogleys and fluvisols are also significantly represented. These are medium to heavy soils on gentle slopes, mostly deep, medium and lowly skeletal. Climatic regions 03 to 08 (warm and moderately dry to moderately cool and moderately moist) are absolutely predominant, occupying up to 86% of the category.

Potential yields are 1.6–2.4 t/ha. According to the typological and production classification of Slovak soils, there are less productive arable soils to productive grassland (O6 to OT3), on which the profit is expected to be around EUR 50/ha and the profitability rate up to 8%.

Area of unsuitable soils. Soils unsuitable for sunflower cultivation cover 39.7% of the agricultural land in Slovakia. They are mainly located in the northern and central parts of Slovakia. From a pedological point of view, they include a whole range of soil types, both light and extremely heavy, acidic, and waterlogged, with unfavourable physical and chemical properties. Cambisols, rheniferous soils, fluvisols and gleys predominate among the soil types. In terms of grain size, medium-heavy, heavily skeletal, shallow soils are predominant on the middle slopes and slopes above 12°. The predominant climatic region is very cold and humid.

Sunflower yields on these soils are below 1.5 t/ha and should, therefore, not be included in the cropping structure in this area. The soils are mainly suitable for permanent grassland (soil typology and production categories OT and T). Economically, sunflower cultivation here is loss-making.

Pedological characteristics of real sunflower areas in 2018–2021

Between 2018 and 2021, sunflower cultivation in Slovakia ranged from 49 300 ha (2019) to 73 600 ha (2021). Sowing is concentrated in the lowland areas (Podunajská lowland, South Slovak lowland, East Slovak lowland), where the soil and climate condi-

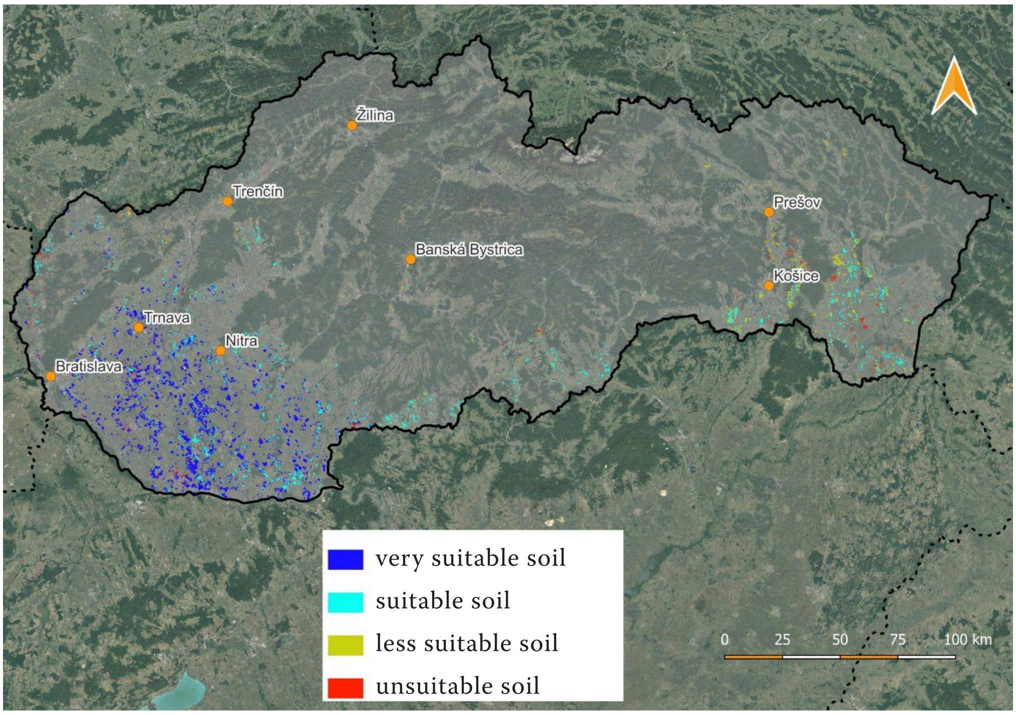

Figure 3. Real sowing of sunflower in 2018–2021 in Slovakia by suitability of soils for its cultivation

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tions are best for the crop, and thus the potential for its efficiency is highest (Figure 3).

The results show that up to 51% of the sunflower area sown between 2018 and 2021 is in the area of soils that are very suitable for growing sunflowers. 32% of the area is in suitable soils, 10% in less suitable soils and 7% in soils unsuitable for cultivation. This shows that Slovakia predominantly chooses locations with the best soil and climatic conditions for sunflower cultivation.

86% of the soils cultivated with sunflowers are located in climatic regions warm to very warm and very dry (00-04), while up to 55% of the soils are located in climatic regions 00 – very warm, very dry, flat.

The most frequently selected soils for sunflower cultivation were Chernozems (31%), Fluvisols (20%), Mollic Fluvisols (19%) and Haplic Luvisols (12%). Sunflower was also grown on Regosols as well as Dystric Planosols in a smaller proportion. Soils on slopes up to 3° (81%) were predominant, but there were also soils on slopes of 3–7° (14%) and even 7–12° (4%). In terms of texture, the soils were predominantly medium-heavy soils, loamy (61%), but also heavy soils of clayey loam (20%). Up to 94 % of the soils fell into the category of deep soils, and 91% of soils without skeleton).

We conclude that the sites selected for sunflower cultivation in Slovakia in 2018–2021 are mostly in line with the requirements of this crop for soil and climatic conditions. The cultivation of sunflowers on potentially unsuitable soils is partly due to the "entrepreneurial" intentions of the growers (smaller sites in the northeast of Slovakia) related to the ongoing climate change. The occurrence of marginal soil types also results from the heterogeneous soil parameters within the soil units (blocks) on which sunflower has been placed.

According to Kováč et al. (2003), sunflowers should be grown in the same place only after 5 years. Our analysis showed that in the years 2018–2021, sunflowers were grown consecutively in Slovakia on 1 042 land blocks (260 cases per year), on an area of 21 940 ha (5 500 ha per year), which represents almost 15% of the sown sunflower.

Our results suggest that Slovakia's soil and climatic conditions are suitable for sunflower cultivation. This crop can be grown successfully on almost 44% of agricultural soils here. The areas of soil suitability for sunflowers are characterised in the paper in terms of pedo-climatic and production-economic parameters.

Such classification and spatial zonation can contribute to a more efficient regionalisation of this crop's cultivation to preserve agroecosystems' economic and ecological sustainability. The advantage of this categorisation, which is detailed down to the level of basic soil units, is that it can be applied immediately to any territorial unit (production block).

DISCUSSION

Due to its ability to grow in different agroecological conditions and its moderate drought tolerance, sunflower may become a preferred oilseed crop, especially considering global environmental changes (Miladinović et al. 2019).

According to the United Nations, Ukraine and Russia are the world's largest producers and exporters of sunflower seed and oil, representing more than 50% of world production. The war in Ukraine will most likely disrupt production in the current season and the supply chain due to limited access to seaports (Earth Daily Agro 2022).

It is thus important to know the potential for growing this crop in other countries, including Slovakia. In line with Meravá (2021), we conclude that Slovakia also has climate conditions favourable for sunflower cultivation.

According to Kandel et al. (2020), sunflower is adapted to different soil conditions but grows best on well-drained soils with high water holding capacity and near-neutral pH (pH 6.5–7.5). Sunflower can use a large rooting volume for soil water. Fields for sunflower cultivation should be selected from those with a higher water-holding capacity and from soils without layers that could restrict the roots. Water-holding capacity depends mainly on soil texture and soil depth. The loam, silt loam, clay loam and silty clay loam soils have the highest water-holding capacity.

In agreement with us, Kandel et al. (2020) confirm the incorrect planting of sunflowers in the same place is successful. They state that growers who do not rotate sunflower fields are likely to face one or more of the following yield-reducing problems: fields infested with diseases and infestations, increased risk of insects, increased populations of certain types of weeds including herbicide-resistant weeds, increased populations of volunteer sunflowers, and soil moisture depletion.

Forchtsam and Prchal (1960) characterised sunflower as an oilseed of the warm lowland regions of Slovakia, which was also confirmed by our research.

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According to them, the most suitable soils for its cultivation are medium-heavy, humous, sufficiently deep, and light with good fertilisation. Heavy, cold and wet soils are unsuitable. It is demanding heat, especially during ripening, when it requires drier weather. It tolerates drought well. Borecký and Stiffel (1995) also state that sunflower does not have any particular requirements for soil properties, but it produces higher yields on fertile, medium-heavy soils than on light soils. The most suitable soils are loamy sand and sandy loam soils, which have also been confirmed in our case. Our results are also in line with Šrojtová and Hnát (2003), according to whom, when selecting sites, it is necessary to avoid uneven land, sloping land that increases the risk of water and wind erosion and defective soils. Unsuitable soils for sunflower cultivation are waterlogged soils with a high groundwater level, which do not allow early preparation and cause anomalies in the water and air regime of the soils. For a good crop, it requires fertile soil (Chernozem, Haplic Luvisols, or Fluvisols). On sandy soils, it gives lower yields.

Sher et al. (2021) report that sunflower production is significantly lower in arid and semi-arid areas due to various crop management problems. Therefore, conservation tillage could be suggested in areas with lower water ability to improve sunflower production. According to Helmy and Ramadan (2009), sunflower is an option for oilseed production, especially in arid areas, due to its good root system development.

The impact of drought on sunflower production has been addressed in several papers (Erdem et al. 2006, Manivannan et al. 2007, Nezami et al. 2008, Yawson et al. 2011, Garcia-Vila and Fereres 2012, Saudy et al. 2020, Siddique et al. 2020, El-Bially et al. 2022). Most of them report that sunflower has good drought tolerance potential due to their well-developed root system, but drought reduces the actual seed yield.

Our results (very suitable soils in Slovakia are mainly in climatically dry areas) confirm this hypothesis.

The effect of soil types on sunflower production under Indian conditions has been addressed by Ramamurthy et al. (2022). Similar to our research, their results showed that selecting the appropriate soil type can increase yield by up to 43%. Sadras and Calviño (2001) reported that the yield of sunflowers is reduced by 0.54% for each centimetre decrease in soil depth.

The presented categorisation of agricultural soils according to their suitability for annual sunflower cultivation basically correlates with the so far known knowledge (Hraško and Bedrna 1988, Demo et al. 1998, Kováč et al. 2003) on the suitability of the Slovak environment for this crop. Its specificity lies primarily in the more precise pedological and spatial characterisation of individual areas of suitability for cultivation and the possibility of application to any spatial unit or production block.

The actual sowing of sunflowers in Slovakia confirmed our assumption that the most productive (highest quality) soils are used for this crop. As much as 83% of the area sown to sunflower in 2018–2020 fell within the suitable area for sunflower cultivation. There is some risk to successful sunflower cultivation if it is grown again on the same block of land in succession at intervals of less than 5 years.

The issues presented are applied in decision-making, planning and management processes, as well as in developing conceptual and implementation plans for using the landscape and its resources.

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