Influence of the hydrological factor on the productivity of winter wheat on the drained soils of the moraine plain

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Abstract In 2010, 2017 and 2019 hydrological conditions and productivity indicators of winter wheat were studied on four groups of soils in a field with hilly terrain within the Sambian moraine plain (Kaliningrad region). The effectiveness of the fertilization system depends on the amount of precipitation and hydrological conditions in the field. The stability of obtaining high yields decreases in the series: Cambisols on hill tops, Stagnic and Gleyic Cambisols on slopes, Gleysols in open depressions, Gleysols in closed depressions.

1. Introduction

Topography has a great impact on the soil and crop. The alternation of hills and depressions within the arable field creates strong soil variability in the degree of hydromorphism [1–4]. The productivity of agricultural crops differs by spatial heterogeneity [5–9]. This problem is especially relevant in regions with a high proportion of drained soils. In the Kaliningrad region, 82% of the soil on agricultural land is drained. In years with a large amount of precipitation, 38.5% of the drained soils have an unsatisfactory reclamation state [10]. Therefore, the success of agriculture depends largely on hydrological and agrometeorological conditions.

Aim of research is to study the influence of the hydrological factor on the productivity of winter wheat on the drained soils of the moraine plain when optimizing nitrogen nutrition.

2. Objects and methods of research

The research was carried out in 2010, 2017 and 2019 on an arable field (the experimental area of "Pereleski") in the Zelenogradsk district of the Kaliningrad region within the Sambian hilly-moraine plain, South-Eastern Baltic Region.

The field area is 100 ha. Coordinates of the extreme points of the field: North-Western part of N 54° 47' 55" E 20° 22' 28", North-Eastern part of N 54° 48' 14" E 20° 23' 33" South-Western part of N 54° 47' 27" E 20° 23' 28", South-Eastern part of N 54° 47' 40" E 20° 24' 01".

The landform is an alternation of asymmetric hills and depressions between them. The soil cover of the field is contrasting. Soil morphology was studied in soil pits. Soil names are given according to WRB [11]. On the tops and slopes of the hills there are Cambisols (including Stagnic and Endogleyic Cambisols). Parent materials for Cambisols are boulder moraine and water-glacial leached sands, sandy loam, loam with layers of clays. Cambisols are most often sandy loam texture. The depressions are
occupied by Gleysols formed on carbonate deposits of complex genesis (lake-glacial clays, moraine loam and sandy loam with some deluvium).

All Stagnic and Gleyic soils are drained by subsurface tile drainage with water discharge into open channels. The water outlet parts of the subsurface collectors in the channel slopes are damaged. This blocks the flow from the drains to the main channel. Such circumstances lead to the fact that on drained gley soils, waterlogging occurs annually in the spring and autumn period. The following rotation of crops was practiced on the field: 2009 – winter rape, 2010 – winter wheat, 2011 – winter rape. In the period 2012 – July 2016, the soil was not plowed. In 2017 – arable land with winter wheat, in 2018 – winter rape, in 2019 – winter wheat.

Winter wheat was sown in all the studied years in the second decade of September, and harvesting in the first or second decade of August. Pre-sowing fertilizer was complex N24P45K90 kg/ha of primary nutrient (p.n.).

During the three years studied, the technology of growing winter wheat has evolved. This was reflected in the use of more productive varieties, effective chemical plant protection products (PPP), and, most importantly, in the improvement of nitrogen nutrition (table 1).

Table 1. The technology of growing winter wheat in the main vegetation period (April–August).

| Indicator                                      | 2010     | 2017     | 2019     |
|-----------------------------------------------|----------|----------|----------|
| Variety                                       | Zentos   | Skipetr  | Skagen   |
| Number of treatments (PPP)                    | 2        | 5        | 4        |
| Mineral fertilizers (p.n.) and stages of wheat development (BBCH⁶) | N70      | N70 (19–22) | N70 (19–22) |
| of wheat development (BBCH⁶)                  | (19–22)  | N26Mg5S44 (28–29) | N26Mg5S44 (28–29) |
|                                               |          | N52 (37–39) |          |
|                                               |          | N28 (55–59) |          |

⁶ BBCH-scale (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie, Germany) is used to identify the phenological development stages of plants.

Agrochemical properties of the arable horizon differed between Cambisols and Gleysols. In Cambisols, the amount of organic carbon is 1.28–1.39%, the content of mobile phosphorus is 115–137 mg/kg of soil, and mobile potassium is on average 130 mg/kg (extract 0.2 M HCl). Gleysols contain an average of 3.36% organic carbon, a large amount of mobile phosphorus (226 mg/kg) and potassium (181 mg/kg). All soils in the field have an acidic reaction of the medium (pH (KCl) 4.7).

Hydrological conditions and productivity of winter wheat on 16 soil areas depending on the topography were studied in the field: 1) four areas of Cambisols on hill tops; 2) four areas of Cambisols on hill slopes; 3) four areas of Stagnosols and Umbri Gleysols in open depressions; 4) four areas of Gleysols in closed depressions.

The hydrological conditions were characterized by the following indicators: the intensity of gleying in the soil profile, the period and depth of perched water formation in the soil, and the duration of surface flooding in closed depressions during the winter wheat growing period.

The moisture regime was studied by drilling 2 times a month. The research period was from April to November each year. The analysis of field moisture content was made using the thermostat-gravimetric method and then converting the data to the volumetric moisture content. Physical properties of soils were determined: particle density (PD) – pycnometrically; soil bulk density (D) with the method of cutting rings (cylinders); total porosity (TP) and porosity of aeration – by calculations [12].

Test sheaves of winter wheat were harvested in August at full ripeness in each soil area in 4-fold repetition on sites of 1 m². We studied the structure of the crop (plant height, length of the ear without spines, number of grains in the ear) and biological yield (weight of grain, straw and their sum; weight of 1000 grains).

Data on the amount of precipitation was taken from the Kaliningrad meteo-station (closest to the field). Statistical and graphical data processing was performed in Excel.
3. Results and discussion
In 2010 and 2019, precipitation was close to the long-term average, and 2017 was very wet (table 2). During the main growing season of winter wheat (April–August) the amount of precipitation was close to the average annual norm in 2010 and 2017, and in 2019 it was 69 mm lower.

Table 2. Total precipitation for the year and for the main growing season of winter wheat in 2010, 2017, 2019.

| Indicator / years                           | 2010 | 2017 | 2019 | Long-term average values (1949–2013) |
|--------------------------------------------|------|------|------|-------------------------------------|
| Annual precipitation, mm                   | 772  | 1090 | 778  | 781                                 |
| Precipitation (mm) for the period April – August | 352  | 322  | 270  | 339                                 |

The degree of soil hydromorphism is expressed in the presence and intensity of gleying in the profile. Gleying occurs with constant or periodic waterlogging of soil horizons [1].

Of the four areas of brown earth on the tops of hills, only one soil was automorphic (without evidence of gleyic or stagnic properties). In the profile of this soil, no perched water is formed. The other three soils are stagnic. The upper boundary of the horizon Bg is at a depth of 30–50 cm. Deeper, the entire profile and the parent sediment have stagnic properties (the blue-gray areas occupy 30–50% of the horizon area). The presence of silty horizons in the profile and clay layers in space creates the conditions for temporary excessive moisture, additional accumulation of water and formation of Stagnic Cambisols [13]. In the areas of Stagnic Cambisols on top hills in the spring (March–April), the perched water was present at a depth of 110–150 cm with a 33% probability (in one profile out of three). In the autumn period, the perched water did not form, if the amount of precipitation is less than 220 mm in September–November. Perched water did not have a negative effect on winter wheat in autumn, and in spring it was a source of additional moisture.

In Cambisols on the hill slopes, stagnic properties occur from a depth of 40–50 cm in the illuvial horizon Bg. Waterlogging of soil occurs as a result of atmospheric precipitation and lateral subsurface flow from the hill tops. In spring, in Stagnic Cambisols, the perched water was at a depth of 80–110 cm. In the autumn, with a total precipitation of about 230 mm (2010 and 2016), the perched water was formed in November at a depth of 80–100 cm (50% probability) and at a depth of 100–150 cm (50% probability). The autumn period of 2018 was arid in region (137 mm of precipitation) and there was no perched water in the profile of Cambisols on the slopes. The flowing perched water, together with the surface runoff, carries out part of the nutrients from the mineral fertilizers. This process worsens the growing conditions for winter wheat on the slopes.

Signs of gleyic properties in Umbric Gleysols are found in open depressions immediately below the arable horizon, and in closed depressions already from the surface. In the dry summer season, bright films of amorphous iron hydroxide are formed on the surface of the aggregates. From a depth of 20–40 cm, a continuous gley horizon (G) is formed. Part of the gley horizon is secondary oxidized (Go) as a result of drainage. Deeper than 50–105 cm, the gley horizon becomes reduced (Gr), which indicates a permanent reducing environment in this part of the profile.

Gleysols in open and closed depressions differ in the degree of surface and ground waterlogging. In the profile of the soils of open depressions, groundwater table is always present in March–April at a depth of 60–110 cm. In autumn, the groundwater table is formed at the beginning of November. Occasionally, it can occur during prolonged heavy rainfall in September or October. According to the drilling data in the summer, the groundwater table was found at a depth of 130–150 cm in 2010 and 2017. Consequently, the profile of Gleysols was constantly in the zone of capillary saturation.

Seasonal surface flooding is a characteristic feature of the hydrologic regime of Gleysols in closed depressions. Water accumulates over local impermeable layers (clay layers) in the subsurface horizon. In spring, the duration of surface waterlogging continued: until the beginning of April (2019), until the
end of April (2010), until May 10 (2017). In autumn, flooding began in November. In spring and November, the groundwater table was located at a depth of 70–100 cm under impermeable layers. In 2018, due to the dry autumn, there was no surface waterlogging, and the groundwater table was located at a depth of 90–130 cm with intermittent lenses in space.

For good development of winter wheat in autumn and spring, an optimal ratio of water and air in the arable horizon (0–20 cm) is necessary. With air porosity (AP) in the profile (or horizon) below the critical level of 10%, unfavorable conditions for root growth occur, and at levels below 5%, anaerobic processes lead to the development of reducing conditions [14].

Air porosity was determined in October (leaf development BBCH 12–17) and April (renewal of vegetation BBCH 18–28). The results showed that there are no differences between the Cambisols on the hill tops and on the slopes (table 3).

**Table 3. Average values of air porosity (%) in the arable horizon (0–20 cm) of soils in April and October.**

| Year | Part of the month | Cambisols | Gleysols |
|------|------------------|-----------|----------|
|      | Hilltops | Hill slopes | Open depressions | Closed depressions |
|      | October |          |          |          |          |
| 2009 | 1     | 24±2 | 23±3 | 18±1 | 15±1 |
|      | 2     | 22±1 | 20±2 | 15±2 | 10±2 |
| 2016 | 1     | 27±3 | 27±1 | 15±1 | 10±2 |
|      | 2     | 23±2 | 25±2 | 9±1  | 5±1  |
| 2018 | 1     | 28±1 | 27±1 | 22±2 | 20±2 |
|      | 2     | 26±2 | 26±2 | 18±2 | 16±2 |
| 2010 | 1     | 25±2 | 24±3 | 14±2 | 0    |
|      | 2     | 27±3 | 25±2 | 18±1 | 5±1  |
| 2017 | 1     | 24±3 | 23±2 | 10±2 | 0    |
|      | 2     | 20±2 | 19±2 | 11±1 | 0    |
| 2019 | 1     | 25±2 | 25±3 | 18±1 | 8±1  |
|      | 2     | 28±1 | 26±1 | 22±1 | 13±1 |

The air porosity in Gleysols of open depressions is significantly lower than in Cambisols. The actual values of the Student's test (t) varied from 3.6 in 2018–2019 up to 8.6 in 2016–2017 with smallest significant difference 3.3. Unfavorable conditions for the development of winter wheat roots developed in October 2016 and April 2017.

In closed depressions, the air porosity is lowest compared to top hills, slopes, and open depressions. This fact led to stress in winter wheat already at the stage of leaf development in October (2009 and 2016). Surface flooding in March and April is the cause of crop death. The remaining rare plants get the conditions to continue development until the end of April or in May.

Correlation analysis showed a strong relationship between the air porosity in the arable soil layer (in October and April) and the number of productive stems. For the first half of April (resumption of winter wheat vegetation), the correlation coefficient was 0.90 (2010), 0.94 (2017), 0.85 (2019).

The crop structure and biological yield of winter wheat are presented in tables 4–5. The height of plants depends to a large extent on varietal characteristics and the use of growth-regulating chemical. Selection is directed towards reducing the length of the stem. Growing high-yield short-stemmed varieties (Skagen) led to a change in the straw: grain ratio in 2019 in favor of grain weight (table 5). On
the background of the optimization of nitrogen nutrition from 2010 to 2019, increased length of ear, number of grains per ear and grain weight in plants grown on the Cambisols on tops and slopes of hills.

**Table 4.** Crop structure of winter wheat in 2010, 2017, 2019 on soils of different degrees of hydromorphism.

| Soils and landforms | Year | Number of stalks with an ear per 1 m², pieces | Plant height, cm | Ear length without awns, cm | Number of grains per ear, pieces | Weight of 1000 grains, g |
|---------------------|------|---------------------------------------------|-----------------|-----------------------------|----------------------------------|--------------------------|
| CMa, CMgb          | 2010 | 405.4±14.1                                  | 98.7±1.5        | 7.1±0.2                     | 31.2±1.5                        | 43.7±0.8                 |
| Hilltops            | 2017 | 318.5±27.0                                  | 82.6±0.6        | 8.5±0.1                     | 35.5±0.8                        | 52.6±1.1                 |
|                     | 2019 | 415.0±9.8                                   | 62.9±0.9        | 8.8±0.1                     | 36.8±1.0                        | 48.6±1.8                 |
| CM, CMg             | 2010 | 428.7±23.3                                  | 84.7±1.3        | 6.1±0.1                     | 25.8±0.9                        | 40.7±0.8                 |
| Hill slopes         | 2017 | 313.5±21.5                                  | 77.8±0.6        | 7.8±0.1                     | 29.7±0.7                        | 51.5±1.1                 |
|                     | 2019 | 472.9±31.2                                  | 64.1±1.0        | 8.9±0.1                     | 35.3±0.9                        | 46.8±1.8                 |
| STc, GSd            | 2010 | 421.0±23.9                                  | 77.1±1.2        | 5.8±0.2                     | 23.4±1.2                        | 40.2±0.7                 |
| Open depressions    | 2017 | 239.0±53.1                                  | 60.1±1.6        | 5.8±0.2                     | 19.9±1.3                        | 40.2±1.9                 |
|                     | 2019 | 484.8±33.7                                  | 67.0±1.0        | 8.7±0.2                     | 36.0±1.3                        | 48.1±1.6                 |
| GS                  | 2010 | 8.1±1.0                                     | 41.0±1.7        | 3.0±0.1                     | 4.2±0.2                         | 28.6±0.5                 |
| Closed depressions  | 2017 | 0                                          | 0               | 0                           | 0                                | 0                        |
|                     | 2019 | 89.8±20.2                                   | 47.0±1.0        | 7.7±0.2                     | 29.0±1.8                        | 44.8±1.7                 |

a Cambisols.
b Stagnic (Endogleyic) Cambisols.
c Stagnosols.
d Gleysols.
Texture of Cambisols is mainly sandy loam, while Gleysols is silt loam.

**Table 5.** Biological yield (t/ha) of winter wheat in 2010, 2017, 2019 on soils of different degrees of hydromorphism.

| Soils and landforms | Year | Grain and straw | Straw | Grain |
|---------------------|------|-----------------|-------|-------|
| CM, CMg             | 2010 | 11.84±0.52      | 7.46±0.37 | 4.39±0.18 |
| Hilltops            | 2017 | 10.67±1.23      | 5.03±0.71 | 5.63±0.60 |
|                     | 2019 | 11.90±1.64      | 4.88±0.59 | 6.86±1.00 |
| CM, CMg             | 2010 | 10.40±0.90      | 6.52±0.60 | 3.88±0.30 |
| Hill slopes         | 2017 | 9.62±1.16       | 4.74±0.57 | 4.88±0.76 |
|                     | 2019 | 12.16±0.78      | 5.79±0.42 | 6.38±0.45 |
| ST, GS              | 2010 | 7.25±0.86       | 4.41±0.42 | 2.84±0.23 |
| Open depressions    | 2017 | 4.73±2.12       | 2.62±1.14 | 2.11±0.99 |
|                     | 2019 | 13.22±1.04      | 6.3±0.27  | 6.91±0.82 |
| GS                  | 2010 | 0.02            | 0.01    | 0.01 |
| Closed depressions  | 2017 | 0              | 0       | 0 |
|                     | 2019 | 2.27±0.45       | 1.19±0.10 | 1.09±0.35 |

For wheat on Gleysols of open depressions, improving nitrogen nutrition is effective only against the background of optimal moisture and air porosity in the autumn and spring periods (2019). This is
reflected in the increase in the values of indicators of crop structure and biological yield due to additional nitrogen nutrition (migration of nitrates with surface and subsurface runoff from increases to decreases). However, a thickened stalk is formed, and grain maturation is delayed for 7 to 10 days. In conditions of waterlogging and low air porosity (2017), the fertilizer system does not have a positive effect on the productivity of winter wheat.

Gleysols in closed depressions are the most problematic soils. They do not manage to get a satisfactory yield even against the background of favorable weather conditions and the fertilization system (2019).

Data on crop structure and biological yield allow us to conclude that the most sensitive indicators to waterlogging are the number of grains in the ear and the weight of grain per unit area (table 6). Correlation analysis showed a strong negative dependence of winter wheat yield on the amount of precipitation during the growing season for soils of slopes and depressions (the correlation coefficient is higher than 0.8).

**Table 6.** Variation of winter wheat productivity on soils of slopes and depressions in % in relation to Cambisols on Autonomous positions in landscape.

| Landforms and soils   | Year | Plant height | Ear length | Number of grains per ear | Grain weight |
|----------------------|------|--------------|------------|--------------------------|-------------|
| Hilltops CM, CMg     | 2010 | 100          | 100        | 100                      | 100         |
| 2017                 | 100  | 100          | 100        | 100                      | 100         |
| 2019                 | 100  | 100          | 100        | 100                      | 100         |
| Hill slopes CM, CMg  | 2010 | 85.8         | 85.9       | 82.7                     | 88.4        |
| 2017                 | 94.1 | 91.7         | 83.7       | 86.7                     |             |
| 2019                 | 101.9| 101.1        | 95.9       | 93.0                     |             |
| Open depressions ST, GS | 2010 | 78.1         | 81.7       | 75.0                     | 64.7        |
| 2017                 | 72.7 | 68.8         | 56.2       | 37.5                     |             |
| 2019                 | 106.5| 98.9         | 97.8       | 100.7                    |             |
| Closed depressions GS | 2010 | 41.5         | 42.2       | 12.8                     | 0.2         |
| 2017                 | 0    | 0            | 0          | 0                        |             |
| 2019                 | 74.7 | 87.5         | 81.7       | 15.9                     |             |

Correlation analysis showed a strong negative dependence of the yield of winter wheat on the amount of precipitation during the growing season for soils on slopes and depressions (the correlation coefficient is higher than 0.8). The Kaliningrad region is located in a humid climate zone. Therefore, relatively favorable weather conditions (similar to 2019) are less common than years with high moisture. The stability of obtaining good yields decreases in the series: Cambisols on hilltops, Cambisols on slopes, gley soils in open depressions, Gleysols soils in closed depressions. The increased acidity of soils also does not allow the biological potential of the variety to be realized.

Let's move from the level of soil areas to the level of the field. It is important to know the area where the studied soils occur. As a result of a soil survey, it was found that Cambisols on hilltops occupy about 8% of the total field area. The proportion of Stagnic Cambisols on the slopes of hills is 35%. Gley soils at the foot of slopes and in open depressions between hills make up 32%. Gleysols in closed depressions are distributed over 25% of the field area. Thus, a decrease in the yield on gley soils in years with intensive development of waterlogging (table 6) leads to large economic losses. For winter wheat on soils in open depressions, losses averaged 1.55 t/ha in 2010 and 3.5 t/ha in 2017. On Gleysols in closed depressions, the death of crops occurred. In 2019, losses were reduced due to the recommendation not
to sow large (2–15 ha) closed depressions. There are two ways to use them: 1) technical works on surface water drainage (crevice, repair and local reconstruction of the drainage network, construction of water-absorbing well); 2) creation of cultural hayfields with moisture-loving grass.

4. Conclusion
In conditions of heterogeneous topography and contrasting soil cover pattern, the optimization of the fertilizer system significantly improves the productivity of winter wheat on automorphic and Stagnic Cambisols of the tops and slopes of hills (in the absence of pronounced erosion).

Hydrological conditions on gley soils (strong gleying, excessive moistening by slope runoff, low porosity of aeration in the autumn and spring in the arable horizon) are a limiting factor in the cultivation of winter wheat.

On drained gley soils in open depressions, the effectiveness of the fertilization system is shown only in years when the amount of precipitation is significantly less than the average annual values. On Gleysols in closed depressions due to seasonal surface flooding, more than 80% of crops are lost even in optimal precipitation years.

The higher the area of gley soils in the field, the lower the stability of obtaining the planned yield, the lower the payback from intensive fertilization, and the higher the risk of crop losses in wet weather conditions. This is typical for fields with unsatisfactory reclamation condition.

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