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Research Article

Assessing the Impacts of Climate Change-induced Variations in Air Temperature and Precipitation on Plant Physiological and Soil Microbial Processes with DNDC Model

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The DNDC (DeNitrification-DeComposition) model (version 9.5) was applied to predict the differences in transpiration and photosynthesis rates of perennial grasses (red clover and timothy), and autotrophic respiration of a sandy Spodosol. The input parameters for two growing seasons (from 1st of May to 31st of August in 2010 and 2015) contrasting in meteorological conditions were used in the modeling experiment. In 2010, the mean air temperature of the period was 14.1 ±3.3 °C and the total precipitation – 0.1796 m, while in 2015 the mean air temperature was 16.8 ±5.5 °C and the total precipitation – 0.538 m. These meteorological parameters were unfavorable for plants in 2010 and favorable in 2015. The results have shown that the DNDC model adequately predicted the weather-induced differences in total and mean transpiration rates of perennial grasses: 0.12204 m. and 0.00099 ±0.00040 $m.day^{-1}$, respectively, under favorable meteorological conditions of 2015 and 0.05969 m. and 0.00049 ±0.00035 $m.day^{-1}$, respectively, under unfavorable meteorological conditions of 2010. Dynamics of daily transpiration rates of plants was significantly ($r = 0.34$ $p < 0.001$) correlated with soil water content only under unfavorable meteorological conditions. Mean values of simulated photosynthesis rates were equal to 84.4 ±27.9 $kg.C.ha^{-1}.day^{-1}$ in 2015 and 52.3 ±23.4 $kg.C.ha^{-1}.day^{-1}$ in 2010. There were significant differences ($p < 0.001$) in the mean values of photosynthesis rates between the two weather scenarios. The results of one-way analysis of variance (ANOVA) have shown that the rates of autotrophic respiration were significantly ($p < 0.001$) higher under favorable (8.14 ±2.25 $kg.C.ha^{-1}.day^{-1}$) than under unfavorable (5.17 ±2.19 $kg.C.ha^{-1}.day^{-1}$) meteorological conditions.

Keywords: DNDC model, air temperature, precipitation, transpiration, photosynthesis, autotrophic respiration

1 Introduction

Soil quality is an important characteristic for evaluating the balance of important soil ecological functions after anthropogenic and natural impacts. The main soil ecological functions include accumulation and distribution of water, heat, and nutrients; biochemical and geochemical cycling, buffering, maintaining biodiversity of living organisms (De Kimpe & Warkentin, 1998; Evangelista et al., 2023). Soil temperature and soil water content are the key soil factors correlating with crop yields and plant growth, nutrient cycling, microbial activity and biodiversity, carbon and nitrogen cycling, and other processes in the system of soil – plant – atmosphere. Field instrumental measurements of these parameters are time-consuming and can be expensive.

There are often drastic changes in current meteorological conditions of North-Western region of Russia. Therefore arable plants can be affected by unpredicted unfavorable and favorable impacts of meteorological factors (air temperature, precipitation) each year. Perennial grasses are convenient scientific objects because they are usually growing for several years without impacts of anthropogenic factors (tillage, fertilization), which can disturb an exact analysis of results of the proposed studies.

The process-based models of plant growth, transpiration, microbial activity, carbon and nitrogen transformation, soil water content changes are often used in many studies. The databases of such models include meteorological parameters (air temperature and precipitation), soil texture, soil chemical and hydrophysical properties and

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data on plants, applied fertilizers and tillage systems. The accuracy and completeness of the input data is important for accurate modeling of the studied processes.

The process-based DeNitrification-DeComposition (DNDC) model is considered as a reliable and useful tool to study these processes in agroecosystems (Abdalla et al., 2011; Balashov et al., 2014; Barneze et al., 2022; Beheydt et al., 2007; Gong et al., 2023; Li, 2000; Li et al., 2006; Tonitto et al., 2010).

The objectives of this study were to predict the changes in: (1) transpiration rate and photosynthesis rate of perennial grasses (red clover, timothy), and (2) soil autotrophic respiration affected by the differences in daily air temperature and precipitation.

2 Material and methods

The study was conducted at the experimental station of the Agrophysical Research Institute in the St. Petersburg region of Russia (59° 34′ N, 30° 8′ E). The studied soil was a sandy Spodosol and contained 91.7 $g.kg^{-1}$ of sand, 5.2 $g.kg^{-1}$ of silt, and 3.1 $g.kg^{-1}$ of clay particles.

The DNDC model (version 9.5) was used in the studies. The DNDC model includes two components. The first component consists of the nitrification, denitrification, fermentation, and soil respiration sub-models, which predict emissions of NO, N_2O, NH_3, CO_2, and CH_4. The second component includes sub-models of climate, crop growth and decomposition, and predicts soil water content, temperature, plant growth and biomass, concentrations of NO_3^-, NH_4^+ and dissolved organic carbon. The relevant sub-models of the DNDC model have been used in our studies. Meteorological input parameters for the DNDC model were: daily maximum and minimum air temperatures, daily precipitation from the 1st January to 31st December in 2010 and 2015. Key soil input parameters for the DNDC in 2010 and 2015 were: soil texture, bulk density (1.3 $Mg.m^{-3}$), soil organic carbon content (20.5–26.7 $g.C.kg.soil^{-1}$), field capacity (22–27% of mass), wilting point (13–15% of mass). In the DNDC model the Penman–Monteith equation was used for calculations of transpiration and evapotranspiration; conventional equation was applied for calculation of photosynthesis rates; soil respiration was calculated using data on rates of decomposition of labile and resistant carbon pools.

The input parameters for two growing seasons (from the 1st of May to the 31st of August) contrasting in meteorological conditions were used in the modeling experiment. In 2010, the mean air temperature of the period was 14.1 ±3.3 °C and the total precipitation – 0.1796 m, while in 2015 the mean air temperature was 16.8 ±5.5 °C and the total precipitation – 0.538 m. From a point of view of available soil water content it was assumed that these amounts of precipitation were unfavorable for perennial grasses, as the modeled crops, in 2010 and favorable in 2015.

Strength of associations between sets of simulated parameters was assessed with Pearson correlation coefficients and Spearman correlation coefficients at $p \leq 0.05$ (De Winter et al., 2016; Spearman, 1904). The standard deviations from the means were calculated using the Excel package. One-way analysis of variance (ANOVA) was applied to evaluate the significance of differences ($p \leq 0.05$) between the means of the normally distributed data. Mann-Whitney U test (Mann & Whitney, 1947) was applied to assess the significance of differences in means (at $p \leq 0.05$) if the distribution was not normal according to the Shapiro-Wilk test (Shapiro & Wilk, 1965).

3 Results and discussion

The results of the study have shown that according to the one-way analysis of variance (ANOVA), mean transpiration rate of perennial grasses was significantly ($p < 0.001$) lower under the unfavorable meteorological conditions of 2010 than under the favorable meteorological conditions of 2015 (Figs 1a and 1 b).

The total and mean transpiration rates for the observation periods were equal to 0.12204 m and 0.00099 ±0.00040 $m.day^{-1}$, respectively, under favorable meteorological conditions of 2015, while under unfavorable meteorological conditions of 2010 they were equal to 0.05969 m and 0.00049 ±0.00035 $m.day^{-1}$, respectively. Dynamics of the plants' daily transpiration rate was significantly ($r = 0.34$ $p < 0.001$) correlated with the soil water content only under unfavorable meteorological conditions. The differences in the mean transpiration values were, presumably, induced by the differences in the soil water content. Mean values of the soil water content for the period of simulation were equal to 21.0% (of mass) under favorable conditions of 2015 and to 16.1% (of mass) under unfavorable meteorological conditions of 2010. According to the Mann-Whitney U test, there were insignificant ($p = 0.06$) differences in soil water content between the two studied periods. According to the Spearman correlation coefficients, dynamics of soil water content was induced by dynamics of precipitation both under favorable ($r = 0.75$ $p < 0.001$) and unfavorable ($r = 0.63$ $p < 0.001$) meteorological conditions.

Transpiration and photosynthesis occur in plants simultaneously. Water stress almost always results in a decrease of stomatal conductivity and transpiration (Liu et al., 2021). The statistical results demonstrated

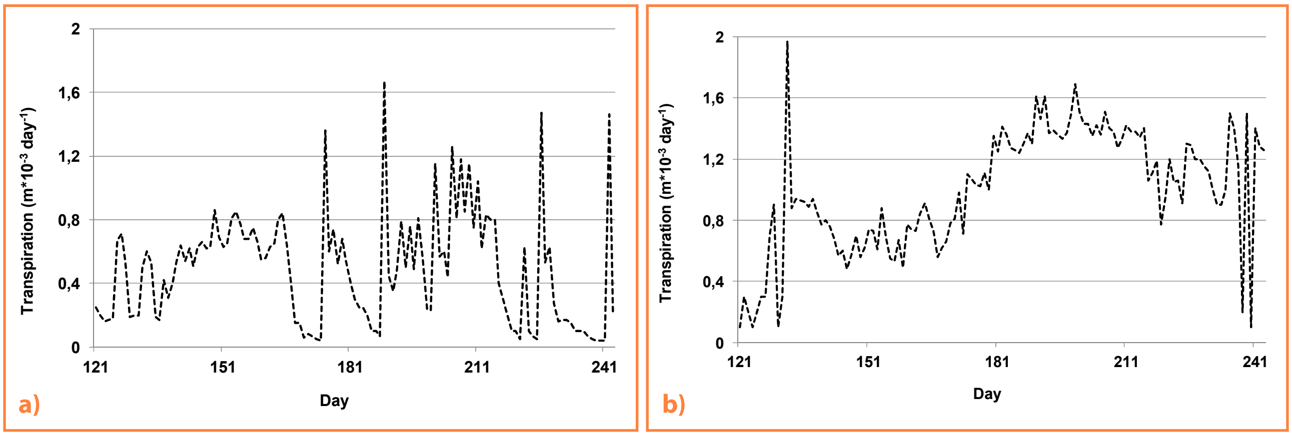

Figure 1 Dynamics of simulated transpiration rates of the perennial grasses (red clover – *Trifolium rubens* L. and timothy – *Phleum pratense* L.) under unfavorable meteorological conditions of 2010 a) and under favorable meteorological conditions of 2015 b)

a significant linear relationship between the dynamics of photosynthesis and transpiration rates under favorable (r = 0.61 p <0.001) and unfavorable (r = 0.75 p <0.001) meteorological conditions.

Mean values of simulated photosynthesis rate were equal to 52.3 ±23.4 kg.C.ha^{-1}.day^{-1} and 84.4 ±27.9 kg.C.ha^{-1}.day^{-1} under unfavorable and favorable meteorological conditions, respectively, and according to the Mann-Whitney U test, the differences between the means were significant (p <0.001).

Dynamics of simulated photosynthesis rate is given in Figs 2a and 2b.

Significant correlation was observed between the dynamics of photosynthesis rate and soil water content only under unfavorable meteorological conditions (r = 0.30 p <0.001), probably because of the lower precipitation as a limiting factor. In general, under favorable meteorological conditions of 2015, the system of soil – plants – boundary layer of atmosphere demonstrated a higher sustainability. The maximum and the minimum photosynthesis rates were observed. The range between the maximum and the minimum photosynthesis rates was wider under unfavorable meteorological conditions, according to the simulated results in 2010. Under unfavorable meteorological conditions of 2010, the studied system was unable to reach the maximum photosynthesis rate of about 120 kg.C.ha^{-1}.day^{-1} observed in 2015 (Fig. 2b).

The results of the modeled autotrophic respiration under unfavorable and favorable meteorological conditions are given in Figs 3a and 3b. Autotrophic respiration reflects mainly respiration of plant roots and it was shown earlier that water deficiency and soil temperature can significantly affect this parameter (Balogh et al., 2016; D'Ottavio et al., 2023; Hopple et al., 2023; Liu et al., 2023; Wang et al., 2014).

Mean values of autotrophic respiration rate were equal to 8.14 ±2.25 kg.C.ha^{-1}.day^{-1} and 5.17 ±2.19 kg.C.ha^{-1}.

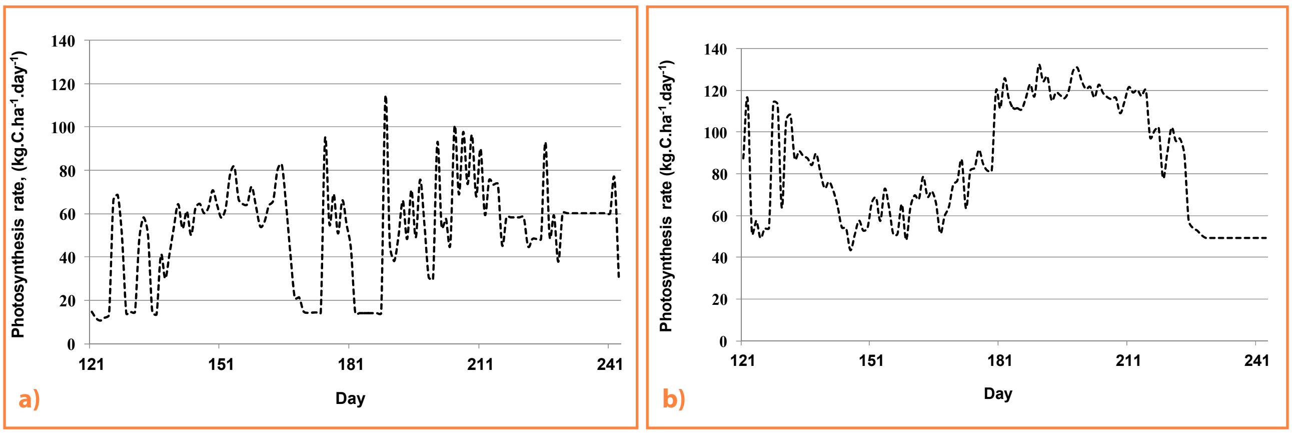

Figure 2 Dynamics of simulated photosynthesis rate of perennial grasses (red clover – *Trifolium rubens* L. and timothy – *Phleum pratense* L.) under unfavorable meteorological conditions of 2010 a) and under favorable meteorological conditions of 2015 b)

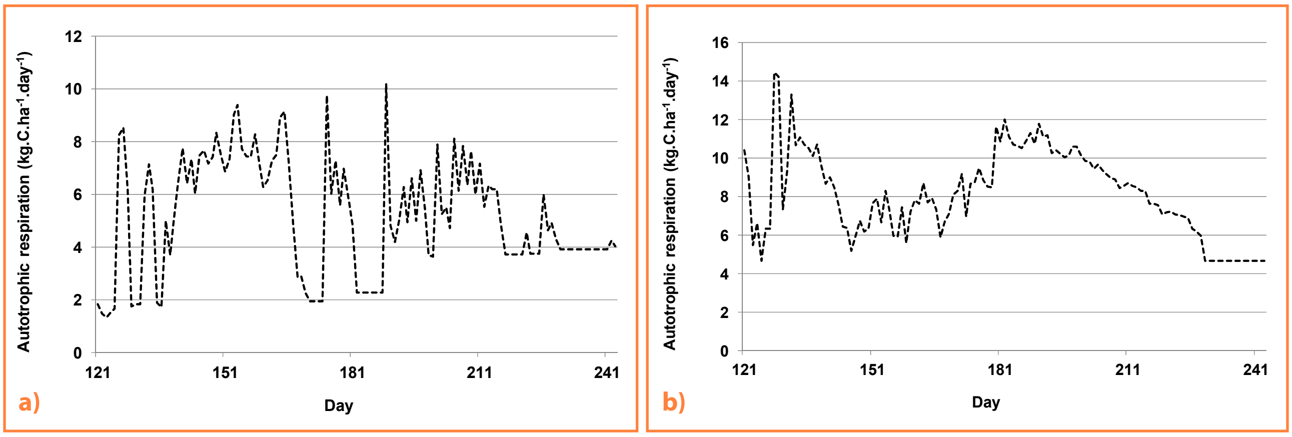

Figure 3 Dynamics of simulated autotrophic respiration of the soil under unfavorable meteorological conditions of 2010 a) and under favorable meteorological conditions of 2015 b)

day^{-1} under favorable and unfavorable meteorological conditions, respectively. The results of one-way analysis of variance (ANOVA) showed that the rate of autotrophic respiration was significantly (p <0.001) higher under favorable meteorological conditions. The rate of autotrophic respiration significantly (r = 0.50 p <0.001) correlated with the changes in soil temperature only under unfavorable meteorological conditions. Significant correlation between the rate of autotrophic respiration and soil water content was also calculated only for unfavorable meteorological conditions (r = 0.30, p <0.001).

4 Conclusions

The results of the study with application of the DNDC model showed that:

1. the simulated transpiration of perennial grasses had a higher degree of sustainability and recovery under favorable meteorological conditions than under unfavorable meteorological conditions;
2. under unfavorable meteorological conditions the system of soil – plants – boundary layer of atmosphere was unable to maintain the maximum rate of photosynthesis of about 120 kg. C. ha^{-1}. day^{-1} observed for the favorable meteorological conditions;
3. the soil temperature and soil water content significantly correlated with autotrophic respiration only under unfavorable meteorological conditions: lower air temperature and precipitation.

A more detailed information on management practices (fertilization rate, tillage method, residue return rate, and biomass fraction of given perennial grasses) should be considered in future DNDC model applications for simulating transpiration and photosynthesis of the studied perennial grasses and autotrophic respiration at daily timescales.

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