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Modelling soil tillage and mulching effects on soil water dynamics in raised-bed vegetable rotations

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ABSTRACT

Reduced tillage and mulching may bring about new production systems that combine better soil structure with greater water use efficiency for vegetable crops grown in raised bed systems. These are especially relevant under conditions of high rainfall variability, limited access to irrigation and high soil erosion risk. Here we evaluate a novel combination of empirical models on water interception and infiltration, with a soil-water balance model to evaluate water dynamics in raised bed systems on fine Uruguayan soils to analyze the effect of reduced tillage, cover crops and organic matter addition on soil physical properties and water balance. In the experiment mulching increased water capture by 9.5% and reduced runoff by 37%, on average, leading to less erosion risk and greater plant available water over four years of trial. Using these data we calibrated and evaluated different models that predicted interception + infiltration efficiently (EF = 0.93 to 0.95), with a root mean squared error (RMSE) from 0.32 to 0.40 mm, for an average observed interception + infiltration of 28.8 mm per day per rainfall event. Combining the best model with a soil water balance resulted in predictions of total soil water content to 1 m depth (SWC_T) with RMSE ranging from 4.5 to 10.3 mm for observed SWC_T ranging from 180.4 to 380.6 mm. Running the model for a four-year crop sequence under 10 years of Uruguayan historical weather revealed that reduced tillage required on average 141 mm yr^{-1} less irrigation water than conventional tillage combined with organic matter application, thus enabling a potential increase in irrigated area of vegetable crops and crop yields. Results also showed the importance of inter-annual rainfall variability, which caused up to 3-fold differences in irrigation requirements. The model is easily adaptable to other soil and weather conditions.

1. Introduction

Land degradation, defined as the temporary or permanent reduction of productive capacity of land, is a process of global importance that affects ca. 25% of the globally productive land, on which 1.5 billion people reside (Bai et al., 2008). Two of the major processes responsible for land degradation and loss of soil fertility are: removal of nutrient-rich soil particles resulting from soil erosion; and decrease in soil water supply capacity associated with soil compaction, decrease in soil permeability and loss of water holding capacity (D'Odorico et al., 2013). These processes, when accelerated by positive feedbacks between human activities (poor land management) and climatic variability, drive the systems into a downward spiral of environmental degradation.

According to the Bai et al. (2008) study, 49.7% of Uruguayan land is degraded. Due to land degradation, vegetable crop production on family farms in South Uruguay is increasingly limited by poor soil physical properties and water availability (Alliaume et al., 2013). On predominantly fine textured soils (Mollic Vertisols and Luvic/Vertic Phaeozems (Pachic/Abruptic/Oxyaquic; IUSS Working Group WRB, 2006) vegetable crops are generally grown on raised beds in order to both increase the volume of the topsoil that can be easily explored by roots and to improve surface drainage after a heavy rainfall. The presence of argillic (Bt) horizons close to soil surface in combination with intense rainfall events leads to rapid saturation of the topsoil, exacerbating surface runoff. In this context, mulching acts as a physical barrier that protects from drop

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impact and soil disaggregation, improving water infiltration, and reducing the risk of erosion (Alliaume et al., 2014).

Farmers in south Uruguay are able to irrigate on average 48% of the vegetable crop area (DIEA, 2011). A predicted increase in the intensity of rainfall (Marengo et al., 2012) and a high erosion risk due to the combination of clayey soils and undulating terrain call for management strategies to increase water productivity with reduced environmental impact, while maintaining or increasing crop yields. Soil conservation practices such as reduced tillage and crop residue mulching provide important components for strategies to achieve these objectives (Alliaume et al., 2014). For vegetable production, reduced tillage and mulching may give rise to new production systems that combine better soil structure with greater water use efficiency. These are especially needed under conditions of high variability of rainfall and limited access to irrigation.

A model able to simulate the effect of different components of the soil water balance under alternative soil-crop management options can facilitate the design of alternative systems. When included in farm level assessment tools (e.g. Dogliotti et al., 2005) it can facilitate the evaluation of alternative resource allocation strategies to explore the potential for adaptation of vegetable systems to climate change. Several mechanistic and empirical methods have been proposed worldwide to estimate the amount of water infiltrating into the soil after a rainfall event. Most of these models have focused on sandy to loam soils (Bonfante et al., 2010). There is as yet little information available for clayey soils or raised bed systems, in combination with crop residue management strategies.

The SCS curve number method (USDA-SCS, 1972) is a widely used empirical model for estimating runoff, although it was conceived to be used at the scale of entire catchments and not for fields or specific soil management alternatives. An extensively used mechanistic model to estimate runoff is Green-Ampt, where infiltration parameters can be directly related to catchment characteristics (Wilcox et al., 1990). However, this model requires disaggregated daily precipitation data that are difficult to obtain. Also, even though the Green-Ampt equation has a physical basis, much of the explanatory power may be lost by the regression equations needed to parameterize the model (Wilcox et al., 1990).

Several models can predict the water balance in different systems, such as STICS (Brisson et al., 2008) and AquaCrop (Constantin et al., 2015), SWAP (Van Dam, 2000), Cropsyst (Stöckle et al., 2003), MACRO (Bonfante et al., 2010), and APSIM (Ranatunga et al., 2008). Holland et al. (2012) evaluated the influence of raised beds on water runoff on layered soils cropped with grains or oilseeds, but did not consider mulching. The runoff dynamics of raised beds covered by mulch was simulated satisfactorily by a physically-based model developed by Findeling et al. (2003), for different soil and climate conditions. Scopel et al. (2004) updated STICS with an empirical module that accounts for effects of surface residue on soil water balance. The module depends on local parameters and was tested on soils without an argillic horizon. Jones et al. (2014) simulated soil water dynamics using DSSAT under drip-irrigated plastic-mulched raised-bedded production systems with satisfactory performance on a fairly homogeneous sandy soil. The authors point out that simulations for highly layered soils should be considered with caution. We could not find a model with satisfactory performance to simulate water dynamics for the conditions of southern Uruguay, and specifically for vegetable crops grown in raised beds of layered soils covered by organic mulch.

The aim of this study was to analyze the effect of reduced tillage with residues left as mulch, on soil water dynamics in raised bed vegetable production systems on the fine-textured soils with an argillic horizon of southern Uruguay. A first objective was to derive a simple, generally applicable, locally parameterizable mathematical model to evaluate the effect of mulching and reduced tillage on soil water capture and soil water content. A second objective was to use the model to explore the impact that these soil management practices might have on different water balance components and irrigation requirements of vegetable crops in southern Uruguay.

2. Materials and methods

2.1. Experiment dataset

We used a dataset of a 4-year field experiment conducted at the South Regional Center research station, Canelones, south Uruguay (two first years reported in Alliaume et al., 2014). Climate is temperate sub-humid with a mean annual rainfall of 976 mm. Rainfall is highly variable but evenly distributed over the year, with frequent droughts in summer and periods of water excess in winter. Mean annual rainfall over the 3-year study period ranged from 820 to 1200 mm. Average slope of the experimental field was 1.5%. The soil was derived from silty clay sediment and represented a common soil in the region. It was described and classified as a Luvic Phaeozem according to the FAO system, with 20 cm of a silty loam top horizon with a particle size distribution of 140 g kg^{-1} sand, 625 g kg^{-1} silt, 235 g kg^{-1} clay, and 15 g kg^{-1} soil organic carbon (SOC), and 50 cm of a silty clay argillic (Bt) horizon with 95 g kg^{-1} sand, 501 g kg^{-1} silt, 404 g kg^{-1} clay (expansive and non −expansive clays), and 5 g kg^{-1} soil organic carbon (SOC). The water content to 40 cm depth at saturation, field capacity (fc), and permanent witling point (pwp) was 208, 149 and 70 mm respectively. Saturated hydraulic conductivity, measured with the double ring infiltrometer method (Bouwer, 1986) was 16.8 mm day^{-1} for the soil at the experimental site.

A crop sequence consisting of black oat (*Avena strigosa* L.; used as winter cover crop)—processing tomato (*Lycopersicon esculentum Mill.*; summer crop) was established during two subsequent years (2010–2012), followed by a sequence of black oat—sweet maize—black oat—onion (2012–2013) in a field of 50 m × 30 m. Black oat was sown in autumn and killed with glyphosate in winter (20 August 2010, 7 September 2011, 2 September 2012 and 16 May 2013). Tomato was transplanted on 22 October 2010 and 1 December 2011 at a density of 26,667 plants ha^{-1}, and harvested weekly from 5 January to 17 February in 2011, and from 8 February to 7 March in 2012. Sweet maize was sown on 5 November 2012 at a density of 50,000 plants ha^{-1}, and harvested on 15 January 2013. Onions were planted on 27 June 2013 at a density of 300,000 plants ha^{-1}, and harvested on 24 December 2013.

Four treatments in three replicates were arranged in a complete random design in plots consisting of two contiguous raised beds, 1.5 m apart. In three conventional tillage (CT) treatments, beds were re-built twice a year before each crop. The fourth treatment was based on reduced tillage (*RTmulch*) where beds were re-built only before sowing black oat. The conventional tillage systems included a control treatment with only artificial fertilizer (*CT*), a treatment with a mixture of chicken manure and rice husk (*CTchm*) commonly used in the region, and a treatment with both chicken manure and green manure (*CTgm*) consisting of black oat incorporated into the soil 20–70 days before planting the next crop. In the reduced tillage treatment chicken manure was incorporated during the re-building of the beds, and black oat was killed off with glyphosate 20–105 days before planting the next crop and left as mulch on the soil surface. Runoff plots, 1.5 m wide × 5 m long with 1% slope, were established for each treatment replicate. Runoff (RO) was measured from October 2010 to November 2013 at every rain event, except for a few too large events that overfilled the tanks. Soil cover by the mulch and the crop canopy was measured monthly and soil moisture content weekly from September 2010 till November 2013. Above ground dry weight of black oat crops was measured just before herbicide application. Leaf area index was measured at

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