Modeling temporal and spatial variability of crop yield

G. Manoli[1,*], S. Bonetti[1], E. Scudiero[2], F. Morari[3], M. Putti[3], and P. Teatini[3]

[1] Duke University, Durham NC, USA [2] USDA-ARS, US Salinity Laboratory, Riverside CA , USA [3] University of Padova, Italy

* Contact: gabriele.manoli@duke.edu

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Background

The increased demand for water and food is compromising global food security and an improved understanding of spatial and temporal crop yield variability is required to preserve resources and optimize land productivity. The design of sustainable irrigation practices requires an accurate modeling of the Soil-Plant-Atmosphere (SPA) system but quantifying the eco-hydrological feedback mechanisms governing field scale crop productivity is still an open challenge. Ecophysiological models (e.g. [1]) are developed and applied at the plot-scale using simplified water budgets while hydrological models (e.g. [2]) generally neglect the feedback mechanisms with plant physiology. For these reasons the ability of existing models to capture both temporal and spatial variability of plant responses to environmental factors (topography, soil type, salinity, etc.) remains to be proven, especially at large scales (field/watershed).

Here we use an innovative 3D Soil-Plant model to quantify temporal and spatial variability of crop productivity at the field scale and we assess simulation accuracy by comparison with spatially distributed crop yield measurements. A 25 ha basin located in the Venice coastland, Italy, cultivated with maize crop, and characterized by a highly heterogeneous soil subject to salt contamination has been extensively studied by soil sampling, geophysical surveys, hydrological monitoring and crop yield mapping (Fig. 1-2).

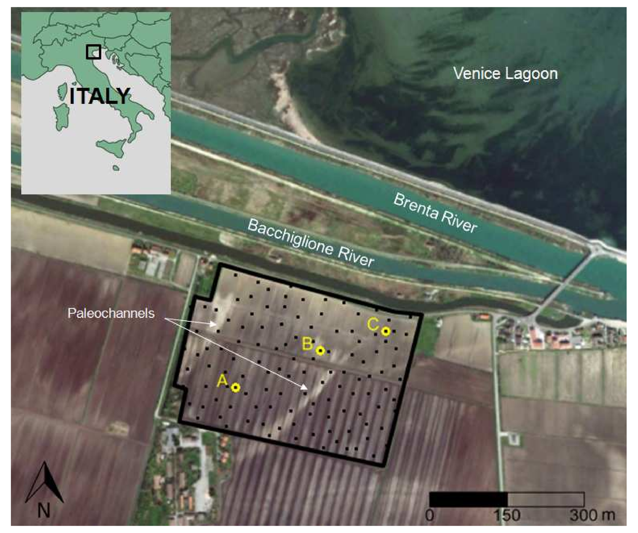

Fig. 1 Location of the study area, monitoring stations (A, B, C) and soil sampling (black dots). The area is crossed by two well preserved paleo-channels and a pumping station and a dense network of open ditches controls the depth of the water table, which is maintained fairly shallow during summer to promote sub-irrigation

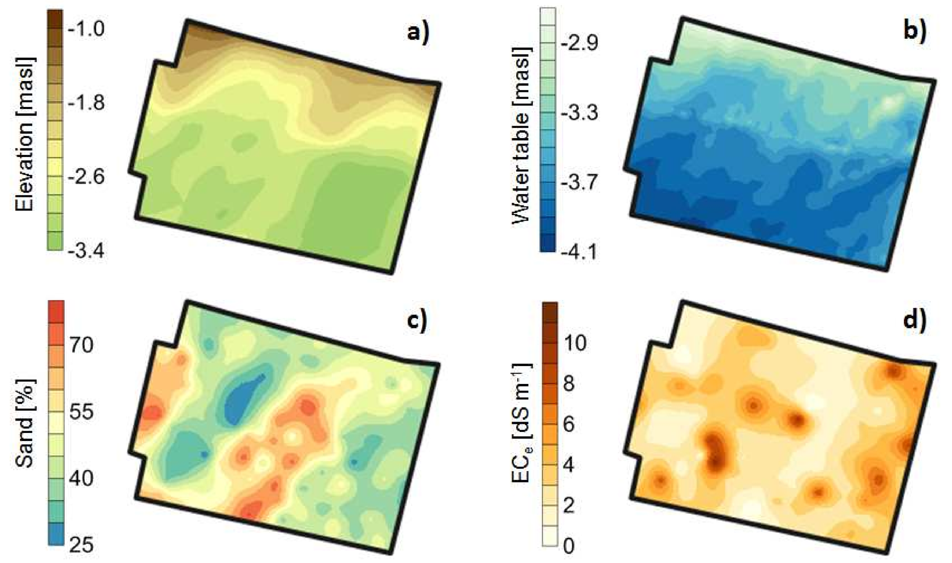

Fig. 2 Site characteristics: **a)** elevation (2012 micro elevation survey), **b)** water table (estimated from apparent electrical conductivity data, 2010-2012 electromagnetic survey, and verified at 8 monitoring wells). Disturbed samples from the 120 sampling locations in Fig. 1 were analyzed for **c)** soil texture and **d)** soil salinity (in terms of electrical conductivity of the aqueous extract of saturated soil-paste EC$_e$ [dS m^{-1}]). Monitoring data confirm the existence of two sandy paleo-channels, generally less saline than the surroundings.

Methods

In this study we use the modeling framework presented in [3] coupled with a crop growth module based on [4]. The Soil-Plant model accounts for soil moisture dynamics (described by the 3D Richards Equation as implemented in the CATHY code [5]), plant photosynthesis and transpiration (Fig. 3a). The transpiration flux is modeled in terms of water potentials in the soil (Ψ_l), in the root xylem (Ψ_R), and in the leaf (Ψ_L). The root water uptake is regulated by the stomatal conductance that is optimized for maximum carbon gain [6]. Salt toxicity is modeled by an empirical salinity response function included in the biochemical photosynthesis model. The carbon flux f_c is used to calculate the dry matter accumulation based on respiration costs and carbohydrates allocation in the different plant organs. First the plant-model parameters are calibrated at the plot scale (Fig. 4) using a 5×5×5m domain and then the model is applied at the field scale (Fig. 3b) using a coarse (G1) and a fine (G2) model grid and hydraulic parameters from laboratory testing (Fig. 3c). The water table in Fig. 2b is used to set hydrostatic Dirichlet boundary conditions at the edges of the domain and on the internal grid nodes occupied by the irrigation channels and top soil salinity (EC$_e$) is set constant in time according to field observations (Fig. 2d).

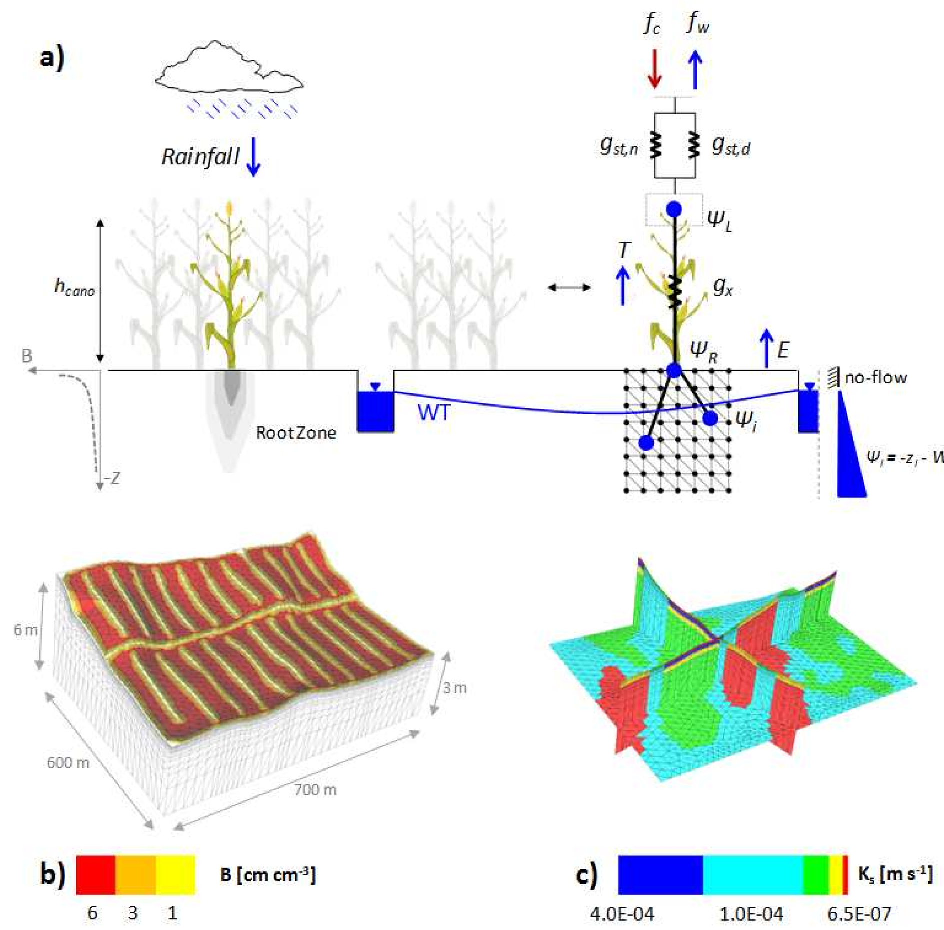

Fig. 3 Field scale simulations: **a)** conceptual model, **b)** simulation grid G2 and root length density B and **c)** spatial distribution of saturated hydraulic conductivity K_s.

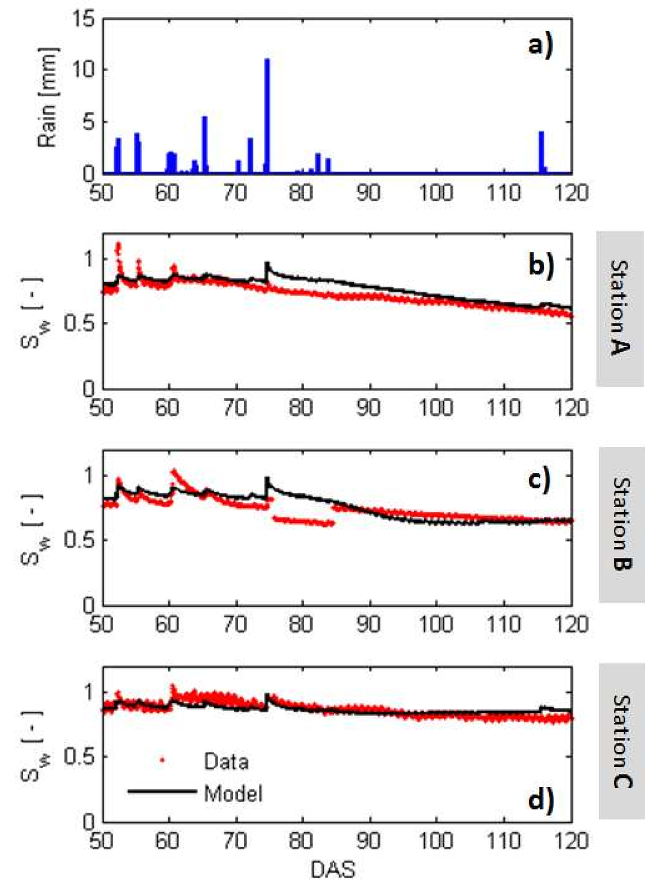

Fig. 4 Observed (red circles) and modeled (black lines) soil moisture at the monitoring station A, B and C at the depth of 10 cm.

Results and discussion

Model results compare well with the observed 2011 yield (Fig. 6b,c). The discrepancies are mostly related to peaks in the measured productivity, that can be related to small scale soil heterogeneities not accounted for in the simulations. Simulations confirm that the sandy zones are highly productive while the South-Eastern part of the site experiences the lowest productivity. However, by employing the same root profile used for the 2011 simulations (R70), it is not possible to predict the yield reduction observed in 2012 (Fig. 6d-f). Year 2012 was in fact very wet at seeding followed by a dry growing season (Fig. 5a). The different rainfall regimes may have promoted deep roots exploring for subsurface water in 2011 and shallower root systems in 2012. Using a shallower root profile (R30) the 2012 simulation results are highly improved (Fig. 6g-h).

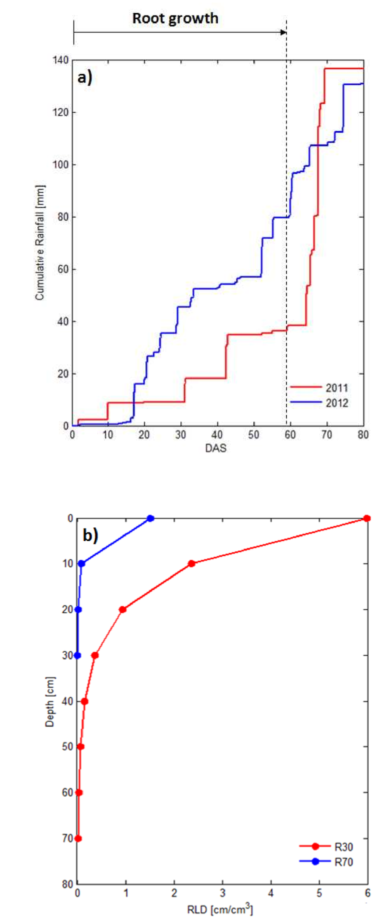

Fig. 5 Cumulative rainfall (**a**) and root profiles used in the simulations (**b**).

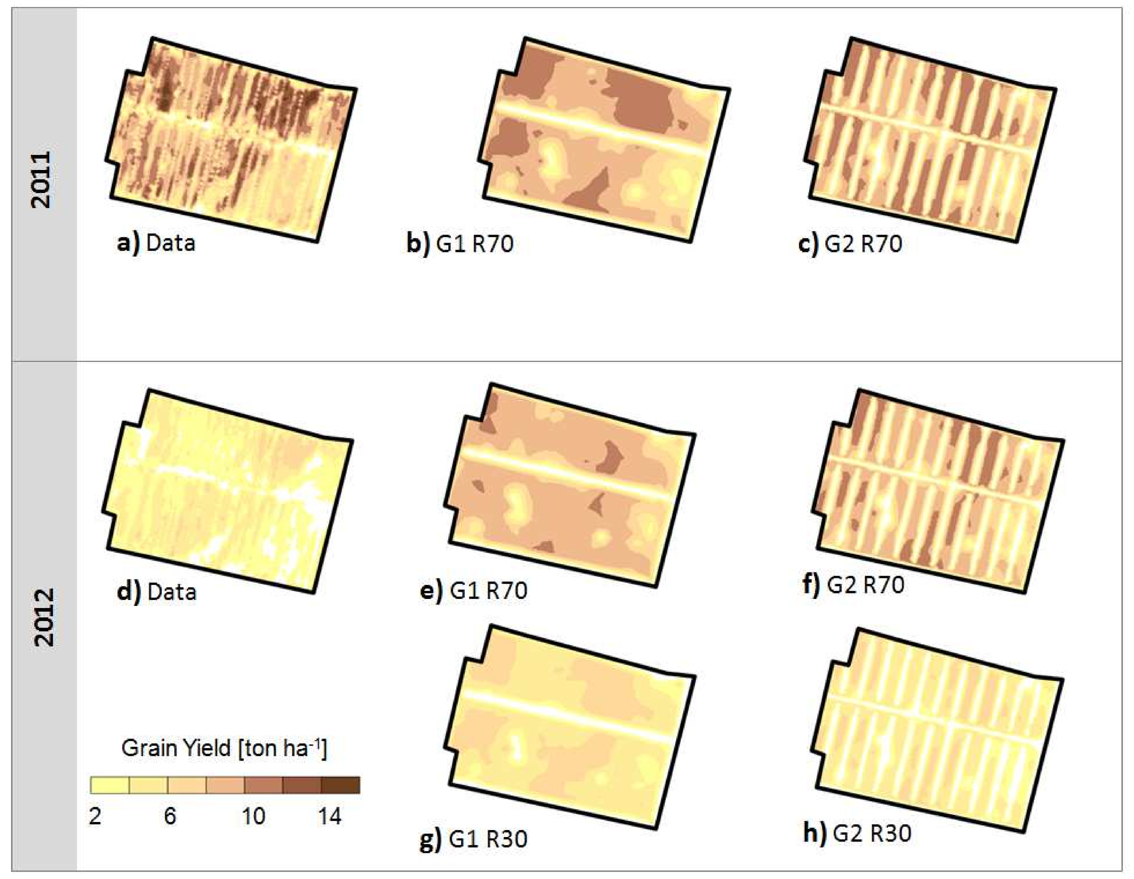

Fig. 6 Observed (**a,d**) and predicted spatial pattern of grain yield during year 2011 (**b,c**) and 2012 (**e,f,g,h**) for different model grids (G1 and G2) and different root profiles (R30 and R70).

Conclusions

An innovative mechanistic land-atmosphere model has been used to predict spatial patterns of crop yield, demonstrating a good agreement with observed temporal and spatial dynamics. Given the model simplifications drought conditions are more difficult to model. However, simulation results suggest that root growth processes (and their interaction with environmental factors such as soil type and rainfall) are crucial to correctly predict land productivity under stress conditions. Despite the simplifying assumptions made, we presented a comprehensive modeling framework linking field scale soil heterogeneities to soil-plant hydraulics, stomatal aperture and plant growth processes, thus paving the way to future large scale modeling of farmland productivity across seasons.

Acknowledgments

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