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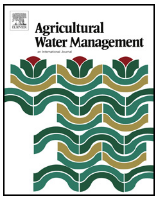

Soil water balance: Comparing two simulation models of different levels of complexity with lysimeter observations

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ABSTRACT

The simulation of the water balance in cropping systems is a useful tool to study how water can be used efficiently. However, this requires that models simulate water balance accurately. Beyond the typical comparison of model outputs with field observations, in this study we present the inter-comparison of models of different complexity with the same field dataset as a powerful method to assess model performance. The compared models were DSSAT (Decision Support System for Agrotechnology Transfer) and WAVE (Water and Agrochemicals in soil, crop and Vadose Environment), both describing one dimensional water transport. The soil water balance in DSSAT uses a simpler "tipping bucket" approach, while the more mechanistic WAVE integrates Richard's equation. The soil parameters were calibrated by using the Simulated Annealing (SA) global optimizing method. A continuous weighing lysimeter in a bare fallow provided the observed values of drainage and evapotranspiration (ET) while soil water content (SW) was supplied by capacitance sensors. An automated weather station recorded the weather data. After optimizing soil parameters with SA, both models performed well simulating the soil water balance components for the calibrated period. The use of cumulative values for ET and drainage in the optimization was more effective than using their daily values. For the validation period, the models predicted well soil evaporation over time but there were differences between models in the soil water and drainage simulations. In particular, WAVE predicted drainage well while DSSAT presented larger errors in the cumulative values. That could be due to the mechanistic nature of WAVE against the more functional nature of DSSAT. Further studies should be conducted to improve the quality of DSSAT drainage simulations. The good results from WAVE indicate that, after soil calibration, it could be used as a reasonable substitute for other models for periods when no drainage field measurements are available.

1. Introduction

Soil water balance simulation in cropping systems is essential to determine crop available water and the potential environmental impact due to solutes lixiviation. Water losses quantification through evaporation and drainage from bare soils in arid and semi-arid regions is important to design effective management strategies to conserve soil water (Aydin, 2008). Simulation models are useful tools to quantify water losses and explore options to water management problems. Several models have been developed in the last decades to simulate accurately soil water balance processes (e.g. SWATRE, Belmans et al., 1983; HYDRUS, Kool and Van Genuchten, 1991; WatBal, Kaczmarek, 1993 and Yates, 1996; AquaCrop, Steduto et al., 2009). Soil water balance models range from functional, as the tipping bucket system models, to mechanistic which includes models based on Richards' equation (Addiscott and Wagenet, 1985).

DSSAT (Decision Support System for Agrotechnology Transfer; Hoogenboom et al., 2010) is a widely used crop growth and nitrogen and carbon cycling simulation model. The suite of crop models (models of 25 crops) included in DSSAT, are linked to a simplified analog (tipping bucket) soil water balance model. Improvement of the performance of the simplified DSSAT water component will lead to improvements in its crop growth and carbon and nitrogen cycling components. The main goal of this study was to improve the soil water balance simulation in the DSSAT model using automatic inverse calibration (simulated annealing) as a first step to better simulate crop growth, nutrient dynamics and nutrient losses. In order to carry out that objective, simulated water balance with DSSAT was compared with the numerical WAVE (Water and

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Agrochemicals in soil, crop and Vadose Environment; Vanclooster et al., 1994), model. Comparing model results with field observations and inter-comparing different models, provides information on model performance and reveals strengths and weaknesses of such models. One of the advantages on comparing with mechanistic models is that they permit obtaining continuous water fluxes which can be difficult to measure in the field, allowing a precise comparison with functional models. Moreover, comparing mechanistic and functional models indicates for which conditions different approaches seem most appropriate (Van den Berg and Driessen, 2002). This is essential in selecting appropriate models for practical applications in water resources analysis and/or identifying required model improvements. Some authors found interesting results when comparing soil water models with different levels of complexity, suggesting changes or improvements on such models according with these results. Maraux et al. (1998), compared some functional models with a previously calibrated mechanistic model to simulate the soil water balance of successive crops, concluding that the difference between models might be partly due to the division of evapotranspiration into evaporation and transpiration, root uptake and drainage. Nevertheless, they concluded that it would be necessary to carry out more studies on the functional models to test this hypothesis. Eitzinger et al., 2004, compared three widely used crop models, CERES, SWAP and WOFOST and concluded that those crop models with soil water flow subroutines based either on the multiple layer plate theory or Darcy law should be preferred in comparable environments. They obtained acceptable values of soil water content in the simulations but overestimated values of actual evapotranspiration. However none of the models had been calibrated on the basis of parameter optimization which probably would have result in better simulations of the evapotranspiration. Ranatunga et al. (2008) made a review of widely used water simulation models in Australia and classified them in simples (or fixed soil layer) with a tipping bucket approach, which can be divided into single layer or multiple layer approaches, and complex (or continuous soil profile), which can be divided in one or two dimensional flow models. They concluded that each model can be used for specific scenarios depending for example on the scale at which water balance simulations are made. They emphasized the need for a balance between available data and model complexity according with the objectives of every specific project. Ines et al., 2001 compared the physically based SWAP model (van Dam et al., 1997) that uses Richards' equation to define the transport of soil water, and the "tipping bucket" DSSAT model based on Ritchie's model. They concluded that each model has their own strengths and limitations and can be appropriate for a specific task: DSSAT model was better in the prediction of the development stage but worse in the prediction of yield, soil moisture and evapotranspiration than SWAP.

Each model requires a number of soil parameters which have to be measured or estimated. Parameters may be unknown or estimated from readily available field or laboratory data (Calmon et al., 1999). With increasing use of soil water balance models, a considerable amount of effort is being dedicated to develop parameter estimation techniques for models (Xu and Singh, 1998). Calmon et al. (1999) distinguished three kinds of procedures to calibrate model parameters: manually by "trial and error" which has demonstrated to be a not really objective method and it can lead to relatively poor fit of the measured data (Ritter et al., 2003), by using statistical models or by using optimization techniques that, combined with models, results in a relatively efficient parameter estimation technique. The conventional optimization algorithms have been commonly used to estimate parameters by moving the objective function uphill or downhill in an iterative manner. One of the main limitations of this approach is that the algorithms may converge on a local optimum and completely miss the global optimum (Goffe et al., 1994). The simulated annealing (SA) global optimizing method has demonstrated to be a very effective system to calibrate model parameters and even superior to multiple conventional optimization routines as was shown in Goffe et al. (1994), Calmon et al. (1999) or Lizaso et al. (2001). Simulated Annealing can avoid local optima and choose the set of parameters corresponding to the global optimum. Simulated Annealing has been applied successfully to numerous problems of soil parameter estimation for functional crop models (Braga and Jones, 1998; Braga et al., 1998; Shen et al., 1998; Paz et al., 1998; Calmon et al., 1999), and thus it was chosen to optimize the soil parameters in this work.

The main goal of this study was to improve the simplified soil water balance simulation in the DSSAT model using automatic inverse calibration (simulated annealing) as a first step to better simulate crop growth, nutrient dynamics and nutrient losses. Simulated water balance with DSSAT was compared with the numerical WAVE model and with lysimeter observations. Specific objectives of this work were (1) to reduce the uncertainty associated to soil water balance components by optimizing selected soil parameters, (2) to compare two different model approaches: a tipping-bucket vs. a Richard's equation, and (3) to evaluate the performance of DSSAT simplified water balance in order to simulate crop growth and C and N dynamics in future works.

2. Material and methods

2.1. Experimental site

Field observations were conducted in the experimental lysimeter station "Las Tiesas" (Albacete, Spain, 39°N, 2°W, 695 m), supported by the "Instituto Técnico Agronómico Provincial" (ITAP), during two periods: 2011–2012 and 2012–2013. The area has a semi-arid, continental climate. A weighting lysimeter on bare soil with continuous electronic data reading devices was used in the experiment (Fig. 1). Water table depth is 60 m (Sanz et al., 2009). The soil was cultivated previously with sunflower that was harvested and the residues removed before the beginning of the experiment. The dimensions of the lysimeter container were 2.3 m × 2.7 m and 1.7 m depth, with approximately 14.5 Mg total mass. The lysimeter recipient was located in the center of a 1-ha plot cultivated following the same procedures and surrounded by a square protection plot to avoid runoff. The station also hosted another weighing lysimeter, cultivated with grass, monitoring reference evapotranspiration (ET_0). In the bare soil lysimeter, soil evaporation (ET) was calculated daily based on the registered weight, corrected by drainage. Drainage was continuously measured with a tipping bucket rain gauge (HOBO 200, Davis Instruments, Hayward, California, USA) installed at the outlet of the lysimeter bottom and connected to a data logger registering the information (Fig. 1). The pluviometer was previously calibrated in the laboratory showing a ratio of 6.5 ml tip^{-1}.

The study was divided into two periods: calibration (2/8/2012–3/29/2012) and validation (10/30/2012–2/27/2013). Water management in the calibration period had two irrigation cycles: in the first (February 8th, 2012 until March 1 st, 2012) the soil profile was replenished, by irrigating with 76.72 mm in three times (3/1/2012, 3/5/2012, 3/7/2012); in the second (March 1st until March 29th, 2012) the soil was irrigated with 77 mm letting it dry during one month. In the validation period (October 30th, 2012 until February 27th, 2013) the soil was irrigated with 41 mm at the beginning letting it dry afterwards.

Weather information was collected by a weather station located in the experimental field. The registered variables were: relative air humidity and air temperature at 2 m, net short wave radiation at 2 m, net long wave radiation at 2 m, soil heat flux at 0.05, 0.1, 0.2 and 0.3 m, atmospheric pressure at 2 m, wind speed and direction, and