Exploring influence of spatial variability of soil hydro-physical properties on crop yield

Vladimir Badenko¹, Vitaly Terleev²

¹St. Petersburg State University, St. Petersburg, Russia
²St. Petersburg Polytechnic University, St. Petersburg, Russia

Correspondence: Vladimir Badenko, Saint-Petersburg State University, 10 Line VO, 24-33, St. Petersburg, 199178, Russia; vbadenko@gmail.com

Received: May 25, 2015 Accepted: June 19, 2015 Online Published: June 30, 2015
http://dx.doi.org/10.17830/j.eaj.2015.02.024

Abstract

Utilizing spatial variability in soil properties to make decision of various farming technologies has been explored. The objective of the work is the development of approaches taking into account spatial variability of hydro-physical properties of soils during plant’s production process simulation (wheat crop) using the AGROTOOL – the crop simulation model – in order to support decision making in practical adaptive landscape agriculture. The studies were conducted using a software package, which was based on coupling GIS with AGROTOOL. Impact of spatial variability of soil hydro-physical properties on crop yield has been evaluated.

Keywords: soil water retention; GIS; yield production modeling; soil hydro-physical properties

How to cite this paper: Badenko, Vladimir, & Terleev, Vitaly (2015). Exploring influence of spatial variability of soil hydro-physical properties on crop yield. European Agrophysical Journal, 2(2), 24-33. http://dx.doi.org/10.17830/j.eaj.2015.02.024
1. Introduction

In agricultural production systems, understanding how to control soil moisture variations can improve effectiveness of fertilizers, manure applications and crop yield management (Zhu & Lin, 2011; Schmidt et al., 2007; Kar et al, 2004, Kurtener & Badenko, 2000). Identification and prediction of soil moisture at different depths and scales have great importance in a wide range of agronomic, agrophysical, and environmental studies (Martinez et al., 2013; Williams et al., 2003; Moret-Fernandez et al., 2011). Understanding and describing spatial and temporal variability of soil water content presents one of the major challenges in modern agrophysics (Martinez et al., 2013; Panet et al., 2012; Terleev et al., 2010; Martinez-Fernandez & Ceballos, 2003). Spatial variability of soil water content has been interpreted using several modeling approaches that accounted for spatial variability in soil hydro-physical properties and precipitation (Kar et al, 2004; Dexter & Bird, 2001; Gerke & Van Genuchten, 1993). Both local controls, such as vertical dominant fluxes governed by soil hydraulic properties and vegetation, and non-local controls, such as lateral processes induced by topography or climate variability, affect spatial and temporal soil water contents across fields (Grayson et al., 1997). Therefore, the inclusion of spatial variability of hydro-physical parameters in the decision-making systems for agricultural landscapes coupled with GIS technology is an actual task (Badenko et al, 2014a; Kar et al, 2004; Aref’ev et al., 1998; Kurtener & Badenko, 2001; Kurtener & Krueger, 2014; Torbert et al, 2014).

The objective of this research was the development of approaches which takes into account spatial variability of hydro-physical properties of soils during simulations of plant production process (wheat crop) using the AGROTOOL, for the purpose of making decisions support practical for adaptive landscape agriculture.

The crop simulation model AGROTOOL (Medvedev et al., 2015; Poluektov et al., 2002a) was developed to estimate the agro-meteorological crop state and to forecast crop yield, as well as to support and analyze the sowing, irrigation, fertilization and harvesting management. Plant growth imitation algorithm is invariant, so the model itself is a generic crop simulator which is applicable for modeling many different species such as: barley, winter and spring wheat, alfalfa, maize and others (Badenko et al, 2014b). It should also be noted that the AGROTOOL model was created and tested for over 30 years period in Russian Federation. Therefore, the expectation is that the simulation results will generate realistic predictions.

To estimate the impact of spatial variability of soil properties on yield process, a special information-analytical system has been developed. It consists of a GIS coupled with the AGROTOOL model. Additional soil hydro-physical properties modeling package has been added to the system (Terleev et al., 2010). The study includes field experiments conducted to determine the hydro-physical properties of soil. Description of the experiment is also presented. All of the results are specific to the North-West of Russia.

2. Materials and Methods

In this study, the exploration of the influence of spatial variability of soil hydro-physical properties on crop yield management included the following steps:
1. Field experiments were conducted to determine hydro-physical soil properties, including the following steps: selection of sampling points, examining soil profiles and soil testing in the laboratory.

2. Survey data was prepared (checking and correction) and loaded into a GIS database. The formation of management units in GIS environment and the calculation of values for the hydro-physical properties for these units were performed.

3. Computer simulations in AGROTOOL were carried out for the management units with the actual weather conditions of 2007-2013.

The studies were conducted on the basis of an agriculture landscape of Menkovo Experimental Station (MES) of Agrophysical Research Institute, located in the Leningrad region, Russia (see Fig. 1 on the left). The selection of the sampling points was based on the hypothesis that wheat crop yield could be used as a representation of soil hydro-physical properties spatial variability. Existing data was used for the agricultural field located at MES with a spatial resolution of 5x5 m² (see Fig.1 on the right).

Fig. 1. Menkovo Experimental Station near Saint-Petersburg, Russia, (on the left). Sample points (#30-35) and wheat crop yield with spatial resolution 5x5 m² (on the right).

In order to determine the values of agrophysical soil properties of this field (Fig.1 on the right) and to create the GIS database, soil samples were taken from six soil profiles to a 1 m depth. In each of these profiles and each soil layer identified, soil samples had been taken for experimental studies of soil indicators needed for the modeling in AGROTOOL. These indicators included soil hydrological constants (hygroscopic water content, wilting point, field capacity and porosity), bulk density, solid particles density, and saturated hydraulic conductivity of soil. These data allowed a complete simulation the water
retention curve to be conducted (Terleev et al., 2010; Poluektov et al., 2002; Poluektov & Terleev, 2002; Poluektov et al., 2003; Poluektov & Terleev, 2005).

Furthermore the soil samples were tested in the laboratory. Standard techniques were used to determine agrophysical soil properties. In particular, pneumatic press (Soilmoisture Model 1000 Pressure Membrane Extractor, 15 bar) was used for measure moisture values at different pressures. These data we used for the determination of the water retention curve for each soil layer.

The simulation algorithm of AGROTOOL can be written in the form of a recurrent discrete expression as follows:

\[ x(k+1) = f(x(k), a, w(k), u(k)), \quad x(0) = x_0, k=0,1...T \]  \hspace{1cm} (1)

where \( x \) - vector of dynamic state variables; \( a \) - vector of constant parameters; \( u \) - vector controlled external impacts (agricultural technologies); \( w \) - vector uncontrollable external impacts; \( k \) - the time step for the model (time step is equal to one day), \( f \) - the evolution operator (a logical essence of the simulation algorithm) (Badenko et al, 2014b). The vector \( a \) includes hydro-physical parameters.

AGROTOOL consists of several rather independent, scalable and replaceable modules, interacting with each other at every time step. The module of soil water dynamics calculates the moisture balance in frames of multi-layer presentation of one meter soil profile (10 layers with 10 cm depth). The available water content is determined taking into account rainfall intensity, plant transpiration, water evaporation from soil, percolation and moisture exchange within soil layers (Poluektov et al., 2002b). The intensity of all the processes caused by the water transport are determined by water potential in soil, so the soil water retention curve is used for simulating these processes (Poluektov & Terleev, 2005). The dependency of volumetric moisture content on water potential in soil is approximately estimated on the base of soil-hydraulic constants such as field capacity, permanent wilting point, saturation capacity and maximum hygroscopy (Terleev et al., 2010).

AGROTOOL is a point model. All variables are dependent on a single coordinate, which is perpendicular to the surface of the soil. Therefore we need to recalculate data from sample points to key points or points for modeling. Here the Shepard method was used (Bonham-Carter, 1994):

\[ att_K = \frac{\sum_{i=1}^{N} w_i \cdot att_i}{\sum_{i=1}^{N} w_i} \]  \hspace{1cm} (2)

Here \( w_i = 1 / d_i^2 \) is a distance between the sample points and the modelling points, \( att_i \) – is a value of hydro-physical properties for \( i \)-sample point, \( N \) – is a number of the sample points, \( att_K \) – is a value of hydro-physical properties for \( K \)-modelling point.
3. Results and discussion

In order to determine the values of agrophysical soil properties along the field and to create the GIS database soil samples were collected from six soil profiles to a 1 m depth (of three texture classes) from all genetic horizons of the soil profile. The soils observe from the sampling points were sand or loamy sand. For illustration purposes in Figure 2, we had pointed out with red bullets the soil textures observed from the soil types found in this study according to the USDA soil classification (Brevik, 2002).

To select location of the sampling points GIS technology was used. Some results of laboratory studies of the samples are shown in the table 1. The sample points designated with 30-35 (see table 1), are shown on Fig. 1 (right). For the research in the GIS database square parcels of 0,125 ha areas were formed, which were the management units. According to AGROTOOL requirements, at each the samples point, data was extracted in such a way that the hydro-physical properties could be determined to a depth of 1 meter with 10 cm increments, using formula (2). On Figure 3a the objects of simulation and their centroids, are shown.
Table 1. Experimental data on hydro-physical properties of soils

<table>
<thead>
<tr>
<th>Sample points</th>
<th>Layer (top-bottom, cm)</th>
<th>Volumetric soil water content (cm(^3)-cm(^{-3})) for different pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0,0 bar</td>
</tr>
<tr>
<td>A (0-24)</td>
<td></td>
<td>0,443</td>
</tr>
<tr>
<td>31</td>
<td>A2B (24-48)</td>
<td>0,367</td>
</tr>
<tr>
<td></td>
<td>B1 (48-...)</td>
<td>0,382</td>
</tr>
<tr>
<td>A (0-32)</td>
<td></td>
<td>0,513</td>
</tr>
<tr>
<td>32</td>
<td>A2Bg (32-53)</td>
<td>0,402</td>
</tr>
<tr>
<td></td>
<td>B (53-...)</td>
<td>0,363</td>
</tr>
<tr>
<td>A (0-36)</td>
<td></td>
<td>0,523</td>
</tr>
<tr>
<td>33</td>
<td>A2B (36-57)</td>
<td>0,393</td>
</tr>
<tr>
<td></td>
<td>B (57-...)</td>
<td>0,396</td>
</tr>
<tr>
<td>A (0-28)</td>
<td></td>
<td>0,471</td>
</tr>
<tr>
<td>34</td>
<td>A2B (28-55)</td>
<td>0,342</td>
</tr>
<tr>
<td></td>
<td>B (55-...)</td>
<td>0,309</td>
</tr>
<tr>
<td>A (0-23)</td>
<td></td>
<td>0,458</td>
</tr>
<tr>
<td>35</td>
<td>A2B (23-43)</td>
<td>0,415</td>
</tr>
<tr>
<td></td>
<td>B (43-...)</td>
<td>0,365</td>
</tr>
<tr>
<td>A (0-24)</td>
<td></td>
<td>0,475</td>
</tr>
<tr>
<td>30</td>
<td>A2B (24-49)</td>
<td>0,353</td>
</tr>
<tr>
<td></td>
<td>B (49-...)</td>
<td>0,344</td>
</tr>
</tbody>
</table>

The thematic maps on Fig.3 show a content of the GIS database. Fig.3 demonstrates the variability of hydro-physical soil properties on the experimental field. A range of available moisture was chosen as the main indicator of the interest for a crop yield. In this case, the maximum values are achieved in different layers of the soil profile and in different parts of the field. According Fig.3, substantial variability of hydro-physical properties of the soil on the experimental field had been discovered.
As a result of the simulation runs, it was observed that the degree of agrophysical soil properties variability in horizontal and vertical directions was significantly affected by weather conditions, specifically precipitation. The simulation experiments were conducted for the period 2007-2013 with the spring wheat. The results showed that the variability of yield and wheat phenological phases was only observed in years 2008 and 2011. For example, the variability in the development phases within these years was more than 5 days, whereas for the other years the variability of yield and the phases were not observed (see Fig. 4).

An explanation for this fact can be offered on the base of an analysis of the dynamics of soil moisture in the first meter of soil, which is one of the simulation results in AGROTOOL and is determined for each day of the growing season. Specific weather conditions have created favorable moisture reserve in the first meter of soil in 2007, 2009 and 2010. In 2008 the dynamics of soil moisture during the growing season has a characteristic dome shape with a concave bottom, which is unfavorable for wheat yield process and increases the effect of the variability of agrophysical characteristics. In 2010 the dynamics of the curve of soil moisture has a bulge up on the contrary, which is favorable for wheat yield process and eliminates the effect of the variability of agrophysical characteristics.
4. Conclusions

The paper presents the methodological approaches to spatial variability of agrophysical soil properties accounting. Applying analytical system consisting of a GIS-integrated simulation model AGROTOOL allows carrying out a computer experiments to predict the effects of reclamation activities on agricultural landscapes. The computer experiments data suggest that the specific weather conditions determine the dynamics of soil moisture and yield process. The examples demonstrate the effectiveness of the proposed approaches.

The examples demonstrate the effectiveness of the proposed approaches. Improved modeling of growth and development of crops by taking into account the spatial variability of hydro-physical properties of soils will increase the validity of the choice of agrotechnological measures applied to adaptive-landscape systems in agriculture. The use of geographic information technologies will allow transferring the modeling results into regional planning information systems. Therefore, the modeling results can use to justify trade-offs on the socio-economic development with sustainable development of natural resources for the choice of appropriate strategies.

Fig. 4. Spatial variation of yield process of wheat in 2008, nitrogen fertilizer rate of 60 kg / ha: yield and flowering phase (Badenkov et al., 2013).
References


http://dx.doi.org/10.17830/j.eaj.2014.01.134


