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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Monitoring and Modeling Farmland Productivity along the Venice Coastland, Italy

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Abstract

The southern portion of the Venice coastland is a very precarious environment and salt contamination of land and groundwater is a severe problem that is seriously impacting the farmland productivity. Geophysical surveys, lab testing and continuous monitoring of hydrological parameters together with crop yield distribution were performed and acquired from 2010 to 2012 in a 21 ha basin cultivated with maize crop and representative of the area. The dataset is here used to set-up a numerical model of soil moisture dynamics coupled with plant transpiration, photosynthesis and growth. The hydraulic model is linked to the atmosphere by the calculation of the stomatal conductance which is optimized for maximum carbon gain. The model is applied to the field site to understand the impact of land elevation, soil heterogeneities, and seawater contamination on land productivity.

Keywords: Ecohydrology, Modeling, Soil-Plant-Atmophere Continuum, Farmland Productivity

1. Introduction

Saving water for agricultural activity is an old, but ongoing, challenge [1,2] and a better understanding of the biophysical processes of root-water uptake is required to develop more sustainable irrigation

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practices. Additionally, saline water intrusion associated with sea level rise is adversely impacting agricultural production of coastal areas at an alarming rate [1,3]. The southern portion of the Venice coastland, Italy, represents a very precarious environment (Fig. 1). Due to an elevation down to 4 mbsl (Fig. 1c), the seawater intrusion from the Venice Lagoon and the encroachment of salty water from the mouth of the river network, salt contamination of land and groundwater is a severe problem that is seriously impacting the farmland productivity [4]. Understanding the complex interactions between vegetation growth, root water uptake, atmospheric and soil dynamics under stressed conditions is therefore necessary to optimize land productivity while preserving water resources.

Mathematical modeling has been successfully applied to support on-farm decision-making processes, but understanding and modeling the field scale soil-plant-atmosphere interactions is an open challenge [5]. Existing modeling approaches can be divided into two categories: 1) ecophysiological models accounting for detailed crop growth but lacking of a detailed description of water flow (typically a one-dimensional water balance) and 2) hydrological models describing plant water uptake as a sink term in the Richards equation but generally neglecting the feedback mechanisms with plant photosynthesis and growth. The most widely used ecophysiological models, e.g. WOFOST [6] and CERES [7], account for water dynamics using a simplified water budget over soil compartments with a fixed water-holding capacity. Other models, such as SWAP [8], are Richards equation-based models but only vertical flow is considered thus limiting the model applicability at the field/watershed scale where soil heterogeneities and land elevation may play an important role on vegetation dynamics. On the other hand most of the existing multidimensional hydrological models account for root water uptake using simplified sink terms in the Richards equation (e.g. HYDRUS [9]) but it is shown that the applicability of simplified macroscopic models is limited in heterogeneous media [10].

Recently Katul *et al.* [11] presented a stomatal optimization theory to describe the effects of atmospheric CO_2 on leaf photosynthesis and transpiration, further coupled with a one-dimensional model of soil moisture dynamics in [12]. The modeling framework presented in [12] is here extended to describe soil productivity at the field/watershed scale and quantify the factors of land degradation on the Venice coastland.

2. Case of study

The study site (Fig. 1) is a 21 ha field located at the southern margins of the Lagoon of Venice, North-East of Italy, in proximity of the Brenta and Bacchiglione Rivers and approximately 7 km to the Adriatic Sea shoreline. The area is crossed by two well-preserved paleochannels (visible from satellite images as shown in Fig. 1b) that could potentially connect the study site to the Lagoon, or to the above-mentioned rivers. In spring 2012 a micro elevation survey was carried out with the Trimble FM 1000 CNH (Trimble Navigation Ltd., USA) real time kinematic system. The survey showed that the study site lies in the range of ca. -1.5 to -3.3 m below average sea level and the paleochannels are generally higher than the neighboring zones (Fig. 1c). Both undisturbed and disturbed soil samples were collected in May 2010 at different depths: disturbed samples were analyzed for soil electrical conductivity ($EC_{1:2}$, dS m^{-1}) and soil texture (%) using a laser particle size analyser while undisturbed cores were analysed for soil bulk density and saturated/unsaturated hydraulic conductivity [13]. The site characterization is illustrated in Fig. 1c-e. The field was cropped with maize (*Zea mais* L.) and harvested for grain. Maize grain yield was measured with a combine harvester equipped with a yield monitor (Agrocom, Claas, Germany) and a DGPS.

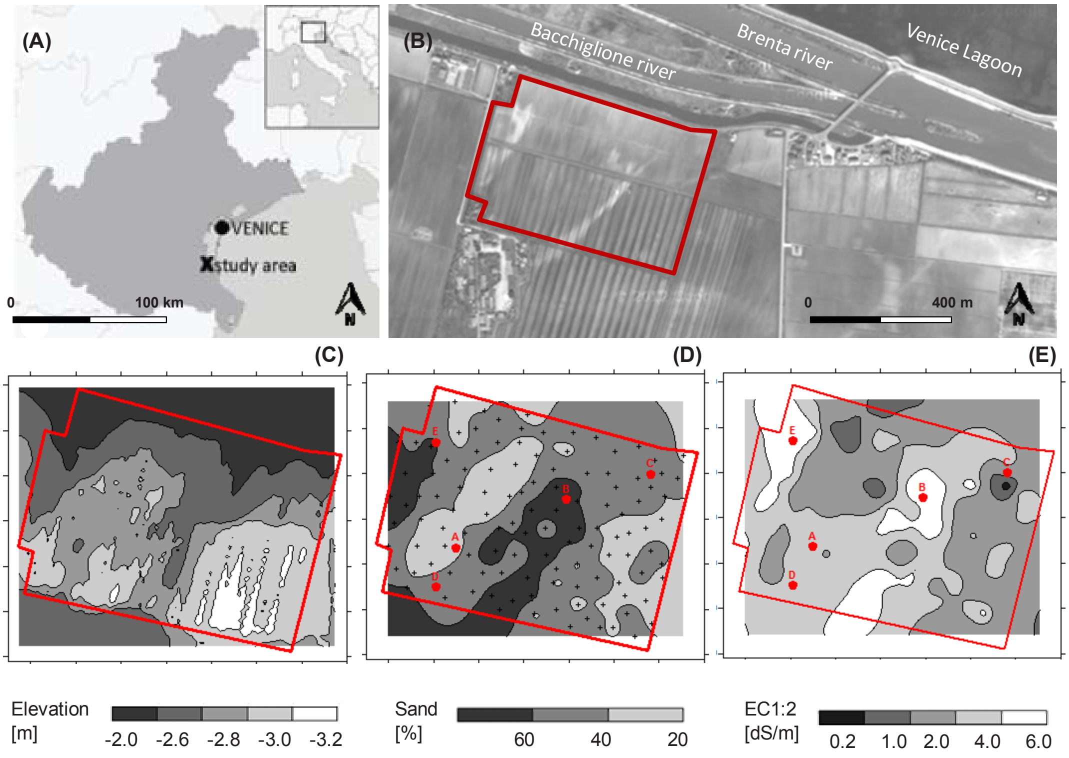

Fig. 1. Study area: (a) location with respect to the Venice Lagoon and (b) the crop field. Site characterization: (c) land elevation, (d) soil texture (as sand percentage) and (e) soil salinity (as EC 1:2). Red dots represent the monitoring stations at the site.

3. Mathematical formulation

3.1. Model description

The model used in this study makes the following assumptions: a) water extracted by roots is instantaneously transpired by leaves and no water storage can occur within the plant, b) each soil layer is directly linked to the xylem by the root biomass allocated in the layer, and c) the model is applied to maize assuming ample supply of nutrients, and without pests, diseases and weeds. Soil moisture dynamics is described by the three-dimensional Richards equation:

$$S_s S_w \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = \vec{\nabla} \cdot \left[\mathbf{K_s} K_r \left(\vec{\nabla} \psi + \eta_z \right) \right] + q \qquad (1)$$

where S_s is the elastic storage term, S_w is water saturation, ψ is water pressure head, t is time, Φ is the porosity, $\boldsymbol{K_s}$ is the saturated hydraulic conductivity tensor, K_r is the relative hydraulic conductivity, $\eta_z=(0,0,1)^T$, being z the vertical coordinate directed upward and q is a source/sink term. Plant uptake is described by the Ohm's law type model developed in [12] and schematized in Fig. 2a. The transpiration flux is modeled in terms of water potentials in the leaf (ψ_L), in the xylem (ψ_R) and in the soil (ψ_i). The uptake of soil water by the roots of plant j in grid node i is defined as follows:

$$q_{i,j} = -g_{i,j} \cdot V_i \frac{\left[\left(\psi_{R,j} - z_{R,j}\right) - \left(\psi_i - z_i\right)\right]}{L_i} \tag{2}$$

where $z_{R,j}$ is the vertical coordinate of the j-th plant, z_i the vertical coordinate and V_i the volume referred to the i-th node, L_i is the distance of node i from the xylem and the root-soil conductance $g_{i,j}$ is calculated as the series of soil ($g_{s,i}$) and root ($g_{r,i}$) conductances [12]. The leaf-atmosphere flux f_w is defined by Fickian mass transfer of water vapor between the leaf and the atmosphere. The flux is controlled by the stomatal conductance g_s which is optimized for maximum carbon gain according to [11]. Carbon assimilation (f_c) is described by a biochemical photosynthesis model [11]:

$$f_{c,j} = \frac{a_{1,j}}{a_{1,j} + c_{in,j}} \left(c_{in,j} - c_p\right) \tag{3}$$

where the photosynthetic parameters a_1 and a_2 are chosen between light-limited or rubisco-limited conditions according to [12], the intercellular CO_2 concentration $c_{in,j}$ is estimated considering Fickian mass transfer between the leaf and the atmosphere and c_p is the CO_2 compensation point [11]. The absorbed CO_2 is reduced to carbohydrates (CH_2O) using the energy supplied by the solar radiation and dry matter accumulation is estimated based on respiration costs and carbohydrates allocation in the different plant organs. We refer to [14] for further details on the crop growth processes. According to [3], the photosynthetic efficiency a_1 is identified as most significantly controlling the behavior of the stomatal optimality model under salt-stress condition. Salinity is therefore assumed to affect the photosynthetic efficiency by an empirical salinity response curve [15]. According to the modeling framework presented herein, an inhibition of the photosynthetic efficiency implicitly influences the water use efficiency (see [12] for details) but other possible impacts (e.g. on soil-root conductances, osmotic pressure, etc.) are neglected.

3.2. Numerical implementation

The starting equation for the numerical implementation of the soil-plant-atmosphere system is the continuity of water fluxes expressed as $f_w = \sum q_i$. Coupling this equation with the Richards equation (Eq. 1) for the soil water dynamics provides a system of two equations in the two unknowns ψ_i, the pressure head at the root tip, and ψ_L, the water pressure at the leaves [12]. Richards equation is solved numerically by the Finite Element (FE) method with backward Euler scheme for the time discretization. The non-linear systems of algebraic equations resulting from the FE discretization are solved using the Picard iterations [16] and the value of ψ_L is evaluated from the soil-plant-atmosphere balance at every Picard iteration by the Newton-Raphson method.

The model is calibrated on a single plant and then applied at the plot scale to obtain a sort of upscaled version of the vegetation model. The procedure is schematized in Fig. 2 and will be described with more details in the next section. Given the model resolution and considering that our interest lies in the simulation of the long term crop productivity, the temporal dynamics of salt concentration in the vadose zone is neglected and assumed equal to the measured soil salinity (Fig. 1e). This assumption is further justified by the steady state condition reached by the farmland-lagoon system. The limited variability in time of salt concentration has been confirmed also by repeated electro-magnetic surveys covering the whole basin and continuous records of groundwater conductivity in a number of piezometers drilled for the purpose.

4. Results and Discussion

Calibration and upscaling proceeds as follows. A first set of simulations has been performed to calibrate the model parameters at the plant scale. A cubic portion of soil of dimensions 5×5×5m (subsequently called "the plot") is discretized in the *x*- and *y*-directions with a 0.2 m spacing (fine grid) allowing a detailed description of 132 plants, i.e. the typical number of plants seeded in a 5×5 m plot (Fig. 1b). The upscaled model is then obtained by calibration of the model parameters on the same plot discretized with a coarse grid (2.5m spacing in *x* and *y*) where a single plant is used to represent the behavior of the whole fine-scale plot. Calibration is considered achieved when the fluxes in the coarse single-plant plot equal the fluxes in the fine scale plot. The coarse grid corresponds to the volume related to a node of the field scale model. All the plant uptake model parameters used at the plant scale are based on literature values and field observations and only the parameters related to the plant dimensions (roots lengths, canopy area, etc.) are modified in the upscaling procedure. Field data (rainfall, temperature, relative humidity, radiation) are used to calculate the atmospheric forcing. Input evaporation is considered as a potential rate, and actual evaporation is evaluated based on system state condition allowing the switching between Neumann and Dirichlet boundary conditions [17]. Since measurements of transpiration fluxes are not available at the site, simulation results are compared with the potential transpiration calculated by the Penmann-Monteith equation (FAO) using the dual-crop coefficient approach [18]. For this purpose, the simulations were run ensuring well-watered conditions. The upscaled plot model is shown to capture the expected dynamics (Fig. 3a). Notice that a perfect match with the potential transpiration by FAO is considered beyond the objectives of this study.

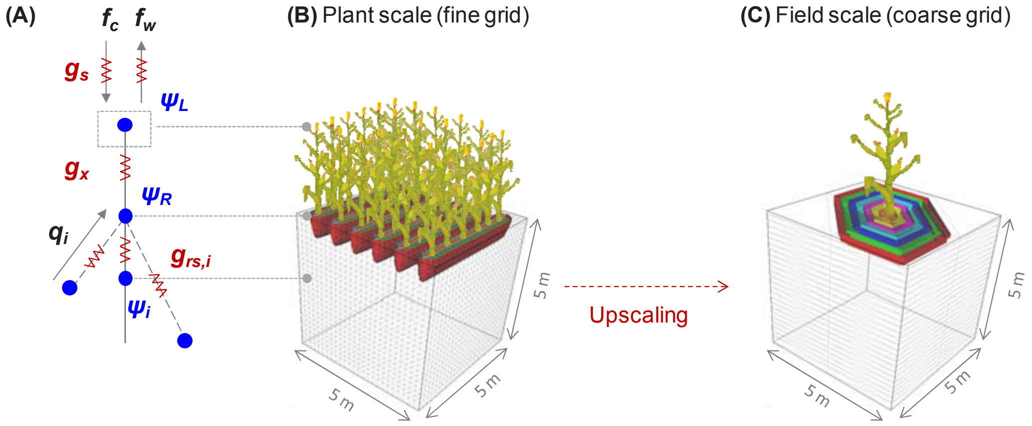

Fig. 2.Conceptual model (a) and simulation grids: plant scale (b) and field scale (c) model grid.

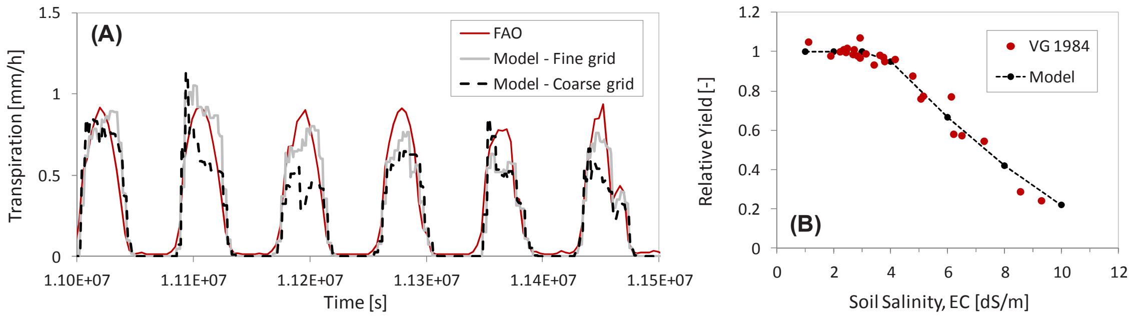

Fig. 3. Calibration of the transpiration flux (a) and the effect of soil salinity on crop yield (b): model results are compared with experimental data from [15] (VG 1984).

To test the response of plant growth to soil salinity, different simulations were run with increasing values of soil salinity. The predicted relative yield is compared with experimental data published in [15] and the model shows a good agreement with data (Fig. 3b). The model is then applied at the field scale, over a 600×600×5m model domain (red square in Fig.1b) to predict the farmland productivity. The surface elevation was built using the micro elevation survey data and the observed soil salinity (Fig. 1e) was interpolated over the model grid by kriging. Water table levels are specified for the Northern and Southern boundaries of the model domain according to the observed water level in the irrigation channels. No flow boundary conditions are set on the other edges of the domain. Preliminary results for year 2011 are shown in Fig. 4. The model is shown to capture the measured crop productivity even if the spatial pattern observed at the small scale is poorly matched. Moreover, model results show that salt stress is the major cause of crop stress and the sandy regions are the most productive (Fig. 4b) as confirmed by the field observations (Fig. 4a).

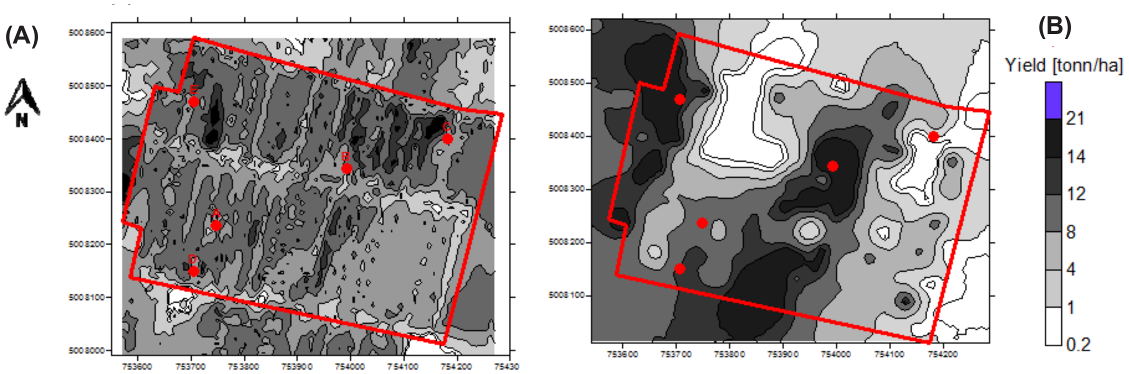

Fig. 4. Observed (a) and simulated (b) crop yield at harvesting for year 2011. Data provided by [19].

5. Conclusions

We have used a Richards equation model coupled to vegetation dynamics to simulate the spatially distributed maize production on a 21 ha instrumented field on the boundary of the Venice Lagoon (Italy). We assumed that no limitation on crop production was due to nutrient scarcity, while the effect of soil salinity was taken in full consideration. This study is a preliminary application of the model developed and a perfect match between simulation results and field observations was beyond the objectives of this work. The aim was to obtain reasonable estimations of crop yield using literature values of the model parameters and investigate the ability of a fully coupled soil-vegetation model to predict the spatial variability of land productivity. Simulation results are in the same range of the precision agriculture measurements but the model was not able to capture all the fine scale spatial variability of the observed vegetation patterns. The discrepancy between observations and simulations are to be attributed mainly to neglected fine scale hydrologic constraints, such as the presence of the ditch network used to keep drained the farmland, and physical processes (e.g., nutrient uptake, salt temporal dynamics, etc.). Future work will be aimed at incorporating these features in order to proper calibrate and validate the model against hydrological records (e.g., groundwater levels, soil moisture content, etc.), crop growth and yield data collected at the site.

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