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Article

Optimising Potato (Solanum tuberosum L.) Cultivation by Selection of Proper Soils

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Abstract: Growing potato demands considerable external inputs of pesticides due to its susceptibility to various pests and pathogens. Here we present an attempt to differentiate the Slovak rural landscape with respect to the possibility of effective potato cultivation and to characterise soil parameters of current potato cultivation areas with the aim to increase the sustainability of the potato production. The selection was based on soil climatic, production and economic parameters. By using the GIS tools and existing databases on soil characteristics in Slovakia, maps of soil suitability categories for potato cultivation were generated. In Slovakia, it was found that 12.3% of farmland is very suitable for potato cultivation and that as much as 43.1% is not suitable. Later the specified categories were characterised in detail and specified with respect to geographic, soil, climatic, production and economic parameters. Currently, most potato crops are cultivated on Eutric Cambisols (27%), Chernozems (20%) and Mollic Fluvisols (18%). Loamy soils (65%), soils without gravel (62%), deep soils (74%) and soil situated on plains (55%) are dominant in these regions. We suggest that potato cultivation should be concentrated on the most suitable areas, thereby increasing the economic profitability, improving the ecological stability of the country and supporting the sustainability of the agriculture.

Keywords: potato cultivation soil suitability; agricultural landscape categorisation;GIS

1. Introduction

There is an urgent need for decreasing external inputs such as fungicides when cultivating potato. Originating from South America where after the Spanish colonization it was first spread to Europe but later globally. Currently (2017), potato cultivation takes about 19.3 million hectares, the world global production is 388 million tons and mean hectare yield is on the level 20.1 tons (FAOSTAT, 2018). The potato consumption is about 35 kg per capita per year. The trend is that the area decreases whilst the production per hectare increases [1]. With an intensified production the need for external inputs such as mainly fungicides increases resulting in a less sustainable production. In Slovakia, the situation follows the global trend. The development of potato production areas has steadily decreased (Figure 1). Currently, potato cultivation is, taking up 8,000 hectares compared to 200,000 ha fifty years ago [2].

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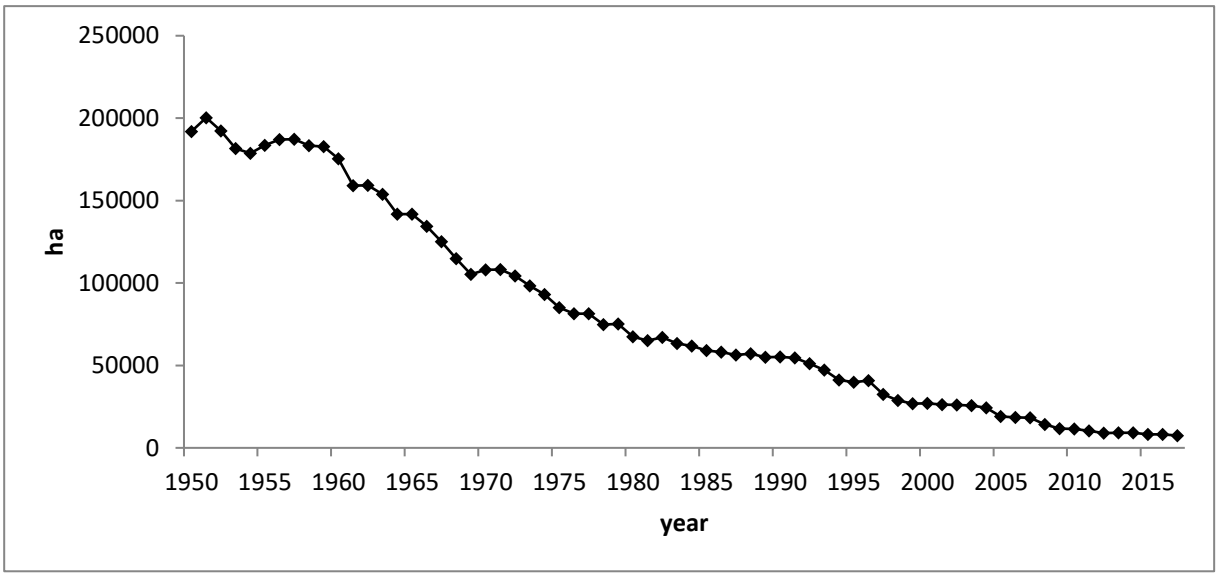

Figure 1. The development of potato cultivation area in Slovakia (1950-2017)

The decreasing trend is a result of changing consumer behaviour usages [3]. While in 1991, the average potato consumption per capita was 90.8 kg, now (2017) it is only 48.9 kg [4].

Simultaneously, the yields per hectare are gradually increasing following the global tendency, although with variations between individual years. Over the last 66 years, the lowest harvest (5.04 t ha-1) was recorded in 1964 and the highest (20.94 t ha-1) in 2011. The increased yields per ha have been followed also by a steadily increasing use of pesticides [5]. Currently, the average pesticides consumption in Slovakia is 1.08 kg per hectare, while the consumption in EU countries is 3.71 kg per ha. The highest pesticides consumption is reached in Benelux countries (11.5 kg ha^{-1}).

The potato is versatile and can be grown in almost any soil type except saline and alkaline soils. Naturally loose soils, which offer little resistance for tuber enlargement, are preferred. Loamy and sandy loam soils rich in organic matter, with good drainage and aeration, are considered the most suitable ones [6]. Ideal soil porosity is about 50%, with a water capacity between 30 and 40% (vol.) and an air capacity of about 15% (vol.). The optimum pH value for potato cultivation ranges between 4.7 and 6.2, while acidic soil is preferred over alkaline soil. Soils originated from weathered granites, flysh sandstones, phyllites and andesites are optimal for potato growing.

Given this, our hypothesis is that it will be possible to grow potato in a sustainable way by properly matching soil and climatic conditions. Here we present an attempt to select optimal soil and regions for potato cultivation in Slovakia by identifying suitable soils by multicriterial GIS analysis using analytical overlapping of data representing soil properties [7].

2. Materials and Methods

An analysis of hectares yields, costs, revenues and profits of chosen farmers in the period 1990-2017 in Slovakia, were executed using data from 120 agricultural farms, which were cultivated the potato and were able to provide us the requested data. In the following, data obtained directly from farmers was assigned to a given point value reflecting the soil production potential of a specific subject (agricultural farm). Point value of soils of individual farms was calculated based as the average of the point values of the occurring soil units (on the base of soil and ecological evaluation) [8], as follows:

$$PV = (ST + SE + GD + ST). TP$$

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).

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

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	warm, very dry, flat	> 3000	200	16-17
01	0.95	warm, very dry, flat	3000-2800	200-15	15-17
02	0.88	sufficiently warm, dry, hilly	2800-2500	150-10	15-16
03	0.95	warm, very dry, flat, continental	3160-2800	200-15	15-17
04	0.94	warm, very dry, basin-like, continental	3030-2800	200-10	15-16
05	0.87	relatively warm, dry, basin-like, continental	2800-2500	150-10	14-15
06	0.86	relatively warm, moderately dry, highland-like, continental	2800-2500	100-50	14-15
07	0.79	moderately warm, moderately moist	2500-2200	100-0	13-15
08	0.73	moderately cold, moderately moist	2200-2000	100-0	12-14
09	0.68	cold, moist	2000-1800	60-50	12-13
10	0.59	very cold, moist	< 1800	< 50	10-11

Notes: TP – coefficient for 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 [14], Škvarenina et al. 2004 [15], Džatko and Sobocká 2009 [16])

T veget °C – average air temperature during vegetation period

Point values (PV) of production potential were analysed for their correlation in the form of nonlinearpolynomial regression in relation to real yields (Y), costs (C), sales (S) and revenues (R) (average value for 1990-2017 per one hectare). The following statistical parameters were determined by this way:

PV↔C: y = -0.1435x2 + 23.122x + 1218.5 (r = 0.4147, n = 109)

PV↔S: y = 0.014x2 + 13.209x + 679.67 (r = 0.5242, n = 110)

PV↔R: y = 0.1619x2 + 15.33x + 883.29 (r = 0.7533, n = 117)

where y = yield, cost, sales, revenues, x = soil point value, r = coefficient of correlation and n = number of paired values.

The regression equations were used to assign potential possible yields of potato for each soil unit (considering the point value) as well as potential economic parameters: costs, sales, profits or losses (Table 2).

Table 2. Potential of yield and economic parameters of potato in dependence on point value of soils

Categories	Soil point value	Yield t.ha^{-1}	Economic parameters of potato cultivation in €.ha^{-1}				
			Cost	Sales	Revenues	Profit	Profitability rate in %
unsuitable soils	5	11.26	1331	746	964	-367	-27.55
	10	11.24	1435	813	1053	-383	-26.65
	15	11.33	1533	881	1150	-383	-25.01
	20	11.53	1624	949	1255	-369	-22.72
	25	11.83	1707	1019	1368	-339	-19.87
less suitable soils	30	12.25	1783	1089	1489	-294	-16.50
	35	12.78	1852	1159	1618	-234	-12.63
	40	13.42	1914	1230	1756	-158	-8.27
	45	14.17	1968	1302	1901	-67	-3.42
	50	15.02	2016	1375	2055	39	1.92
suitable soils	55	15.99	2056	1449	2216	160	7.78
	60	17.07	2089	1523	2386	297	14.20
	65	18.26	2115	1597	2564	449	21.21
	70	19.56	2134	1673	2750	616	28.86
	75	20.96	2145	1749	2944	798	37.21
very suitable soils	80	22.48	2150	1826	3146	996	46.33
	85	24.11	2147	1904	3356	1209	56.31
	90	25.85	2137	1982	3574	1437	67.25
	95	27.70	2120	2061	3801	1681	79.28

Profit is given as the difference between revenues and costs and profitability rate is the share of profit and cost expressed in%.

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

- unsuitable soils: 25 points and less
- suitable soils: 26-50 points
- less suitable soils: 51 – 75 points
- very suitable soils: more than 75 points.

Thereafter, a final map of spatial distribution of particular categories (Figure 2) was created by using ArcGIS software based on vector maps in scale of 1:5000, which graphically identify soil point diffusion (Soil Science and Conservation Research Institute database in Bratislava, Slovakia). Analytical overlay of this map layer with layers represented data of soil type, soil texture, climatic region or geomorphological parameters allowed create soil-ecological characteristic of individual categories (regions). Their characteristics are mentioned in the part Results and Discussion. Except these, the characteristics of potatoes cultivation suitability is added with the productive categories of cultivated lands [8] and integrated index of agricultural soils quality of Slovakia [7].

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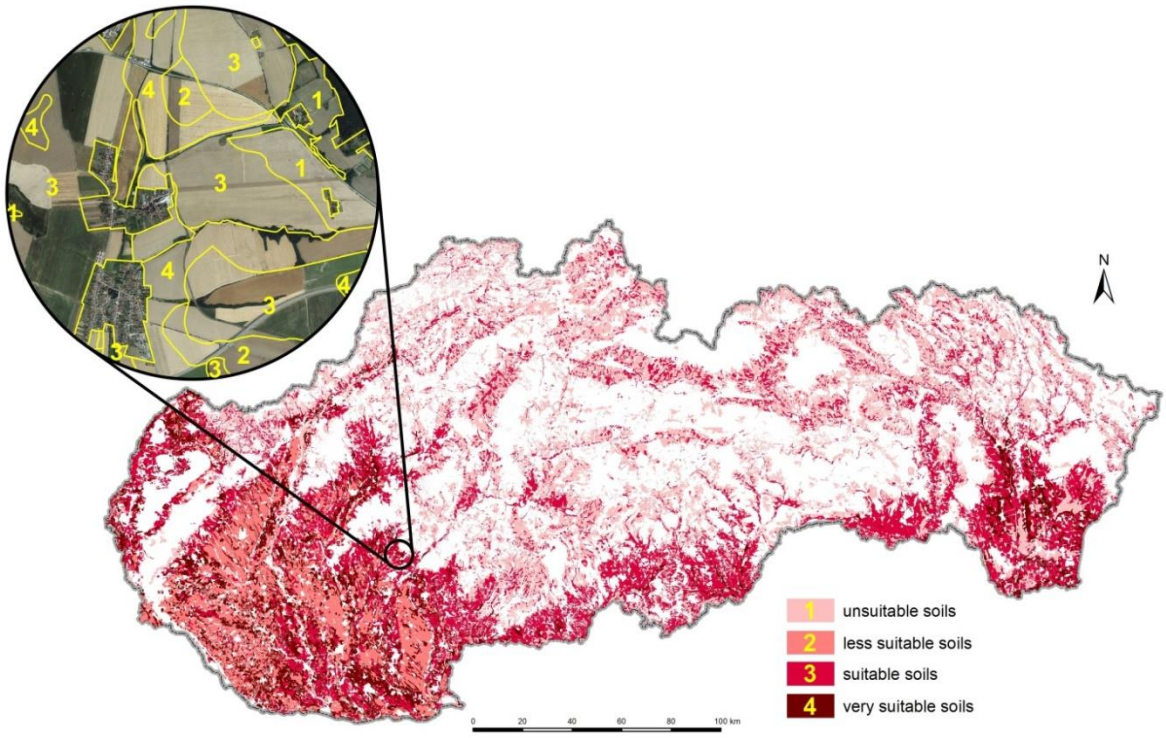

Figure 2. Suitability of agricultural soils in Slovakia for potato cultivation

Productive categorization of cultivated lands (Table 3) divides agricultural soils of Slovakia into types of their rational use (type O - typical arable lands, type OT – arable land or grasslands, type T – typical permanent grassland, while type T does not occur in potato cultivation).

Table 3. 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

Note: * from 100-points scale

When determining the soil quality index, the methodology according to Vilček and Koco (2018) [7] was used. According to its, the quality of soils is the result of the assessment of their production potential, environmental potential and potential threat (erosion, compaction, organic matter content).

Integrated indices are defined as follow: 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. Identification of potato cultivation areas in the years 2011-2015 was processed on the basis of information of farmers who demanded subsidies by means of the LPIS (Land Parcel Identification System). The LPIS is a system based on aerial or satellite photographs recording all agricultural parcels in the member states of the European Union. A unique number is given to each land parcel to

provide a unique identification in space and time. We linked the statistical cultivation data with spatial data using this unique identification and selected all parcels where potato was cultivated during the 2011-2015 period. Description of soil properties in selected LPIS parcels where potato was cultivated was obtained using analytical overlay with relevant spatial databases and spatial identifications of various soil parameters. These databases for the whole Slovakia territory are managed by Soil Science and Conservation Research Institute in Bratislava; spatial analysis where performed using ArcGIS 10.3 software environment.

3. Results and Discussion

The above mentioned methodological processes and pedological data enabled us to create a regionalization of the suitability of soils (rural areas) for growing potatoes in Slovakia. Individual regions are characterized and specified on the basis of production, economic and soil-ecological parameters.

The spatial analysis of current potato cultivation areas was created as well.

3.1 Characteristics of rural areas with regard to potato cultivation suitability

Region of very suitable soils

This region covers about 12.3% of the agricultural soils in Slovakia. In this region the dominant soil types are Chernozems, Mollic Fluvisols, Haplic Luvisols and Fluvisols, which are moderately heavy, deep and without soil gravel. They can be found in the warm to very warm, dry to very dry climatic regions with continental climate. Highly productive to productive arable soils were included in this region (76-100 soil points), with a potato production potential greater than 21tons per hectare and a share of crop rotation on arable soil of up to 7%. According to the production soil categorisation, this region includes the six most productive soil categories (O1–O6). It is possible to obtain a profit of over €800 per hectare and a profitability rate higher than 37% for potato cultivation. This region is extremely suitable for early and semi-early potato varieties. Agricultural soils evaluated according to five scale index of soil quality [7] reach 1.79 points, which means they belong to the category of very high to high quality soils.

Region of suitable soils

This region covers about 32.7% of agricultural soils. The dominant soil types are Cambisols, Fluvisols, Haplic Luvisols, Dystric Planosols and Regosols, with a soil point value between 51 and 75 points. The soils are mostly moderately heavy to heavy, without soil gravel or slightly gravelly and deep, situated on plains and slight slopes. This area is represented by the climatic regions 05–10 (relatively warm and dry to very cold and moist). Potato production potential is 15–21 tons per hectare and its share of crop rotation on arable soil should be up to 9%. According to the Slovak production soil categorisation, this area includes very productive arable soils to less productive arable soils (O3–O6). It is possible to obtain a profit of €60-800 per hectare and a profitability rate of 7-37% for potato cultivation. Agricultural soils evaluated according to five scale index of quality [7] reach 2.14 points, e.g. they belong to the category of high quality soils.

Region of less suitable soils

This region covers about 12.9% of all agricultural soils, with the dominant soil types Chernozems, Molic Fluvisols and Haplic Luvisols, with a soil point value between 26 and 50 points. The soils are moderately heavy, deep, without gravel, and situated on plains. Less suitability for cultivation of potato is result of the predominance of the very warm and very dry climatic regions 00-01 that occupy 98% of the soils. There are moderately heavy, deep soils on variably steep slopes. Potato yields reach 12–15 tons per hectare. According to the Slovak production soil categorisation, the area includes the medium productive arable soils to poorly productive fields (O5–OT3). The profit is under €60 per hectare, with a potato cultivation profitability rate of 1%. Agricultural soils

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evaluated according to five scale index of quality [7] reach 2.83 points, which puts them into the category of medium quality soils.

Region of unsuitable soils

Soils that are not suitable for potato cultivation make up about 42.1% of agricultural soils in Slovakia. They occur mostly in the northern and central regions of the country, as well as on heavy to very heavy soils of the Eastern Slovak lowland. From a soil science perspective, there is a great variety of soil types, including light, extremely heavy, acid and loose soils with unfavourable physical and chemical characteristics. Cambizems, Rendzics, Fluvisols and Gleysols are the predominant soil types here. In terms of grain size, moderately heavy, strongly gravelly, shallow soils, occurring on steep and very steep hills, are predominant. The climatic regions 07–10 are dominant. Potato yields do not exceed 12 tons per hectare in the long term, so it should not occur in the crop rotation. These soils are mostly suitable for permanent grass overgrowth. In terms of economic values, potato cultivation will incur losses in these areas. Agricultural soils evaluated according to five scale index of quality [7] reach 3.65 points, it means they belong to the category of low quality soils. The spatial locations of the above mentioned regions are presented in Figure 2.

3.2 Distribution of potato cultivation at present time

Due to the biological, but also agronomic requirements of potato, the selection of suitable sites is based on climatic, geomorphological and soil conditions. In terms of climate regionalization of Slovakia, 26% of the potato cultivation areas are located in a very warm and very dry region. In contrast, almost 14% of the areas are located in a very cold and wet region.

Most potato crops are cultivated on loam (65%), clay loam (14%) and sandy loam (13%) soils. In terms of soil types, potatoes are most often cultivated on Cambisols (27%), Chernozems (20%), Fluvisols (18%) and Dystric Planosols (11%), mainly in soils without gravel (62%) or with little gravel content (18%). The soils are predominantly deep (74%) on the plains (55%) or on slight slopes up to 7° (28%). Up to 17% of the potato areas are located on slopes above 7°, which adversely accelerates water soil erosion.

When comparing the different categories of soil suitability for potato cultivation (potential) with real cultivation areas (Figure 3), 12% of the selected areas have very good conditions for potato cultivation, 33% are suitable, 13% less suitable, and up to 42% are not suitable for potato cultivation.

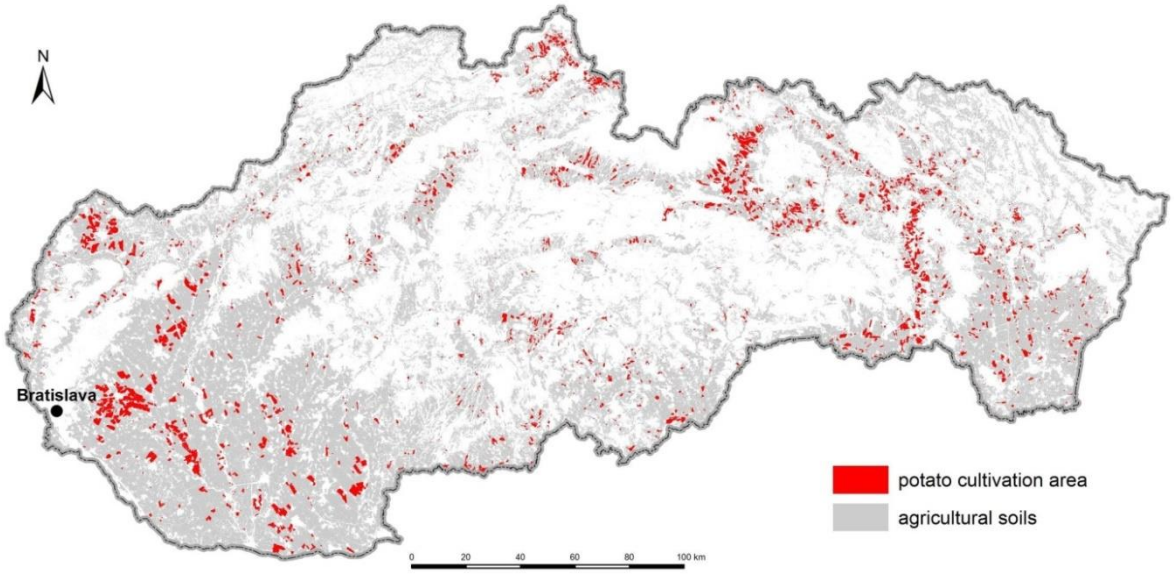

Figure 3. Areas with potato cultivation between 2014 - 2018

The cultivation of potato on less suitable and unsuitable soils inevitably requires increases input, such as irrigation, erosion protection, fertilisation, etc., which is reflected in the economic outcome. An analysis of various soil parameters on the production capacity of potato under Slovak conditions [2] showed that the yield potential on slight slopes (to 7°) was 8.3% lower, while on moderately steep slopes (7-12°), it was 15.9% lower when compared with cultivation on plains. Soils with strongly eroded soils obtained 16.6% lower yields. DeFauw et al. [9] reviewed the effect of erosion on the yield of potato by using GIS tools in Maine (USA). They stated that close to 85 % of potato production soils are classified as either "potentially highly erodible" or "highly erodible" and they required the highest standards in soil conservation practices.

The potential for negative effects on soil quality and erosion at potato cultivation is significant also due to levels of low plant residues input to the soil following potatoes, and the effect of tillage on soil structure, particularly in sandy-textured soils. Similar results have been achieved also by Moulin et al. [10]. Zarzyńska and Pietraszko [11] report about the impact of unfavourable weather conditions results in greater losses in crop value.

For potatoes, therefore, it is necessary to choose structural soils with a good stock of organic matter without the threat of water erosion in favourable climatic regions. The choice of suitable soils brings not only economic, but also ecological benefits. If potato were cultivated only in regions very suitable for this crop (higher yield assumption), it would be possible to decrease the growing area by about 2000 hectares. Reducing pesticides consumption (by about 25%) would be another environmental benefit. A good choice of cultivation area of agricultural plants (not only potato) is an ecological stabilizing factor for agrarian landscape. Vilcek and Torma [12, 13] defined the areas for winter wheat and sugar beet cultivation using similar methods and process. Based on their calculations, the correct location of winter wheat could save 153,000 hectares of land and save 165,000 tons of pesticides (saving 19.8%). In the case of sugar beet this would be 4,700 ha of land and 5.1 thousand tons of pesticides (saving 24.1%), respectively.

4. Conclusions

The natural and soil ecological conditions of Slovakia represent suitable conditions for potato cultivation. However, heterogeneous soil climatic factors do not allow efficient and long term sustainable cultivation of this crop in all regions. Based on the results of this study, decreased potato cultivation in Slovakia is related to inadequate selection of cultivation sites, resulting in low yields and poor economic profitability. To maintain and intensify potato production in Slovakia, it will be necessary to pay particular attention to the selection of appropriate cultivation areas. Current potato cultivation areas in Slovakia do not guarantee sustainability of this crop in the long term. We suggest that potato cultivation should be concentrated on the most suitable areas, thereby increasing the economic profitability, improving the ecological stability of the country and supporting the sustainability of the agriculture.

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