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Field validation of DNDC and SWAP models for temperature and water content of loamy and sandy loam Spodosols

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A b s t r a c t. The objectives of the research were to: fulfil the preliminary assessment of the sensitivity of the soil, water, atmosphere, and plant and denitrification and decomposition models to variations of climate variables based on the existing soil database; validate the soil, water, atmosphere, and plant and denitrification and decomposition modelled outcomes against measured records for soil temperature and water content. The statistical analyses were conducted by the sensitivity analysis, Nash-Sutcliffe efficiency coefficients and root mean square error using measured and modelled variables during three growing seasons. Results of sensitivity analysis demonstrated that: soil temperatures predicted by the soil, water, atmosphere, and plant model showed a more reliable sensitivity to the variations of input air temperatures; soil water content predicted by the denitrification and decomposition model had a better reliability in the sensitivity to daily precipitation changes. The root mean square errors and Nash-Sutcliffe efficiency coefficients demonstrated that: the soil, water, atmosphere, and plant model had a better efficiency in predicting seasonal dynamics of soil temperatures than the denitrification and decomposition model; and among two studied models, the denitrification and decomposition model showed a better capability in predicting the seasonal dynamics of soil water content.

K e y w o r d s: agroecosystem modelling, model validation, soil water content, soil temperature, Spodosols

INTRODUCTION

Maintenance of soil quality is an important feature of sustainable agriculture because of its role in the assessment of magnitude, intensity, and direction of key soil ecological functions. Good quality of arable soils means that any soil management applied is capable of maintaining a stable balance of such soil ecological functions as biochemical and geochemical cycling, accumulation and distribution of water, nutrients, and heat, buffering, providing biodiversity of living organisms (De Kimpe and Warkentin, 1998). In turn, reduced soil quality is linked to an imbalance of these functions and, as a result, to:
– increasing soil degradation,
– disturbing nutrient, gas, moisture and heat regimes, and
– declining crop productivity.

Soil moisture and temperature are key variables in agricultural management because they affect plant growth, crop yields, soil carbon and nitrogen cycling, biodiversity, rates of soil formation, greenhouse gas emissions, and other related processes in the agroecosystems.

Apart from field instrumental monitoring, numerical and process-based models of soil temperature and hydrological regimes, plant growth, carbon and nitrogen biogeochemistry are being used in the agroecosystem studies. One of the preliminary stages of modelling studies is an assessment of the sensitivity of the models to changes in air temperature and precipitation on the basis of existing databases of climate and soil properties. The databases of models can include a wide set of various input data, which are often difficult to continuously measure under field conditions. Nevertheless, there is a need to carry out the preliminary assessment of the models sensitivity even with a limited amount of input data in order to attempt an initial step ahead to the modelling studies.

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The SWAP (soil, water, atmosphere, and plant) model is a one-dimensional physically based agro-hydrological model. The model is designed to simulate water flow, solute transport, and plant growth in a soil-water-atmosphere-plant environment (van Dam *et al*., 1997). The SWAP model is widely used to predict the transport of water, solute, and heat in soils. The model has been tested and applied at many locations (Bastiaanssen *et al*., 2007; Droogers *et al*., 2000, 2010; Jiang *et al*., 2011; Rallo *et al*., 2012).

The DNDC (denitrification and decomposition) model has been developed as a process-based model of carbon and nitrogen transformation in soils of agroecosystems (Li, 2000; Li *et al*., 1992, 1997, 2006). The main climate input parameters in the DNDC model are air temperature and precipitation at a daily time step. The modelled biochemical processes (nitrification, denitrification, fermentation, mineralization, and heterotrophic respiration) are microbially induced processes governed by the main climate and soil factors (temperature and water content). These biochemical processes are instrumentally difficult to measure at the daily time step under field conditions. Therefore, the DNDC model can be a useful and reliable tool for assessing the biochemical soil properties, processes, and emissions of CO_2, N_2O, and CH_4 from arable soils (Babu *et al*., 2006; Balashov *et al*., 2010; Hergoualc'h *et al*., 2009; Smith *et al*., 2008; Tonitto *et al*., 2010). The model demonstrated a remarkable capacity of predicting trace gas emissions and soil organic carbon dynamics in agroecosystems (Li, 2000; Li *et al*., 1992). The DNDC model consists of two components. The first component, consisting of a soil climate sub-model, a crop growth sub-model, and a decomposition sub-model, predicts soil temperature, water content, Eh profiles, plant development and growth, and concentrations of dissolved SOC, NH_4^+, and NO_3^-. The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts NO, N_2O, CH_4, and NH_3 production, consumption, and diffusion based on the modelled soil environmental variables. The DNDC model has been adopted as a central model in the NitroEurope project (2005-2008). The model has also been applied in many studies on greenhouse gas emissions from arable soils (Beheydt et al., 2007; Cai *et al*., 2003; Ludwig *et al*., 2011; Smith *et al*., 2008; Zhang *et al*., 2002).

The objectives of the present research were to:
– carry out the preliminary assessment of the sensitivity of the SWAP model and the DNDC model to variations of climate variables (air temperature, precipitation) based on the existing soil database,
– validate the SWAP and DNDC modelled outcomes against measured records for soil temperature and water content.

MATERIALS AND METHODS

The existing soil database was received for two study sites, which were located on loamy sand and sandy loam Spodosols and represented agroecosystems typical for the northwestern region of Russia. Experimental studies were carried out at:
– the Menkovo experimental station (59°34'N, 30°08'E) of the Agrophysical Research Institute during the growing seasons (May-September) of 2004 and 2006;
– a pasture near Suida village (59°38'N, 30°07'E) during the growing season of 2010.

The Menkovo experimental station and the Suida village are located approximately 60 and 50 km southwest from St. Petersburg. The study sites at the Menkovo experimental station were agricultural plots on the loamy sand Spodosol planted with spring barley (*Hordeum vulgare* L., cv. Suzdalets). The rates of N fertilizers were equal to 90 and 110 kg N ha^{-1} in 2004 and 2006, respectively.

The experimental designs at the Menkovo experimental station are comprehensively described in our previous papers (Buchkina *et al*., 2010; Rizhiya *et al*., 2011). The pasture site was located on the sandy loam Spodosol under perennial grasses. The loamy sand Spodosol and sandy loam Spodosol were characterized by the following properties: field capacity at a moisture potential of -30 kPa (0.32 and 0.46%, g g^{-1}), permanent wilting point at a moisture potential of -1 500 kPa (0.15 and 0.18%, g g^{-1}), total porosity (0.43 and 0.57%, vol.), bulk density (1.1 and 1.2 g cm^{-3}), and saturated hydraulic conductivity (0.12 and 0.39 m h^{-1}), respectively. Soil field capacity and permanent wilting point in undisturbed soil samples were determined by a pressure-plate apparatus; soil bulk density was measured by cutting cylinders (100 cm^3), while measurements of saturated hydraulic conductivity were done in disturbed soil samples in a filtration device at a constant water head (Vadjunina and Korchagina, 1986; Soil Survey, 1996). The loamy sand Spodosol contained 91.7% of sand, 5.2% of silt, and 3.1% of clay particles, whereas the sandy loam Spodosol contained 84.7% of sand, 3.6% of silt, and 11.7% of clay particles.

During the three growing seasons, soil temperature was recorded daily by soil temperature sensor probes (DS 1920), while soil water content was gravimetrically measured once in one-three weeks. These soil properties were measured only at a depth of 0-10 cm. Air temperature and precipitation were measured daily at local meteorological stations. All the soil properties were measured in three replicates. The mean values of the soil properties were calculated for each of the plots. Significance of the differences between the means was tested by analysis of variance (one-way ANOVA) at $p \leq 0.05$.

In the present study, the DNDC model (version 9.2) was applied for modelling the dynamics of soil temperature and water content. The prediction of these properties was done for the modelled depth of 0-10 cm within which the direct field measurements had also been made. The SWAP model (version 2.0.7d) was applied for predicting the dynamics of average values of soil water content within the modelled depth of 0.5 to 8.8 cm and of soil temperature within the modelled depth of 1 to 7.5 cm to assess and compare the modelled soil properties with those measured in the field within the soil depth of 0-10 cm. The SWAP model can predict the dynamics of soil temperature and moisture content in deeper profile layers (compartments) of 20 to 200 cm and 11.3-135 cm, respectively. The DNDC model can predict the dynamics of these properties up to the depth of 50 cm. Because the instrumental measurements of the soil properties were carried out within the layers of 0-10 cm, all the predictions of soil temperature and water content by both models were done only for the measured depth of 0-10 cm. All the required input soil parameters for the DNDC model were instrumentally measured before modelling studies. Apart from the measured input soil data, many default input soil data were applied for the SWAP model because the dataset used for the modelling study did not have the entire dataset of measured input soil properties for this model.

In the SWAP model, a soil profile of 200 cm is divided up to 10 horizontal layers and the soil is also subdivided maximally up to 60 compartments, which are used in the finite difference scheme. Minimizing the number of compartments might result in a mass balance error. The bottom compartment number should be defined for each layer and the thickness should be defined for each compartment. The SWAP model simulates vertical soil water flows in the saturated and unsaturated zone by solving the Richards equation (van Dam *et al*., 1997). The Mualem – van Genuchten equations are used to calculate the relationships between soil water content and hydraulic conductivity as a function of the water pressure head. Among various input climate data, the SWAP model also requires the daily air temperature and precipitation to predict the distribution of temperature, water content and matric potentials in soil profiles. These modelled soil properties are related to such predicted outcomes as evaporation, transpiration, and evapotranspiration (Kroes *et al*., 1999; van Dam *et al*., 1997). The SWAP model includes seven submodels (meteo, irrigation, crop, soil, water, solute, and heat transport) with specified input parameters. The sub-model of soils has upper and bottom boundary conditions. The upper boundary conditions are described by precipitation, irrigation, and evapotranspiration. The bottom boundary condition is defined by free drainage. In the soil sub-model, such input parameters as initial water pressure head, soil water content, soil porosity, soil full saturation, saturated and unsaturated hydraulic conductivity, thickness of soil and ponding water layer, number of soil layers, soil evaporation and textural classes, depth of rooting limitation, swelling/shrinkage parameters, hysteresis option (no hysteresis, wetting or drying), preferential flow, and scaling of hydraulic functions need to be specified for each soil layer. Each of the soil input parameters should be exactly measured to achieve the highest efficiency of the SWAP model in predicting the dynamics of soil water content.

The DNDC model simulates soil moisture dynamics by one-dimensional, vertical water transport from surface to the depth of 50 cm. The soil profile is divided into five horizontal 10-cm layers having uniform soil texture and soil water content. In the DNDC model, the water transport between soil layers is governed by gradients of soil water potentials at one-hour time step according to Ritchie *et al.* (1988). If the rainfall and irrigation intensity is greater than input saturated hydraulic conductivity, the DNDC model simulates formation of ponding water and its runoff. If the soil water content is higher than field capacity in one of the layers, a gravitational water distribution occurs. In general, the DNDC model predicts the soil moisture dynamics taking into account precipitation, saturated hydraulic conductivity, field capacity, wilting point, gravity drainage, ponding water, runoff, transpiration, evaporation, and plant interception.

The relationship between the measured and modelled parameters was assessed with Pearson correlation coefficients using a computer statistical package at $p \leq 0.05$ (Hergoualc'h *et al*., 2009). The Nash-Sutcliffe model efficiency coefficient E (Nash and Sutcliffe, 1970; Tisseuil *et al*., 2008) and the root mean square error (RMSE) (Droogers *et al*., 2010; Eitzinger *et al*., 2004; Ludwig *et al*., 2011) for linear regression between the measured and modelled values were used to calculate the predictive power of the SWAP and DNDC models Eq. (1) and Eq. (2):

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \bar{Q}_o\right)^2}, \tag{1}$$

where: Q_o – the mean of the measured values, Q_o^t – the measured value at time t, Q_m^t – the modelled value. The E value can range from -∞ to 1. The E value of 1 reflects a perfect match between the measured and modelled values. If the E value is less than zero, the measured mean is a better predictor than the model. If the E value is equal to zero, the modelled values are as accurate as the mean of the measured data:

$$\mathrm{RMSE} = \frac{100}{\bar{O}}\sqrt{\sum_{i=1}^{n}\frac{(P_i - O_i)^2}{n}}, \tag{2}$$

where: $\bar{O}$ – the mean of the measured values, P_i – the modelled value, O_i – the measured value, n – the number of paired values. The RMSE ranges from 0 to ∞. At an ideal fit, the RMSE is equal to zero. The RMSE values are widely used to compare the errors of models as compared to the measured data.

A sensitivity analysis of the DNDC and SWAP models was carried out for the growing seasons (May-September) of 2004, 2006, and 2010. In the case of modelled soil temperature, the sensitivity analysis of the SWAP and DNDC models was to quantify the effects of changes in daily air temperature on those in predicted daily soil temperature. The changes of the daily air temperature and modelled daily soil temperature were considered as relative values and were calculated as portions of their mean seasonal values. Three levels of relative changes in daily air temperature were chosen: ±4/±5%, ±9/±11%, ±15/±17% because these variations were more often observed during the studied growing seasons. During the growing seasons of 2004, 2006, and 2010 the daily air temperatures varied in the following ranges: 5.5-21.9°C, 4.7-26.8°C, and 8.2-26.6°C, respectively.

In the case of modelled soil water content, the sensitivity analysis was performed to assess the effects of changes in daily precipitation on the variations in predicted daily soil water content. The changes in daily precipitation were calculated as relative values from 0.7 to 100% of its maximum daily values during the three selected growing seasons.

RESULTS AND DISCUSSION

Because the air temperature and precipitation are the key environmental input data for the DNDC and SWAP models, an initial assessment of their predicting capabilities can include two stages. The first stage of the assessment is an analysis of sensitivity of the modelled outcomes (soil temperature and moisture content) to changes in air temperature and the amount of precipitation.

According to meteorological data, the mean values of daily air temperature were equal to 14.7, 15.8, and 18.2°C during the growing seasons (from the middle of May to the end of September) in 2004, 2006, and 2010, respectively. There were significant differences in the mean air temperatures for the growing seasons of 2004 and 2010 ($p<0.001$), 2006 and 2010 ($p<0.001$), except those of 2004 and 2006 ($p=0.08$).

The dynamics of daily air temperature during the growing seasons of 2004, 2006, and 2010 at the studied locations is presented in Fig. 1.

There were also strong and significant Pearson correlations between the measured daily soil and air temperatures during the growing seasons in 2004, 2006, and 2010 ($R = 0.83$, $p<0.001$; $R = 0.73$, $p<0.01$; $R = 0.85$, $p<0.001$, respectively). The predicted mean soil temperatures during the growing seasons reached 15.7, 15.3, and 14.7°C (2004, 2006, and 2010). The dynamics of the predicted daily soil temperatures was not similarly associated with that of the measured daily air temperatures. These discrepancies could be caused by non-uniform daily changes in soil water content before and after rainfall events during the growing seasons. As a result of non-linear changes in the soil particles – water – air paths for heat conduction during wetting-drying processes, both thermal conductivity and heat capacity of soils with different porosity and bulk density usually showed:

– a non-linear and more or less rapid increase with increasing soil water content, and
– a non-linear decrease with declining soil water content (Guan *et al*., 2009; Smits *et al*., 2009; Usowicz, 1995).

The results of the sensitivity analysis demonstrated that the soil temperatures predicted by the SWAP model, compared to those after the DNDC model, had a lower variability at the relative changes in daily air temperature ranking from ±4-5% to ±15-17% (Fig. 2).

In the case of the SWAP model, the differences between the values of the relative changes in daily soil temperatures and those of the relative changes in daily air temperatures at all the three levels of their rankings (±4%/±5%, ±9%/±11% and ±16%/±17%) did not exceed 3%. In the case of the DNDC model, these differences increased up to 9% at the highest level of ranking (±16%/±17%) of relative variations in daily air temperatures. Thus, the SWAP model showed better reliability in the prediction of sensitivity of soil temperatures to the changes in daily air temperatures during the growing seasons of 2004, 2006, and 2010.

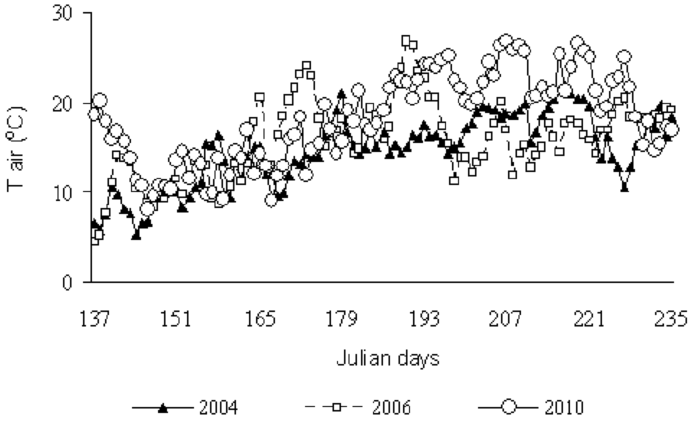

Fig. 1. The daily dynamics of air temperature during the growing seasons of 2004, 2006, and 2010.

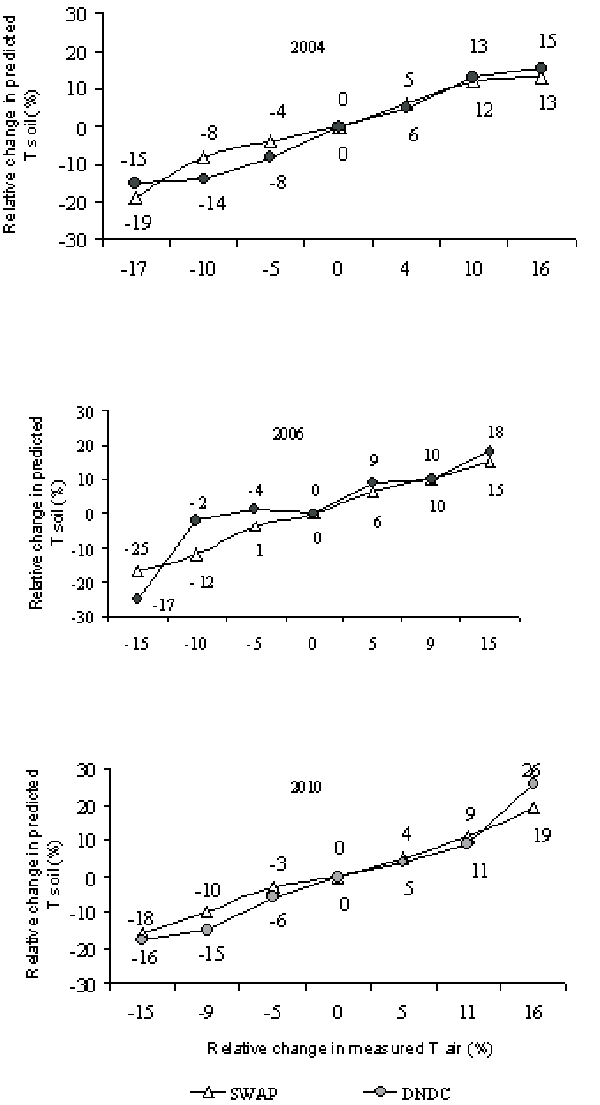

Fig. 2. Sensitivity analysis of the DNDC and SWAP models using data on air temperature during the growing seasons of 2004, 2006, and 2010.

In our studies with the SWAP model, only such input soil parameters as initial water content, porosity, saturated hydraulic conductivity, and textural class were precisely specified. Other input soil properties for this model were accepted as default values. The sensitivity analysis of the model was difficult to carry out efficiently with such a limited dataset of measured input soil parameters. Therefore, this sensitivity analysis was considered to be a preliminary step in the prediction of a dynamics of soil water content by the SWAP model.

The total amount of precipitation during the growing seasons reached 701, 263, and 435 mm in 2004, 2006, and 2010, respectively. There was a significant difference in the total amounts of precipitation for the growing seasons of 2004 and 2006 ($p<0.05$), whereas insignificant differences

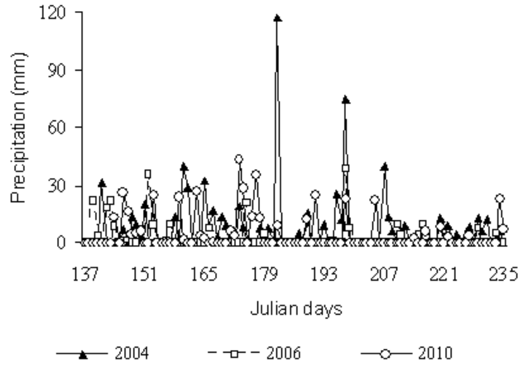

Fig. 3. Dynamics of the daily amount of precipitation during the growing seasons of 2004, 2006, and 2010.

in the total amounts of rainfall were observed for the growing seasons in 2004 and 2010 ($p=0.14$) and 2006 and 2010 ($p=0.08$). Actual rainfall events occurred once in 1-2 weeks (Fig. 3). The maximum daily values of the amount of rainfall reached 117.4, 38.4, and 42.9 mm (2004, 2006 and 2010, respectively). As indicated above, these values of rainfall were accepted as 100% in the analysis of sensitivity of the SWAP and DNDC model in terms of the predicted soil water content.

There were stronger and more significant positive correlations between the modelled water content and the daily amount of precipitation for the DNDC model than for the SWAP model. Pearson coefficients of the correlation between these parameters were 0.46, 0.44, 0.35 (all at $p<0.001$) for the DNDC model, and 0.17 ($p=0.10$), 0.15 ($p=0.14$), 0.28 ($p<0.01$) for the SWAP model during the growing seasons of 2004, 2006, 2010, respectively.

The observed discrepancies in the Pearson correlation coefficients, as criterions of the relationship between the above-mentioned parameters, could be explained by differences in the approaches of the DNDC and SWAP models to the simulation of water transport in soils as described in the Materials and Methods.

In the sensitivity analysis of both models, the relative changes in daily amounts of precipitation ranged from 0.7 to 100%. The responses of the predicted soil water content were taken into account if the latter did not exceed the field capacity of soils to avoid the modelled formation of ponding water on the soil surface and to ensure the unsaturated conditions in the soil layers. The mean seasonal water content (%, g g^{-1}) predicted by the DNDC model was equal to 0.19, 0.14, 0.29 (2004, 2006, and 2010), and did not exceed the above-mentioned field capacities of both soils. However, the mean water content (%, g g^{-1}) after the SWAP model reached 0.35, 0.35, 0.41 (2004, 2006, and 2010), and exceeded the field capacity of the soils. The SWAP model often overestimated the field capacity of both soils during the studied growing seasons (van Vosselen *et al*., 2005).

The stronger positive correlations between the modelled soil water content and amount of precipitation confirmed that the DNDC model was more reliable than the SWAP model in the sensitivity to the changes in the amount of rainfall (Fig. 4).

Cai *et al*. (2003) reported on high sensitivity of soil water content predicted by the DNDC to changes in the amount of precipitation.

If precipitation events occurred rather rarely (once in a week or two weeks), the predicted water content decreased to very low values of 0.09 (%, g g^{-1}) in loamy sand soil and 0.14 (%, g g^{-1}) in sandy loam soil. Under such conditions of the predicted soil moisture regime, the DNDC model showed a drastic increase in the relative change of the predicted water content by 210% in loamy sand soil and by 194% in sandy loam soil as the response to the relative change in extremely high amounts of rainfall of 33.8, 100 and 54.3%, respectively (Fig. 4). Although the DNDC model is capable of predicting plant interception and evapotranspiration, this model was very sensitive to hydrologically effective rainfall during the growing seasons. The hydrologically effective rainfall is an amount of precipitation penetrating into soil after evapotranspiration and plant interception losses (Bastrup-Birk and Gundersen, 2004). As shown in our previous results, the high sensitivity of the DNDC model to extremely high amounts of daily rainfall was reflected in a drastic increase in the predicted N_2O emissions from the loamy sand Spodosol, whereas the measured direct N_2O emissions from the soil showed a lower increase after the same extreme rainfall events (Balashov *et al*., 2010).

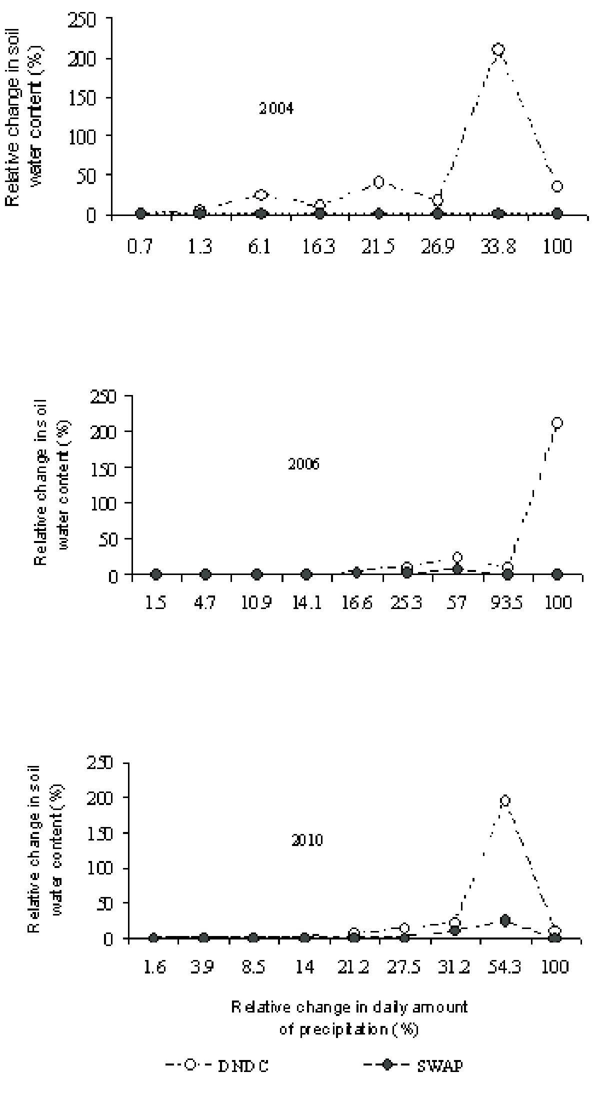

Fig. 4. Sensitivity analysis of the DNDC and SWAP models using data on the amounts of precipitation during the growing seasons of 2004, 2006, and 2010.

The second stage of assessment of the two models was to compare the measured and predicted outcomes. There were strong positive correlations between the measured soil and air temperatures in 2004 (R=0.83, p<0.001), 2006 (R=0.73, p<0.01), and 2010 (R=0.85, p<0.001). The daily dynamics of the measured and modelled soil temperatures during the growing seasons in 2004, 2006, and 2010 is shown in Fig. 5.

The starting date of the DNDC simulations has to be January 1 each year. The SWAP model had also run from the beginning of the calendar year in order to define the same initial conditions for both models. For this reason, the measured and simulated values do not necessarily match on the starting day of the reference measurements (Figs 5 and 8).

The Pearson correlation coefficients showed a strong relationship between the measured and predicted soil temperatures and reached values of 0.82 and 0.84 (at p<0.001), 0.76 and 0.75 (at p<0.01), and 0.96 and 0.96 (at p<0.001) for the DNDC and SWAP models, respectively, during the growing seasons of 2004, 2006, 2010. Hence, the strong relationship of the measured and modelled soil temperatures was considered to be a reliable basis for assessing their coincidence using the RMSE and the Nash-Sutcliffe model efficiency coefficients.

The mean values of the RMSE between the measured and predicted soil temperatures after the DNDC and SWAP models almost did not differ much and were equal to 2.6 and 2.5°C under the combined assessment of the three growing seasons. The RMSE of the linear regression between the measured and predicted soil temperatures for the SWAP model was lower than that for the DNDC model during the growing seasons of 2004 and 2010, except for 2006 (Fig. 6).

The coefficients of the RMSE variations were also lower for the SWAP model (17.8 and 14.3%) than those for the DNDC model (18.8 and 16.9%) for the growing seasons of 2004 and 2010. This was probably due to the fact that the SWAP model, in terms of the predicted outcomes, showed lesser sensitivity to the changes in daily air temperatures and therefore had a higher efficiency in predicting soil temperatures.

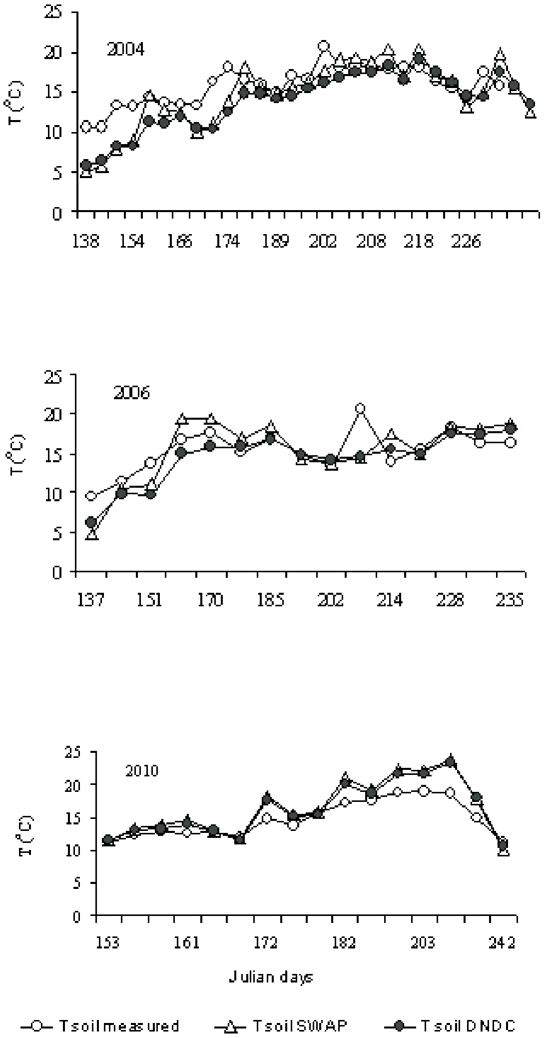

Fig. 5. Dynamics of the measured and predicted soil temperatures simulated by the DNDC and SWAP models during the growing seasons of 2004, 2006, and 2010.

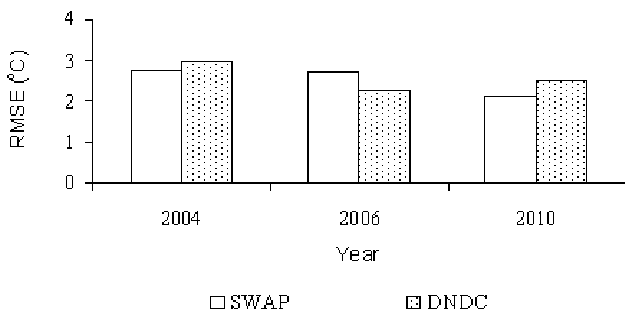

Fig. 6. Distribution of the RMSE values between the measured and predicted soil temperatures simulated by the SWAP and DNDC models during the growing seasons of 2004, 2006, and 2010.

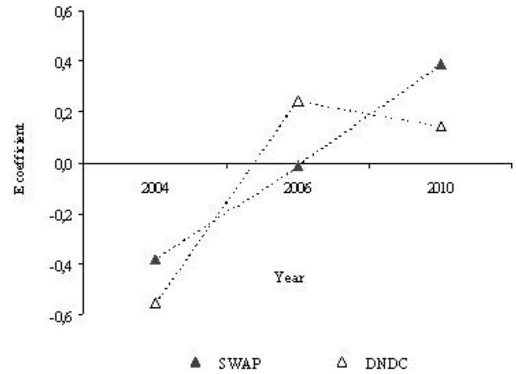

Fig. 7. Nash-Sutcliffe efficiency (E) coefficients between the measured and predicted soil temperatures simulated by the SWAP and DNDC models during the growing seasons of 2004, 2006, and 2010.

The Nash-Sutcliffe coefficients (E) supported the results of the statistical analysis of the RMSE (Fig. 7).

The mean values of the E coefficients for the SWAP and DNDC models were equal to -0.002 and -0.05 under the combined assessment of the three growing seasons. These data showed that both models were slightly worse predictors of the measured soil temperatures than the mathematical average. However, the SWAP model predicted the soil temperatures better than the DNDC model in 2004 with negative E coefficients and especially in 2010 when positive E coefficient values (0.39 and 0.15) were achieved. According to Aherne *et al*. (2008), the E coefficients of 0.6-0.7 are acceptable for the SWAP model. Nevertheless, in 2006 the DNDC model predictions showed a better match of the simulated soil temperatures to the measured data compared to those obtained by the SWAP model. As shown by Nakagawa *et al*. (2008), the DNDC model demonstrated high sensitivity to air temperatures as well as a satisfactory efficiency in predicting soil temperatures at the depths of 15 and 35 cm.

There were mainly positive and insignificant correlations between the measured and predicted soil water content in:

– the SWAP model: R=0.84, $p<0.05$ (2004); R=-0.41, p=0.42 (2006); R=0.78, p=0.07 (2010), and
– the DNDC model: R=0.55, p=0.20 (2004); R=0.37, p=0.47 (2006); R=0.77, p=0.07 (2010).

Zhang *et al*. (2002) reported that linear correlation coefficients between measured and predicted soil water content after the Crop-DNDC model ranged from 0.30 to 0.60.

Nevertheless, according to the statistical results (Fig. 8), both models predicted soil water contents better in the year with the higher amount of precipitation (2004 versus 2006) and in the soil with a heavier texture (sandy loam versus loamy sand). Cai *et al*. (2003) also reported on the high sensitivity of the DNDC model to changes in soil texture.

On average, the DNDC model slightly underestimated while SWAP model highly overestimated the soil water

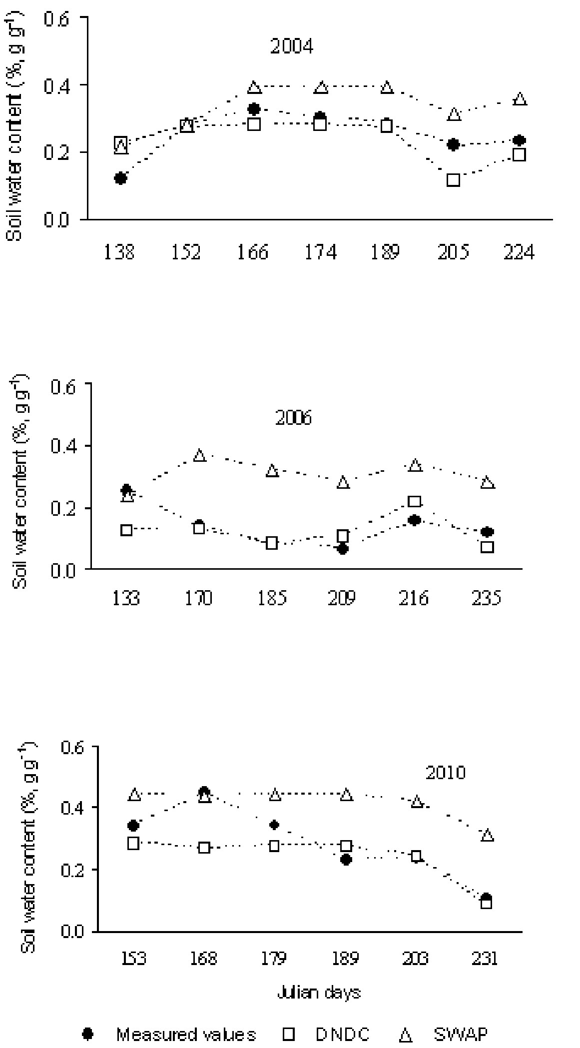

Fig. 8. Dynamics of the measured and predicted soil water content simulated by the DNDC and SWAP models during the growing seasons of 2004, 2006, and 2010.

content compared to the measured data during the three growing seasons. During the growing seasons of 2004, 2006, and 2010, the mean values of the measured soil water contents were equal to 0.28, 0.14, and 0.34 (%, g g^{-1}), reflecting the differences in the total amount of precipitation and in the soil texture. Similarly, the mean predicted soil water content after the DNDC model was 0.24, 0.12 and 0.25 (%, g g^{-1}), respectively. Although the SWAP model was capable of responsing to the above-mentioned differences in precipitation, the mean soil water content predicted by this model was much higher - 0.34, 0.31, and 0.42 (%, g g^{-1}).

According to the mean values of the RMSE between the measured and predicted soil water content, the DNDC model (RMSE = 0.08) was slightly more successful than the SWAP model (RMSE = 0.16) under the combined asses-

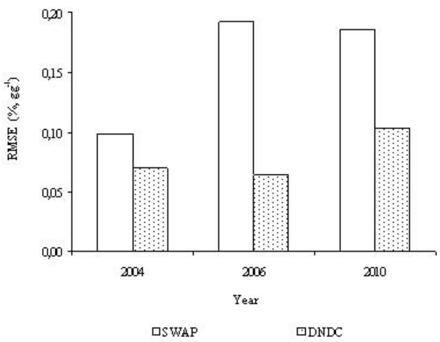

Fig. 9. Distribution of the RMSE values between the measured and predicted water content simulated by the SWAP and DNDC models during the growing seasons of 2004, 2006, and 2010.

sment of the three growing seasons. The values of the RMSE between the measured and predicted soil water content are presented in Fig. 9.

The RMSE values also showed that the DNDC model was a better predictor of soil water content than the SWAP model during all the growing seasons and even in 2006 with the lowest total amount of precipitation (263 mm). The mean coefficients of variation of the RMSE evidenced the better efficiency of the DNDC model (27.0%) than that of the SWAP model (56.2%) in predicting soil water content. Eitzinger *et al*. (2004) found that the SWAP model (version 2.0.7d) insignificantly underestimated the measured soil water content on plots with spring barley, whereas the RMSE values ranged from 1.7 to 3.5% depending on soil type. Ma *et al*. (2011) reported that there were strong correlations (R^2 = 0.77-0.86) between the measured and predicted soil water content after the SWAP model and the average RMSE values of simulated soil water content varied from 2.7 to 4.3% at the depth of 0-20 cm. However, the results of Jiang *et al*. (2011) showed that the SWAP model could overestimate the soil water content at the depth of 15 cm and predict it efficiently at the depths of 35, 65, and 95 cm. Nakagawa *et al*. (2008) reported that the DNDC model overestimated the soil water content but produced a better efficiency if the measured input parameters were used instead of default ones.

The Nash-Sutcliffe efficiency (*E*) coefficients supported the results of the statistical analysis of the RMSE values. The mean values of the *E* coefficients for the SWAP and DNDC models were equal to -3.67 and 0.13 under the combined assessment of the three growing seasons. These statistical data showed that the measured mean was a much better predictor than that of the SWAP model. The DNDC model demonstrated a better match between the modelled and measured soil water contents especially during the growing season in 2010 when the value of the positive *E* coefficient reached 0.38.

CONCLUSIONS

1. When an existing soil database was used, the soil, water, atmosphere, and plant model showed more reliable and adequate sensitivity to the variations of the input air temperatures than the denitrification and decomposition model.

2. The denitrification and decomposition model exhibited better reliability in the prediction of sensitivity of soil water content to the variations of daily amounts of rainfall compared to the soil, water, atmosphere, and plant model. The applied amount of measured input soil data from the existing soil database was insufficient for the soil, water, atmosphere, and plant model to assess efficiently the sensitivity of changes in the predicted soil water content to variations of precipitation.

3. The root mean square error values and Nash-Sutcliffe efficiency coefficients demonstrated that the soil, water, atmosphere, and plant model had a better efficiency in predicting seasonal dynamics of soil temperatures than the denitrification and decomposition model when the existing soil database was used. In the same circumstances, the denitrification and decomposition model showed a better capability of predicting the dynamics of soil water content than the soil, water, atmosphere, and plant model.

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