Risk of phosphorus losses in surface runoff from agricultural land in the Baltic Commune of Puck in the light of assessment performed on the basis of DPS indicator

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Background. In order to counteract the eutrophication of waterways and reservoirs, a basic risk assessment of phosphorus (P) losses in the surface runoff from agricultural land should be included in water management plans. A new method has been developed to assess the risk of P losses by estimating the degree of P saturation (DPS) based on the P concentration of the water extract (water-soluble P – WSP).

Methods. The risk of P losses in surface runoff from agricultural land in the Puck Commune on the Baltic Sea Coast was assessed with the DPS method. The results were compared to an agronomic interpretation of the soil test P concentration (STP). Research was conducted on mineral and organic soils from 50 and 11 separate agricultural plots with a total area of 133.82 and 37.23 ha, respectively. P was extracted from the collected samples using distilled water on all soil samples, acid ammonium lactate on mineral soils, and an extract of 0.5 mol HCl•dm^{-3} on organic soils. The organic matter content and pH values were also determined. The results of the P content in the water extracted from the soils were converted into DPS values, which were then classified by appropriate limit intervals.

Results & Discussion. There was a high risk of P losses from the soil via surface runoff in 96.7% of the agricultural parcels tested (96% of plots with mineral soils and 100% of plots with organic soils). Simultaneously, a large deficiency of plant-available P was found in soils from 62% of agricultural plots. These data indicate that the assessment of P concentration in soils made on the basis of an environmental soil P test conflicts with the assessment made based on STP and create a cognitive dissonance. The risk level of P losses through surface runoff from the analyzed plots as determined by the DPS indicator is uncertain. This uncertainty is increased as the DPS index is not correlated with other significant factors in P runoff losses, such as the type of crop and area inclination.

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Abstract

21   **Background.** In order to counteract the eutrophication of waterways and reservoirs, a basic risk

22   assessment of phosphorus (P) losses in the surface runoff from agricultural land should be

23   included in water management plans. A new method has been developed to assess the risk of P

24   losses by estimating the degree of P saturation (DPS) based on the P concentration of the water

25   extract (water-soluble P – WSP).

26   **Methods.** The risk of P losses in surface runoff from agricultural land in the Puck Commune on

27   the Baltic Sea Coast was assessed with the DPS method. The results were compared to an

28   agronomic interpretation of the soil test P concentration (STP). Research was conducted on

29   mineral and organic soils from 50 and 11 separate agricultural plots with a total area of 133.82

30   and 37.23 ha, respectively. P was extracted from the collected samples using distilled water on

31   all soil samples, acid ammonium lactate on mineral soils, and an extract of 0.5 mol HCl·dm^{-3} on

32   organic soils. The organic matter content and pH values were also determined. The results of the

33   P content in the water extracted from the soils were converted into DPS values, which were then

34   classified by appropriate limit intervals.

35   **Results & Discussion.** There was a high risk of P losses from the soil via surface runoff in

36   96.7% of the agricultural parcels tested (96% of plots with mineral soils and 100% of plots with

37   organic soils). Simultaneously, a large deficiency of plant-available P was found in soils from

38   62% of agricultural plots. These data indicate that the assessment of P concentration in soils

39   made on the basis of an environmental soil P test conflicts with the assessment made based on

40   STP and create a cognitive dissonance. The risk level of P losses through surface runoff from the

41   analyzed plots as determined by the DPS indicator is uncertain. This uncertainty is increased as

42   the DPS index is not correlated with other significant factors in P runoff losses, such as the type

43   of crop and area inclination.

45   **Introduction**

46   The Baltic Sea is a basin affected by strong eutrophication (*Andersen et al., 2011; HELCOM,*

47   *2018b*) resulting in many adverse changes in the marine flora and fauna (*Ojaveer et al., 2010*),

48   which can lead to large social and economic losses (*Ahtiainen et al., 2014*). One of the main

49   reasons for the eutrophication of the Baltic Sea waters is the excessive river inflow of

50   phosphorus (P). The inflow from the entire Baltic basin is estimated at 29.3 tons per year, of

51   which 35.7% comes from dispersed sources, mainly agriculture (*HELCOM, 2018a*). About 12.7

52   tons of P is estimated to come from Poland to the Baltic Sea by river waters (*HELCOM, 2018a*)

53   and 21% to 33% of this comes from the agricultural sector, depending on the method of

54   assessment (*NWMB, 2016a*). In order to counteract the eutrophication of the Baltic Sea, various

55   initiatives have been taken at the regional and national level to limit the supply of P to the waters

56   of the Baltic Sea. Important measures were prepared at the Conference of Ministers for the

57   Environment of the HELCOM countries in Copenhagen on 3 October 2013, specifying the

58   expected reduction of the total P loads discharged into the Baltic Sea by the HELCOM member

59   states (*HELCOM, 2013*). Accordingly, Poland is expected to reduce the P inflow to the Baltic

60   Sea by 51% of that expelled during the reference period from 1997-2003 (*NWMB, 2016a*).

61   Poland approved this level of reduction as a rough estimate, noting that a final figure would be

62   accepted after relevant analyses were conducted. In light of this measure, Polish agriculture is

63   expected to face major challenges in meeting this requirement, including the impact it will have

64   on inland surface waters. According to Polish monitoring data, eutrophication parameters

65   (nutrient and chlorophyll-a concentration, water transparency) between 2012 and 2015 were

66   exceeded by 42% for sites located on flowing waters (rivers) and by 66% for stands on stagnant

67   waters (lakes/water reservoirs) (*NWMB, 2016b*). Effective solutions to reduce P loss from

68   agricultural sources to waters are needed in light of the Conference's provisions and certain

69   economic factors. Tools and procedures for controlling agricultural lands in case of P loss in

70   surface runoff should minimize the threat posed by excess P in aquatic ecosystems. The threat to

71   rivers and reservoirs by P loss from agricultural soils has been of interest to researchers for years.

72   This problem is most commonly considered in terms of interactions between the content of plant-

73   available P in soil (determined by various methods, for example Mehlich 3, Olsen, Egner-

74   Riehm), and P concentration in runoff water; it has been proven that an increase in the P content

75   in soil will correspond to an increased amount of P in surface runoff (*Pole et al., 1996; Torbert*

76   *et al., 2002; Sharpley & Kleinman, 2003; Pietrzak, Wesołowski & Brysiewicz, 2017*). However,

77   the system for cultivating plants and the type of soil also have an impact (*Gaj, 2008 after:*

78   *Sharpley et al., 1981*). The existing agrochemical tests for evaluating P levels are not equally

79   useful for testing in all soil types, limiting their use.

80   Another applied approach to assessing P loss from agricultural soils via rainwater and the risk of

81   surface water eutrophication is based on the determination of the degree of P saturation (DPS)

82   (*Alleoni, Fernandes & de Campos, 2014*). The DPS in its classical formula is expressed in a

83   percentage relation of the P content in the soil extract to the P absorption capacity of soil,

84   wherein various approaches are used for the determination of the components in this formula

85   (*Nair et al., 2004; Casson et al., 2006*). The procedure for determining the DPS index according

86   to this formula is unique for different types of soil, which can create specific methodological

87   problems and limit the possibilities of its wider use (*Sapek, 2007*). Pöthig et al. (*2010*) recently

88   developed a different method for determining this index, in which the DPS indicator only

89   depends on the P content in soil as determined by the use of distilled water – WSP (water-soluble

90   P). This method is attractive for its simplicity and broad application with different soil types. In

91   the MONERIS model (Modelling Nutrient Emissions into River Systems), developed for

92   quantifying the amount of nutrient emissions from point and diffuse sources in river catchments

93   (*Venohr et al., 2011 after: Behrendt et al., 2000*), the method proposed by Pöthig et al. (*2010*) is

94   used to determine the P concentration in surface runoff.

95   This work sought to estimate the risk of P loss in surface runoff from agricultural soils in the

96   Puck Commune using the DPS indicator determined on the basis of WSP, and to identify the

97   practical utility of the DPS index.

98

99   **Material & Methods**

100   Research was conducted on the western shore of Puck Bay on the Baltic Sea in the Puck

101   Commune, which is located in the north-eastern region of the Pomeranian Voivodeship, Poland.

102   The Puck Commune is dominated by agricultural land (57.3% of the total area of the commune),

103   the vast majority of which is characterized by high yield potential. The area is largely undulating,

104   with land falls up to approximately 9% (5.14°). Such landform features increase the risk of P loss

105   in surface runoff.

106   This study is a part of the project "Modelling of the impact of the agricultural holdings and land

107   use structure on the quality of inland and coastal waters of Baltic Sea set up on the examples of

108   the Municipality of Puck region – Integrated info-prediction Web Service WaterPUCK"

109   (*Dzierzbicka-Głowacka et al., 2019*).

110   In the spring of 2018, soil samples from 61 agricultural plots on 22 farms were taken (field work

111   was conducted with the landowners'/farmers' permission) for chemical analysis based on the

112   guidelines included in the PN-R-04031:1997 standard. An aggregate sample was created by

113   combining and thoroughly mixing a set of primary (individual) samples of up to 20 items.

114   Laboratory analysis of the aggregate samples determined the organic matter content in the layer

115   of 0-5 cm, pH in the layer 0-30 cm, the concentration of plant-available P in layers 0-5 cm and 0-

116   30 cm, and the content of WSP in the layer of 0-5 cm (WSP_w1). In this regard:

117   (1) fraction content below 0.02 mm was determined by the sedimentation (pipette) method

118   according to PN-EN ISO 17892-4:2016 standard;

119   (2) organic matter content was determined as a loss on ignition at 550°C by the weight

120   method according to the PN-EN 12879:2004 standard;

121   (3) pH measurement of soil was conducted in 1N suspension of KCl solution by

122   potentiometric method according to PN-ISO 10390:1997 standard (pH_{KCl});

123   (4) the concentration of available P forms (in agronomic soil P test – STP) in mineral soils

124   was determined by acid ammonium lactate (pH ~ 3.55) according to the PN-R-04023:1996

125   standard (P_{AL}) and by the extract of 0.5 mol HCl·dm^{-3} according to PN-R-04024:1997

126   standard (P_{HCl}) in organic soils; the content of WSP (in environmental soil P test) in mg P·kg^{-1}

127   of soil, was determined by Inductively Coupled Plasma Optical Emission Spectroscopy ICP-

128   OES after drying soil samples in the air and sieving them through a <2 mm sieve, preparing a

129   suspension in the ratio of 1 g of soil in 50 ml of distilled water, agitating for 2 hours, and

130   filtering through a 0.45 μm filter.

131   Soil samples analysis was ordered and evaluated according to the following criteria:

132   (1) Based on the soil organic matter (SOM) content, the soils were divided into mineral and

133   organic soils. With the SOM content of more than 10% (threshold value between mineral

134   and organic soils) organic soil was classified as organic (*Szymanowski, 1995; PN-R-*

135   *04024:1997*).

136   (2) The assessment of soil acidification was conducted according to the accepted standards.

137   Soils were defined by their reaction classes: very acidic, acidic, slightly acidic, neutral

138   and alkaline under conditions where their measured pH was in the following ranges: ≤4.5,

139   4.5-5.5, 5.5-6.5, 6.5-7.2, and >7.2, respectively.

140   (3) An assessment of P content in soil was conducted with respect to threshold values given

141   the following standards: PN-PN-R-04023:1996 and PN-R-04024:1997 for the following

142   abundance classes: very low, low, medium, high, and very high (Table 1). The basis for

143   the assessment was the percentage share of the soil samples tested in individual

144   concentration classes.

145   (4) Based on the results of the P content determination in soil using water extract, DPS, in %,

146   indices were calculated using the equation (*Pöthig et al., 2010*):

147    $DPS(\%) = \{1/[1 + (1.25 \cdot WSP^{-0.75})]\} \cdot 100$

148   where: WSP – is the content of water soluble P, mg P·kg^{-1} of soil.

149   The risk of P loss by surface runoff was assessed using the limit intervals specified by Pöthig et

150   al. (*2010*) and the established P saturation indexes (Fig. 1). There is a high risk of P loss from the

151   soil by surface runoff if the DPS value exceeds 80%, DPS values lower than 70% were

152   considered safe, and values between 70 and 80% were considered to be tolerable.

153   The laboratory results were evaluated statistically to determine the basic parameters of the

154   descriptive statistics and any correlations between the analyzed soil indices. The statistics of the

155   results were prepared with Statistica 6 software (*StatSoft*).

156   Indoor work and interviews with farmers from 22 farms were conducted to determine the

157   consumption of P fertilizers, the area and type of development of the agricultural plots, the

158   categories, types, soil types and subtypes, and the inclination of the slopes in the research areas.

159   Specially prepared questionnaires were completed by the farmers based on their own

160   observations of the terrain, a soil agricultural map of the Puck Commune in a vector format

161   (*IUNG-PIB*), and maps of selected agricultural plots acquired from Google Earth Pro.

162

163   **Results**

164   Soils were taken from 61 separate agricultural plots with a total area of 171.05 ha. 50 plots with a

165   total area of 133.82 ha were agricultural lands (AL) with mineral-derived soils and an organic

166   matter content of 2.53-7.01%; 11 plots were AL with organic soils characterized by organic

167   matter content of 25.60- 68.17% with a total area of 37.23 ha. The following types and subtypes

168   of soils occurred in the research area in the given proportions: brown soils, 61.9%; brown soils,

169   lessive soils, podzolic soils, and rusty soils made from gravel and sands, 10.2%; lessive soils,

170   3.7%; black soils, 2.4%; and peat and muck-peat soils, 21.8%. Among mineral soils, medium

171   soils with a 21-35% content of particles with diameter less than 0.02 mm were the majority,

172   covering 49.7% of their area, followed by very light (up to 10% content), and light soils (11-20%

173   content), whose share in the mineral soil area was 39.1 and 11.2%, respectively. Grains were the

174   predominant crop on most of the plots with mineral soils, while most of the plots with organic

175   soils were covered with permanent grassland. These plots was largely undulating (Fig. 2), with

176   landfalls of up to 9% (5.14°), increasing the danger of P loss from surface runoff.

177   In 2017, the average consumption of P fertilizers on the farms where the agricultural plots were

178   located was 11.1 kg P·ha^{-1} of AL with a range of 0-24.9 kg P·ha^{-1} AL on the individual farms.

179   This type of fertilizer was used in over 54% of agricultural holdings in doses of 5-10 and 10-15

180   kg P·ha^{-1} AL (Table 2).

181   The analyzed soils in the 0-30 cm layer were characterized by a pH$_{KCl}$ within 4.2-7.2 (average

182   5.4) and 4.9-6.3 (average 5.5) in the case of mineral and organic soils, respectively; this soil

183   depth is treated as a diagnostic layer in the analysis of the agrochemical properties of soils to

184   determine proper fertilizer use. The available P, concentrated in the 0-30 cm layer of the

185   analyzed soils, reached values from 3.6 to 66.5 mg P$_{AL}$·kg^{-1} (average 33.3 mg P$_{AL}$·kg^{-1}) in

186   mineral soils, and from 171.0 to 707.0 mg P$_{HCl}$·kg^{-1} (average 340.6 P$_{HCl}$·kg^{-1}) in organic soils.

187   The highest amounts of P were found in light soils (average 42.2 mg $P_{AL}{\cdot}kg^{-1}$) while in very light

188   and medium soils the P content was similar (25.6 and 25.8 mg $P_{AL}{\cdot}kg^{-1}$). In the 0-5 cm soil layer

189   the P concentration ranged from 3.6 to 68.8 mg $P_{AL}{\cdot}kg^{-1}$ (average 35.4 mg $P_{AL}{\cdot}kg^{-1}$) in mineral

190   soils and from 136.0 to 526.0 mg $P_{HCl}{\cdot}kg^{-1}$ (average 284.6 $P_{HCl}{\cdot}kg^{-1}$) in organic soils; this soil

191   depth is treated as a standard in environmental research for establishing relationships between

192   the quantitative state of P in soil and surface runoff (*Sharpley et al., 1985; Schindler, German &*

193   *Gelderman, 2002; Schierer, Davis & Zumbrunnen, 2006; Hansen et al., 2012*). In this layer, the

194   P concentration in mineral soils was 6.5% higher, on average, than in the 0-30 cm layer.

195   However, the P concentration was 16.6% lower in organic soils. In turn, the WSP_w1 content in

196   the tested mineral and organic soils as determined by water extract was in the range of 2.2-58.5

197   mg $WSP{\cdot}kg^{-1}$ (average 24.6 mg $WSP{\cdot}kg^{-1}$) and 13.7-79.5 mg $WSP{\cdot}kg^{-1}$ (average 40.3 mg

198    $WSP{\cdot}kg^{-1}$), respectively. At this level of mineral soils there was 39.0% less P, on average, than in

199   organic soil. In mineral soils the content of WSP_w1 was variable depending on their type; on

200   average it was 20.0, 32.8, and 17.0 mg $WSP{\cdot}kg^{-1}$ in very light, light, and medium soils,

201   respectively.

202

203   **Discussion**

204   **Soil pH and abundance in plant-available P**

205   pH is one of the most important factors determining the physical, chemical, and biological

206   properties of soil. It affects the availability of P accumulated in soil for plants and the P loss to

207   the environment (*von Tucher, Hörndl & Schmidhalter, 2018*). The soil acidity test revealed that

208   62.3% of plots were characterized by a very acidic or acidic reaction; 31.1% of plots were

209   slightly acidic and 6.6% were neutral, whereby the share of mineral and organic soils in

210   individual reaction classes was varied (Fig. 3). These conditions are common in the Puck

211   Commune where 13% and 54% of the soils are considered very acidic and acidic, respectively

212   (*Puck Commune Office, 2016*). In the Pomeranian Voivodeship and Poland these fractions

213   reduce to 10% and 31%, and 12% and 25%, respectively (*GUS, 2018*). The range of optimum pH

214   values are assumed to be 5.6 to 7.0 for mineral soils (in which the majority of cultivated species

215   of plants in Poland grow) (*Kocoń, 2014*) and 4.5 to 5.5 for organic soils (*Barszczewski,*

216   *Jankowska-Huflejt & Mendra, 2015 after: Moraczewski, 1996*). These values represented the

217   soils covering 34.4% of plots, including 30% of plots with mineral soils and 54.5% of plots with

218   organic soils. These data indicate that more than 1/3 of the soil pH from the research areas were

219   very unfavorable from an agronomic and environmental point of view.

220   Results of STP revealed that in about 62.3% of plots the P content was very low to low, while

221   32.8% had a medium content of P (Fig. 4). In 4.9% of all plots, soil fertility had high or very

222   high levels of P. Organic soils were not as abundant in the very low and low classes of P content

223   but were much higher in the medium and very high classes of P content, compared with mineral

224   soils. Soils with high P deficiencies (very low and low P content) should be intensively fertilized

225   with P to protect high plant yields and increase the soil fertility (*Jadczyszyn, Kowalczyk &*

226   *Lipiński, 2010*). During the research period relatively large P fertilizer doses were used on the

227   farms studied, with an average of more than 11 kg P·ha^{-1} AL. These doses are comparable to the

228   level of P fertilization used on a Poland-wide basis of 10.3 kg P·ha^{-1} AL (*GUS 2019*). However,

229   these doses exceed the average amount of P fertilizers used in EU countries with well-developed

230   agriculture, such as in Germany where the dose is 7.5 kg P·ha^{-1} AL, or in Denmark and Sweden

231   where the doses are 5.5 kg P·ha^{-1} AL and 3.1 kg P·ha^{-1} AL, respectively (*GUS 2018*).

232   The distribution of soil pH and the available P forms concentration had a rather irregular spatial

233   arrangement (Fig. 5). Very low or low P content in the 0-30 cm layer of soil with very acidic and

234   acidic reaction was noted.

235

236   **Assessment of DPS indicator**

237   The DPS index was calculated based on the WSP in the analyzed soils and was in the range of

238   59.1-95.5% (average 88.4%) (Table 3). It should be noted that organic soils were characterized

239   by higher DPS values than mineral soils.

240   DPS values were set at 80% and higher for soils from 59 plots, including 48 mineral soils and 11

241   organic soils (Table 4). There was a high risk of P losses to water when the approach to

242   determining this risk suggested by Pöthig et al. (*2010*) was followed, however the accuracy of

243 this method is in question. In order to verify the method, additional studies determining the

244 relationship between WSP/DPS and P concentration in surface runoff need to be conducted.

245 Studies of this nature conducted in northwestern Poland (53°16'2.46"N, 14°46'9.42"E) showed

246 that the soluble phosphate concentration (P-PO$_4$) in surface runoff from mineral soils with a P

247 content of 10.3-86.1 mg WSP·kg^{-1} (average 23.2 mg WSP·kg^{-1}) ranged from 0.34 to 17.89

248 mg·dm^{-3} (average 3.11 mg·dm^{-3}) (*Pietrzak, Majewska & Wesołowski, 2016*). From mineral soils

249 with an average WSP content of 24.6 mg·kg^{-1} P-PO$_4$ in surface runoff were obtained under

250 specific conditions.

251 The high DPS values observed over the majority of the research area suggest that P fertilization

252 should be limited for environmental reasons. This conclusion is in contrast to the conclusion

253 made based on the results of the STP; more research is needed to reconcile the observed conflict

254 between the results of P soil tests obtained by agronomic and environmental testing methods.

255 Soil sorption properties researched in close proximity to the current research area as part of the

256 arable soils chemism monitoring in Poland can indirectly assist in understanding these

257 antagonistic assessments (Table 5). The results of this research indicated that the soil was

258 characterized by its content of exchangeable aluminum (ExAl), a relatively low cation exchange

259 capacity (CEC), and low soil buffering capacity. Typical CEC and ExAl values for similar soils

260 in Poland are from 7.18 to 10.38 and from 0.33 to 0.41 cmol(+)·kg^{-1}, respectively (*Fotyma &*

261 *Mercik, 1995*). A small ExAl content in the monitored soil could have been caused by the

262   applied P fertilization which resulted in the reduction of free Al^{3+} ions (*Filipek, 1989; Brzeziński*

263   *& Barszczak, 2009*) due to the precipitation of insoluble aluminum phosphates. In the soils

264   obtained from the majority of research plots, the Al^{3+} content level may have been low, which

265   may explain large deficiencies in available P as established by STP. More reliable assessments of

266   P content in the tested soils were obtained by the agronomic test method compared to

267   environmental test methods.

268

269   **Statistical analysis of research results**

270   There were numerous interactions between the analyzed soil indices. These interactions occurred

271   between indices describing mineral soils in which each parameter analyzed was correlated with

272   all others (according to the peer-to-peer mechanism) (Table 6). These revealed positive,

273   moderate-to-strong dependencies.

274   There was a relatively low correlation between the pH_{KCl} value of the soil and the P_{AL} content

275   determined in the layer up to 5 and 30 cm. However, this correlation indicates that by reducing

276   the acidity of soils, the available P would increase. The pH_{KCl} of soil is has a major and direct

277   impact on the P availability. In acidic soils, a large part of this component is immobilized by

278   manganese (Mn), iron (Fe) or aluminum (Al) compounds. The use of liming on such soils

279   increases the amount P available for plant uptake.

280   The P_{AL_w2} and P_{AL_w1} contents were most strongly correlated with each other, which

281   indicated that P was uniformly accumulated in the topsoil (0-30 cm). Therefore, the data

282   regarding the P state may prove equally useful to quantify P loss in surface runoff from

283   agricultural land at each of the mentioned levels. The possibility of using soil samples from

284   levels deeper than 5 cm to assess the risk of P losses in surface runoff was also suggested by

285   Fischer et al. (*2018*) in studies conducted in Brazil that used P determinations in the 0-20 cm

286   layer using the Mehlich-1P test (M1P) to calculate the DPS indicator values on the basis of the

287   M1P-WSP correlation as determined by a set of soil samples.

288   There were fairly strong correlations between $WSP_{\_w1}$ and P_{AL} content. Similarly strong

289   relationships were found between WSP and P_{AL} content in Brazilian and German soils defined

290   by M1P and CAL (calcium-acetate-lactate) methods based on the P-extraction by a mixture of

291   calcium lactate and calcium acetate (*Fischer, 2018*). In case of such correlations, it is possible to

292   convert the results obtained with one method to another with great accuracy. The existence of a

293   relatively strong relationship between $WSP_{\_w1}$ and P_{AL_w2} and P_{AL_w1}, continued as the latter

294   two indices also remained in a strong relationship with the DPS indicator as a result that DPS is a

295   function of $WSP_{\_w1}$ (R=1).

296   While all the analyzed indices in mineral soils were correlated, in organic soils only P_{HCl_w1} and

297   P_{HCl_w2} were statistically correlated, with a moderate degree of correlation (Table 7), ignoring

298   the natural relationship between DPS and $WSP_{\_w1}$.

299   The correlation between the P_{HCl} content in organic soil at depths of 0-5 and 0-30 cm was weaker

300   than in mineral soils, which may be due to the fact that they were not usually mixed when used

301   and therefore did not favor the homogenization of their top layer composition, including P

302   content. The lack of correlation between WSP_w1, P_{HCl}_w2, and P_{HCl}_w1 indicates that P

303   transfers from soil to water and to 0.5 mol HCl extracts differently and in disproportionate

304   amounts due to their different extraction possibilities.

305

306   **Discrepancy between DPS indicator and STP' results**

307   In the light of the results and analyses, the risk of P loss to waters based on the DPS is arguable.

308   The overall percentage of agricultural plots with soils at high risk for P loss by surface runoff

309   (DPS $\geq$ 80) was 96.7%, correlating with 96% of plots that had mineral soils and 100% of plots

310   that had organic soils. The obtained results indicate that soils were overly supplied with P and

311   suggest that measures need to be taken in this area to prevent its outflow to waters, e.g. by

312   decreasing phosphate fertilizer applications. However, the results of STPs revealed that in order

313   to obtain satisfactory crops, the P content in assessed soils should be significantly increased

314   rather than decreased (therefore, in terms of soil P management various or even contradictory

315   conclusions emerge from environmental and agronomic assessments). Deficient soils were

316   characterized by very low or low levels of P. In the case of plots with mineral soils, 72% were

317   affected by this problem. In cases of serious P deficiencies in the soil, relatively small amounts

318   of this component were found in the surface runoff (*Pietrzak, Wesołowski & Brysiewicz, 2017*).

319   Given the episodic character of runoff, the risk of surface water quality problems under these

320   conditions should not be overestimated and STP and environmental soil P tests may have yielded

321   opposite assessments due to the P retention capacity in deficient soils. Such soils may be marked

322   by low P content as determined by an agronomic test method and a high risk of P release (*Nair &*

323   *Harris, 2004; Nair et al., 2010*).

324   With regard to the STP, the vast majority of analyzed soils require increased applications of

325   phosphate fertilization and liming in order to optimize their pH for agricultural purposes. This

326   treatment would increase the solubility of the bound form of P in the soil and thus increase the

327   plant-available P. This treatment would be productively justified but could be considered

328   unnecessary in terms of WSP analysis.

329   Doubts over the adequacy of determining the risk of P loss from soil to water by means of DPS

330   threshold values were increased by the results of the assessment conducted with respect to all

331   analyzed organic soils, which were mainly under grasslands. DPS for these soils exceeded 80%

332   each time so the risk of P loss to waters was high. However, it is difficult to take it as a deciding

333   conclusion as grassland is a biological filter that protects against the release of pollutants into

334   waters. This approach overlooks the contribution of landform features to the uncertain risk of P

335   loss in surface runoff from agricultural soils to waters as determined by the DPS index. In these

336   assessments, the inclination factor should be taken into account as it contributes to the risk of

337 surface runoff (Table 8); significant landfalls which undoubtedly affected the dynamics of P

338 outflow to waters were identified in the research area. The outflow was shaped by a number of

339 other factors, including the physical and chemical soil properties (pH and organic matter

340 content), soil and plant cultivation methods and atmospheric conditions (*Ulen, 2013; Sapek,*

341 *2014)*. These factors should be considered comprehensively in the identifying of areas

342 susceptible to P losses. This approach is contained in a P index (*Lemunyon & Gilbert, 1993;*

343 *Sharpley et al., 2003*), which is a measure of soil vulnerability to P movement from the field site

344 to waters. The P index is a widely used tool in the USA and Europe to assess the risk of P losses

345 from agricultural landscapes to surface waters (*Buczko & Kuchenbuch, 2007*).

346 The problem of determining the risk of P loss in surface runoff from agricultural soils to waters

347 is complex. The assessment of such a risk should not depend solely on the value of the DPS

348 index. Therefore, the DPS indicator should be considered in conjunction with a set of parameters

349 characterizing the possibility of P losses from agriculturally used soils to watercourses and water

350 reservoirs.

351

352 **Conclusion**

353 The research was conducted on a typical undulating area of agricultural land in the Puck

354 Commune, 78.2% of which consisted of arable land and 21.8% of grassland. In terms of

355 mechanical composition, agricultural soils were predominantly medium and light textured,

356   whereas alluvial soils were entirely of organic origin. The majority of the soils were

357   characterized by high acidity (more than 62% of agricultural plots had a very acidic or acid

358   reaction) and a deficiency of plant-available P. In the latter case, over 62% of the analyzed soils,

359   including 72% of mineral soils and over 18% of organic soils, were characterized by very low

360   and low P content. The DPS exceeded 80% in almost all of the assessed soils as determined on

361   the basis of P content extracted in the water extract. There was a high risk of P loss in surface

362   runoff to water after taking into the account the existing criteria of the DPS index assessment.

363   However, this assessment should be approached cautiously as it does not correspond to the

364   results of the agronomic assessment of the P content in soil in terms of the requirements for the

365   application of phosphate fertilization. It also disregards other factors affecting P loss in runoff,

366   such as the type of crop or area inclination.

367   The research results show that the risk assessments of P losses from agricultural soils performed

368   on the basis of soil P content testing with an environmental test method (e.g. using WSP content

369   and calculated DPS indicator) and an agronomic one (e.g. using P-AL content) can be

370   antagonistic. This indicates that there is still a problem in determining the risk of P loss in

371   surface runoff from agricultural land to water and further research is needed to develop a

372   solution.

373

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Figure 1

Correlation between DPS and WSP indicators of soils; own elaboration (*Pöthig et al., 2010*).

Explanation: r^2 – value refers to the data of *Pöthig et al., 2010*.

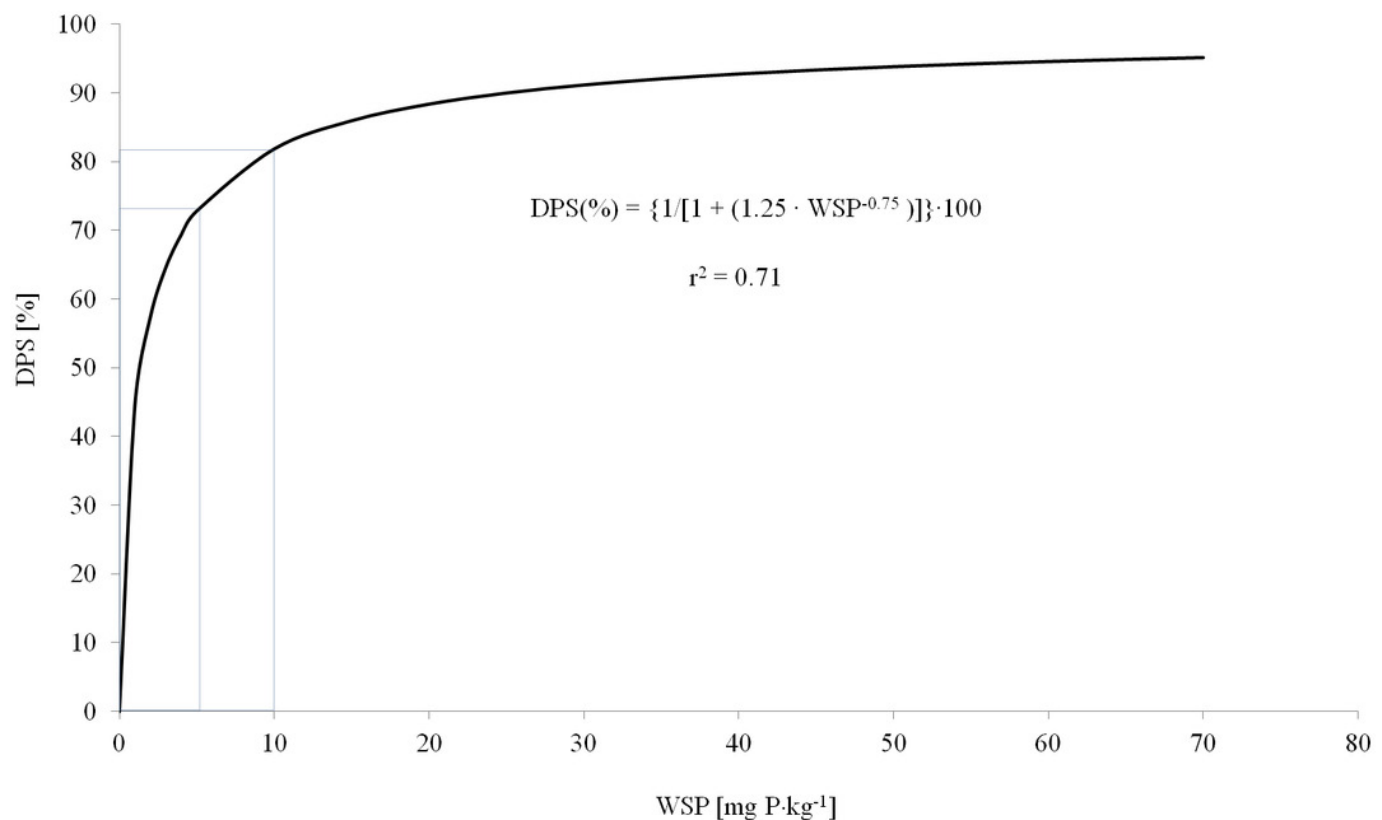



Figure 2

View of an exemplary agricultural plot from the research area and the shape of its longitudinal profile (Google Earth Pro 7.3.2.5776.2019. Agricultural plot in Sławutowo (Poland) 54°40'12.58"N, 18°21'1.79"E, elevation 40M. 3D map. Viewed 22 February 2019)

Map Credit: Google Earth, Digital Globe (C) 2018

Figure 3

Distribution of soil pH in tested agricultural plots in the 0-30 cm layer.

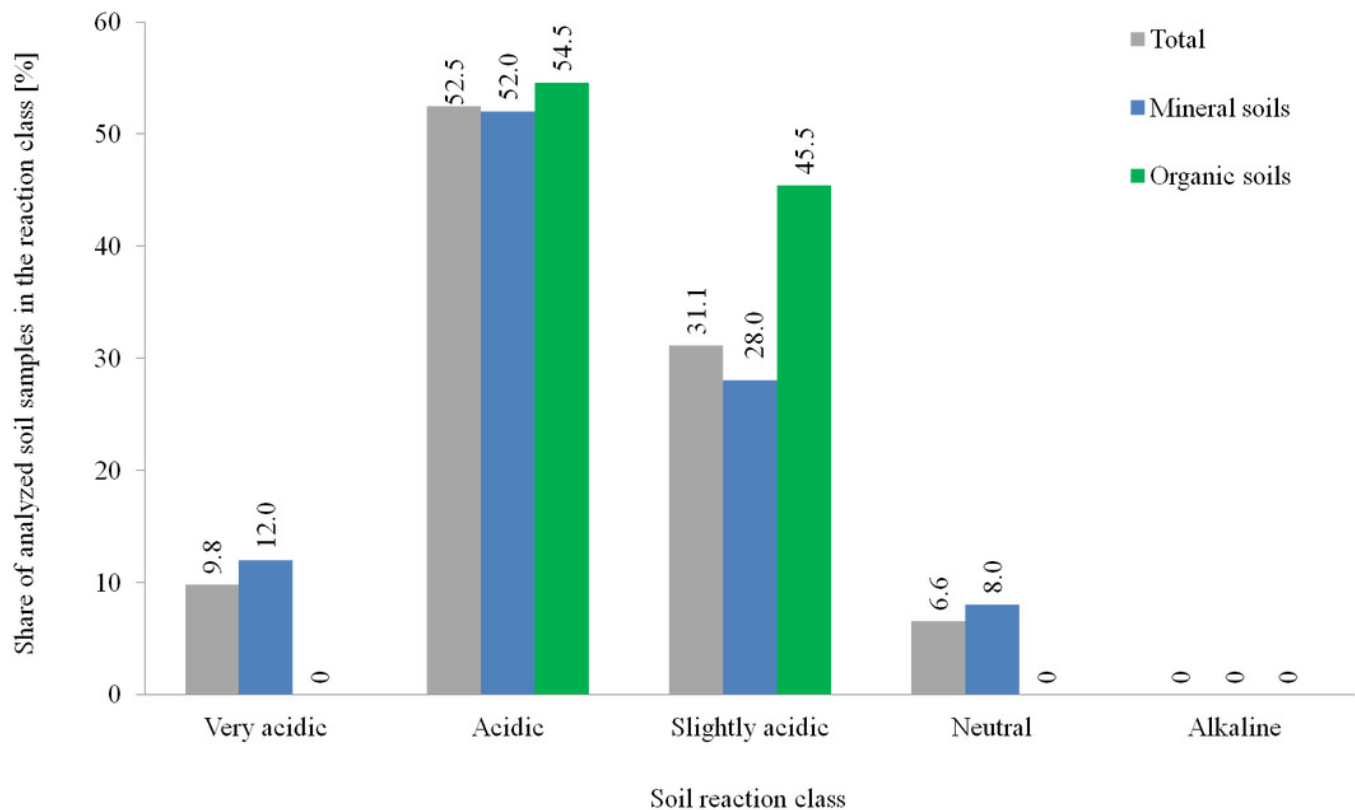



Figure 4

Distribution of soil P content in tested agricultural plots in the 0-30 cm layer.

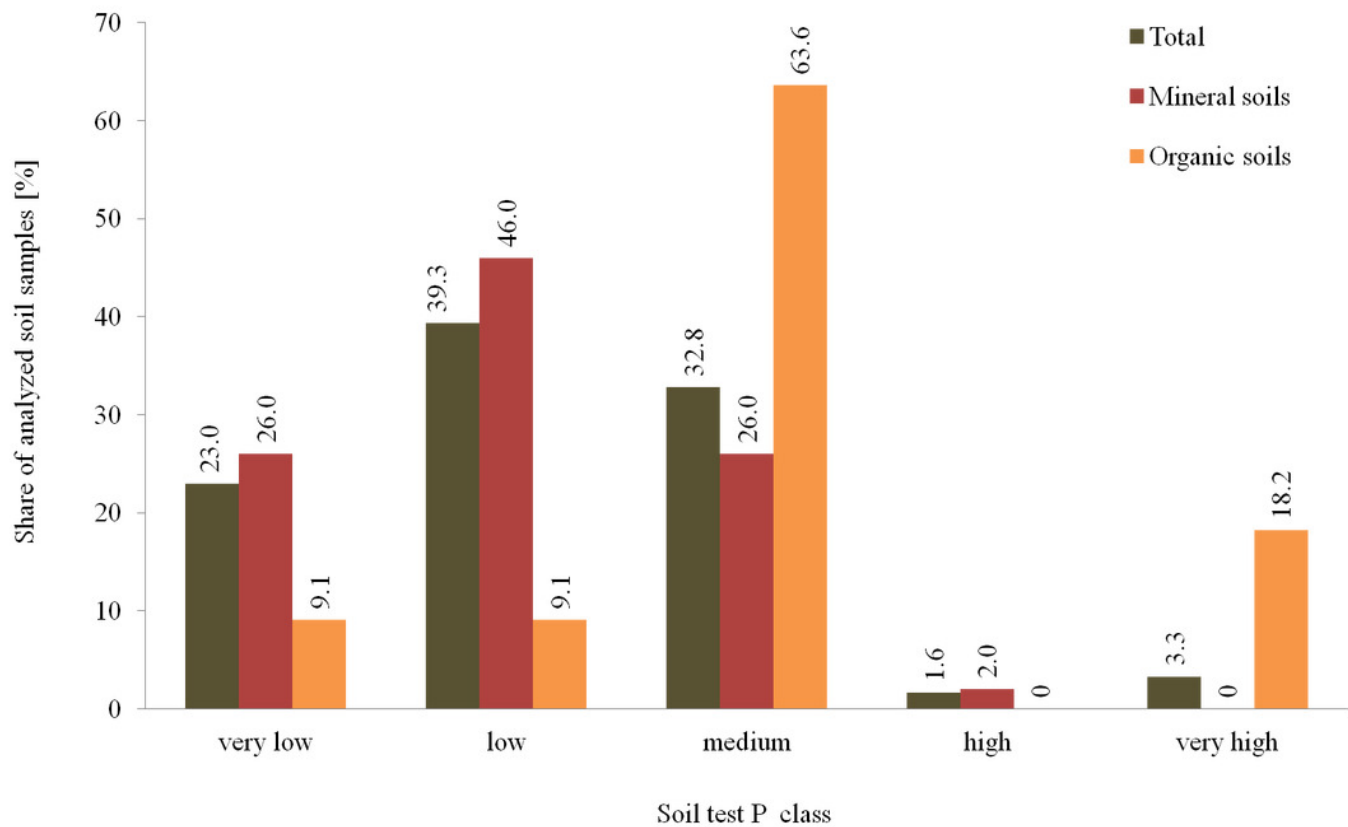



Figure 5

Spatial arrangement of studied agricultural plots in the Puck Commune with marked soil pH and P content in the 0-30 cm layer; own elaboration.

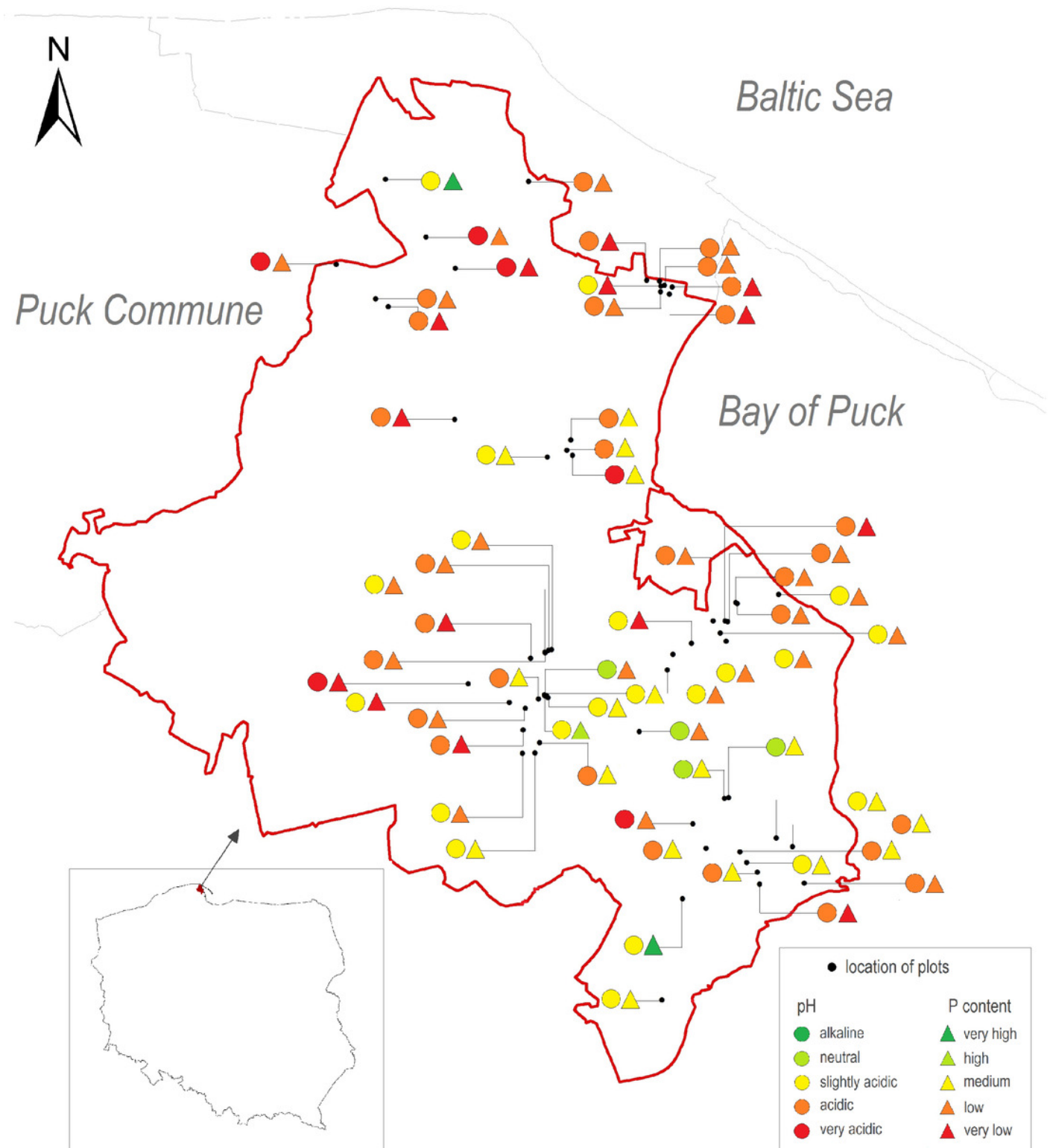
Baltic Sea

Puck Commune

Bay of Puck

location of plots

pH
- alkaline
- neutral
- slightly acidic
- acidic
- very acidic

P content
- very high
- high
- medium
- low
- very low

Soil test P concentrations according to the Polish agronomic interpretation; own elaboration (*PN-PN-R-04023*; *PN-R-04024:1997*).

Concentration class	Content, mg P·kg⁻¹ of soil dry matter	
	mineral soils	organic soils
very low	≤ 22	≤ 174
low	(22-44]	(174-262]
medium	(44-65]	(262-349]
high	(65-87]	(349-523]
very high	> 87	> 523

Distribution of mineral P fertilizers consumption in a group of 22 farms.

Specification	P fertilizers doses, kg P·ha⁻¹ AL					
	0	(0-5]	(5-10]	(10-15]	(15-20]	>20
Share of farms, %	13.6	9.1	22.7	31.8	4.5	18.2

Statistical characteristic of the DPS indicator for studied plots.

Explanation: n – number of samples, X – mean, SD – standard deviation, Max – maximum value, Min – minimum value.

Parameter	DPS value, %		
	mineral soils (n=50)	organic soils (n=11)	total soils (n=61)
X	87.8	91.4	88.4
SD	5.7	3.4	5.5
Max	94.4	95.5	95.5
Min	59.1	85.1	59.1

Share of agricultural plots with soils in various DPS classes.

DPS classes, %	Risk of P loss from soil:	Type of soil		
		mineral	organic	total
		Number of plots (share, %)		
70<	lack	1 (2.0)	0 (0.0)	1 (1.6)
[70-80)	acceptable	1 (2.0)	0 (0.0)	1 (1.6)
≥80	big	48 (96.0)	11 (100.0)	59 (96.7)

Sorption properties of brown soil made of sandy loam which originates from agriculture land located near the research area (54°45′22″N, 18°16′44″E) according to data from 2015 (*Siebielec et al., 2017*).

Parameter defining soil sorption properties	Value
Hydrolytic acidity (HAC), cmol(+)·kg^{-1}	4,65
Exchangeable acidity (EA), cmol(+)·kg^{-1}	0,46
Exchangeable aluminium (ExAl), cmol(+)·kg^{-1}	0,27
Total exchangeable bases (TEB), cmol(+)·kg^{-1}	3,99
Cation exchange capacity (CEC), cmol(+)·kg^{-1}	8,64
Base saturation of soil (BS), %	46,16

Correlations between analysed indices of mineral soils.

Explanation: pH_{KCl} – soil acidity measured in a suspension of KCl solution; P_{AL} – P content in soil determined in acid ammonium lactate; WSP – water soluble P content; DPS – degree of P saturation; w1 – soil layer 0-5 cm; w2 – soil layer 0-30 cm; * - correlation significant at α = 0.05; ** - correlation significant at α = 0.01.

Index	pH$_{KCl}$	P$_{AL\_}$w1	P$_{AL\_}$w2	WSP_w1	DPS
			Spearman rank correlation coefficient (R)		
pH$_{KCl}$		0.3244*	0.3655**	0.4017**	0.4017**
P$_{AL\_}$w1			0.9552**	0.8474**	0.7474**
P$_{AL\_}$w2				0.8176**	0.8176**
WSP_w1					1**

Correlation between analysed indices of organic soils.

Explanation: P_{HCl} – P content in soil determined in the extract of 0.5 mol HCl $\cdot$ dm^{-3}; for additional explanations refer to Table 6.

Index	pH$_{KCl}$	P$_{HCl}$_w1	P$_{HCl}$_w2	WSP_w1	DPS
	Spearman rank correlation coefficient (R)				
pH$_{KCl}$		0.4771	0.4828	0.4863	0.4863
P$_{HCl}$_w1			0.6196*	0.0866	0.0866
P$_{HCl}$_w2				0.3091	0.3091
WSP_w1					1**

Assessment of runoff risk for all soil types; own elaboration (*DEFRA 2005*).

Specification	Inclination:			
	>7° (12.3%)	3-7° (5.2-12.3%)	2-3° (3.5-5.2%)	<2° (3.5%)
runoff risk	high	moderate	lower	lower