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Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Córdoba, Argentina

H.P. Apezteguía [a,*], R.C. Izaurralde [b], R. Sereno [a]

[a] Grupo de Gestión Ambiental de Suelo y Agua, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Av. Valparaíso s/n, Ciudad Universitaria, CC 509, 5000, Córdoba, Argentina

[b] Joint Global Change Research Institute (Pacific Northwest National Laboratory and University of Maryland), 8400 Baltimore Avenue, Suite 201, College Park, MD 20740-2496, USA

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ABSTRACT

Soil carbon sequestration has been recognized as an effective, low-cost technology to mitigate climate change. Simulation models, alone or in combination with soil sampling and other techniques, can help monitor changes in soil carbon levels as affected by climate, soil, and management conditions. The objective of this paper is to test the ability of the Environmental Policy Integrated Climate (EPIC) model to simulate total organic carbon (TOC) dynamics in soils of the central region of the Province of Córdoba (Argentina) and evaluate, through modeling, the capacity of Córdoba's agricultural soils to act as sources or sinks of atmospheric CO_2. We tested EPIC against measurements made in a spatially distributed 40-year chronosequence of a temperate shrubland forest transitioning to agricultural use with conventional practices and in two long-term tillage (moldboard plow, chisel plow, and no till) and crop rotation (maize [*Zea mays* L.]–soybean [*Glycine max* L. Merr.]) field studies. Overall, the EPIC model demonstrated a good capability for simulating TOC dynamics. In the chronosequence, the TOC lost during 40 years of cultivation after deforestation was calculated at 38.4 Mg ha^{-1} while that simulated by the model was 44.1 Mg ha^{-1}. These values represented losses of 44% and 45% of the original TOC content, respectively. In the two long-term field experiments, the TOC simulated over the entire depth was close to the observed values and reflected the trends of the various treatments. For the most common conditions of croplands in Córdoba, crops grown in rotation with conservation tillage, particularly no till, would make soils act as sinks of atmospheric CO_2.

1. Introduction

Soil organic matter (SOM) plays a key role in ensuring agroecosystem productivity and the long-term conservation of soil resources. Adequate levels of soil organic matter are essential to maintain or improve chemical fertility, soil porosity, infiltration capacity, moisture retention, and resistance to water and wind erosion. On a global scale, SOM functions as a large repository of C (~1500 Pg C) and, thus, it is a key component of the modern C cycle. Changes in land use and management can have profound effects on both the quantity and dynamics of SOM, which in practice is measured as soil total organic carbon (TOC). These management impacts on TOC have been so large on a global scale that they contributed to increase the concentration of atmospheric CO_2 (Cole et al., 1996; Allmaras et al., 2000). A large-scale implementation of C sequestration practices offers the potential to mitigate the increase in atmospheric CO_2 and thus attenuate the effects of global warming (Rosell and Galantini, 1998; Izaurralde et al., 2001; McCarl and Schneider, 2001).

It is well established that converting natural forests or grasslands into agricultural fields generally leads to a decline in TOC (Ellert and Gregorich, 1996; Apezteguía, 2005) and that different tillage systems and crop rotations can increase or decrease it (Lal et al., 1998; Post and Kwon, 2000; Apezteguía and Sereno, 2002). The final impact of management on TOC cannot be easily predicted since many environmental variables (Trumbore et al., 1996; Huggins et al., 1998) and initial conditions (Nyborg et al., 1995) can influence the trajectory of TOC.

The study of the effects of land use and management practices on TOC dynamics can be greatly enhanced by the use of simulation models (McGill, 1996; Parton et al., 1995; Molina and Smith, 1998; Izaurralde et al., 2006). Simulation models could be useful for estimating the influence of management practices on TOC stocks and extrapolating these changes over large regions (Izaurralde et al., 2001). This latter point is important because field

* Corresponding author. Tel.: +54 351 4334105; fax: +54 351 4334103.
E-mail address: hapezte@agro.uncor.edu (H.P. Apezteguía).

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measurements of soil TOC changes are relatively expensive to make and time consuming.

The Environmental Policy Integrated Climate (EPIC) model was originally designed to quantify the effects of erosion on soil productivity (Williams et al., 1984; Williams, 1990). Numerous improvements and tests conducted since its first version released in 1984 have transformed it into a model capable of describing many agroecosystem processes including crop growth, water and nutrient balances, erosion, CO_2 fertilization effects, and pesticide fate (Williams, 1995). In one of these improvements, concepts and equations from the Century model (Parton and Rassmussen, 1994; Vitousek et al., 1994) were used to build a sub model describing C and N transformations and flows in as many as 15 soil layers (Izaurralde et al., 2006). The SOM sub model in EPIC includes an algorithm to calculate changes in soil bulk density (D_b) as affected by changes in SOM content.

While the goodness-of-fit of EPIC has been tested at several sites in North America (Causarano et al., 2007; He et al., 2006; Izaurralde et al., 2006, 2007), it has never been tested against field data in South America. Thus, the objectives of this paper are to (a) test the performance of the EPIC model in simulating plant productivity and TOC dynamics of Haplustolls of the central region of the Province of Córdoba (Argentina) and (b) evaluate, through modeling, the capacity of these soils to act as source or sink of atmospheric CO_2.

2. Materials and methods

2.1. Description of the EPIC model

The EPIC is a daily-time step, small watershed scale model that was originally developed to evaluate the effects of soil erosion and agricultural productivity (Williams et al., 1984; Williams, 1990, 1995). Over time, it developed into a comprehensive agroecosystem model (Williams, 1995) capable of simulating a wide array of agricultural management as well as non-agricultural land uses such as tree plantations, grasslands, and biomass crops (Gassman et al., 2005). Recent model improvements introduced in EPIC include new biogeochemical modules to simulate C and N dynamics (Izaurralde et al., 2006) and microbial denitrification (McGill et al., 2004).

In order to simulate crop growth, EPIC utilizes the concept of radiation-use efficiency whereby a fraction of the daily photosynthetically active radiation is intercepted by the plant canopy and converted into plant biomass. Daily gains in plant biomass are affected by vapor pressure deficits and atmospheric CO_2 concentration. Stress factors for water, temperature, nutrients (N, P, and K), aeration, and soil strength are calculated daily and the most severe is used to reduce potential plant growth and development. Weather information can be input into the model either from daily records or estimated from precipitation, air temperature, solar radiation, wind, and relative humidity parameters. A minimum set of soil properties (e.g., soil layer depth, texture, bulk density, and C concentration) are required to run EPIC.

Three major soil compartments of different turnover times are used in EPIC to distribute C and N: microbial biomass, slow humus and passive humus (Izaurralde et al., 2006). Plant residues C, root C, and manure C added to soil are split into two litter compartments (metabolic and structural) based on lignin and N content. Losses of C and N from the soil occur via leaching (soluble C, NO_3^-), gaseous losses (CO_2, $N_2O + N_2$), and erosion (particulate and soluble organic C, particulate N and NO_3^-).

Changes in D_b in EPIC are simulated as a function of tillage, precipitation, and SOM content (Williams, 1995; Izaurralde et al., 2006). Soil bulk density decreases as a proportion of the mixing efficiency of tillage operations performed to apply nutrients, control weeds, or incorporate crop residues (Williams, 1995). Soil bulk density of the plow layer also changes between rainfalls due to soil settling caused by water infiltration (Williams, 1995). Finally, all soil layers change their D_b annually due to changes in SOM content according to the Adams equation (Adams, 1973) as described in Izaurralde et al. (2006). Increases in SOM reduce D_b and vice versa. EPIC makes annual adjustments of soil layer depth in order to preserve the balance of soil mass and SOC.

2.2. Climate and soils

The central part of the province of Córdoba (31°S, 63°W) is located in the semiarid region of Argentina (Fig. 1). Spring and summer temperatures are high. Average temperature in January is 23.2 °C, with maximum values reaching sometimes >40 °C. Seventy percent of the 760 mm of annual precipitation occurs between October and March. The hydrologic balance determined by the Thornthwaite method (1955) indicates that there is a water deficit in every month of the year except during March (Casagrande and Vergara, 1996). The average values of weather variables at INTA Manfredi Experiment Station during 1983–1999 are presented in Table 1.

The soils of the region developed over æolian sediments called the ‘‘Pampean loess’’. The soils are classified as Typic Haplustolls and are generally silt loam in texture. The application of non-conserving agricultural practices, in combination with topographic and climatic factors, has led to the wide occurrence of water and wind erosion. However, the sites where these studies were conducted reveal little if any evidence of soil erosion. Selected characteristics of two Typic Haplustolls described in the chronosequence (series Piquillín) and in the long-term field trials (series Oncativo) at INTA Manfredi Experiment Station (Province of Córdoba, Argentina) are presented in Table 2.

2.3. Native vegetation

The natural vegetation is a temperate shrubland forest known as the ‘‘Espinal’’ ecoregion. This forest has three strata:

Table 1
Average values of weather variables at INTA Manfredi Experimental Station (Province of Córdoba, Argentina) during 1983–1999

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Maximum T (°C)	30.2	28.5	27.0	23.7	20.5	17.0	16.6	19.4	21.3	25.1	27.6	29.7	23.9
Minimum T (°C)	17.6	15.9	14.6	11.2	7.3	4.1	2.5	3.8	6.6	11.0	14.0	17.0	10.5
Precipitation (mm)	127	109	84	46	23	6	14	13	33	62	95	147	759
Wind speed (m s^{-1})	1.8	1.8	1.8	2.0	2.0	2.0	2.3	2.6	2.7	2.7	2.5	2.2	2.2
Radiation (MJ m^{-2})	22.6	20.0	16.4	12.2	9.4	7.9	8.9	11.8	14.4	17.6	20.6	22.4	15.3
Relative humidity (fract.)	0.72	0.74	0.76	0.74	0.74	0.75	0.72	0.68	0.66	0.67	0.70	0.71	0.72