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Predicting soil loss and sediment characteristics at the plot and field scales: Model description and first verifications

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ABSTRACT

Soil loss models are useful tools for making land management decisions to prevent soil and water quality problems. Several soil loss models have been developed, including the process-based Water Erosion Prediction Project (WEPP) model and the empirical Revised Universal Soil Loss Equation (RUSLE). Although process-based models provide accurate soil loss estimates, they are infrequently used for conservation planning because of their complexity and data need. On the other hand, models such as RUSLE cannot predict the soil loss nor the sediment composition associated with individual events, both of which are critical for designing accurate soil and water conservation practices. Therefore, the objective of this study was to develop a model for estimating sediment delivery on an event scale while predicting its clay, silt and sand fractions. For this purpose, the WEPP model was implemented using measured soil and climate data from Central Chile to generate a soil loss database for many hillslope configurations and management practices. More than 200,000 erosion events were generated using data from 83 sites. Using multiple regression analysis, the main variables controlling soil loss were identified, which included rainfall erosivity, soil erodibility, hillslope geometry, antecedent soil moisture and total precipitation. These variables were incorporated into a soil loss model, which was calibrated using data from 32 sites (R^2 = 0.81–0.83) and validated for the remaining 51 sites (R^2 = 0.66–0.89). The model provided accurate estimates for the clay and silt fractions (R^2 = 0.86 and 0.78, respectively) but showed difficulties for predicting the sand fraction (R^2 = 0.31). Contour plowing and vegetative filter strip routines were also incorporated into the soil loss model, providing reliable soil loss (R^2 = 0.51–0.78), clay (R^2 = 0.54–0.75), and silt (R^2 = 0.57–0.68) estimates. The developed model is remarkably easy to use and, due to its simplicity, allows incorporating other soil conservation routines, providing a flexible tool for soil conservation planning. This study provides a detailed description and methodology for building such a model and discusses its advantages and limitations.

1. Introduction

Soil erosion is a major environmental problem worldwide because of its effects on water quality, soil productivity and the ecosystems (Kinnell, 2007; Zhang et al., 1996). Soil loss is often triggered and accelerated by poor or non-existing soil conservation practices, which promote the transport of sediments and potentially hazardous pollutants via runoff to rivers and streams (Carpenter et al., 1998; Lin et al., 2009; Bagarello et al., 2010;). Thus, effective soil conservation practices that minimize sediment transport must be designed and implemented to overcome or prevent soil and water quality issues (Merritt et al., 2003).

Erosion and sediment delivery prediction models are useful tools for making land management decisions (Stroosnijder, 2005). Compared to actual soil loss measurements, soil loss models require significantly less time and resources to implement, making them an attractive alternative for designing soil conservation practices (Amore et al., 2004). Moreover, these models can be used to evaluate the soil loss impacts on the environment, providing tools for assessing soil and water degradation under different scenarios (Nearing et al., 2004; Nearing et al., 2005). However, the applicability of soil loss models is usually limited to the landscapes or regions in which they were validated, especially in the case of empirical soil loss relationships (Renard et al., 1991).

Several soil loss models with different complexities have been developed, including empirical and process-based models (Eisazadeh et al., 2012). Among the empirical models, the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1991) is the most widely used soil loss estimation tool worldwide (Kinnell, 2010). The use of RUSLE is appealing because it provides reasonable, long-term, annual

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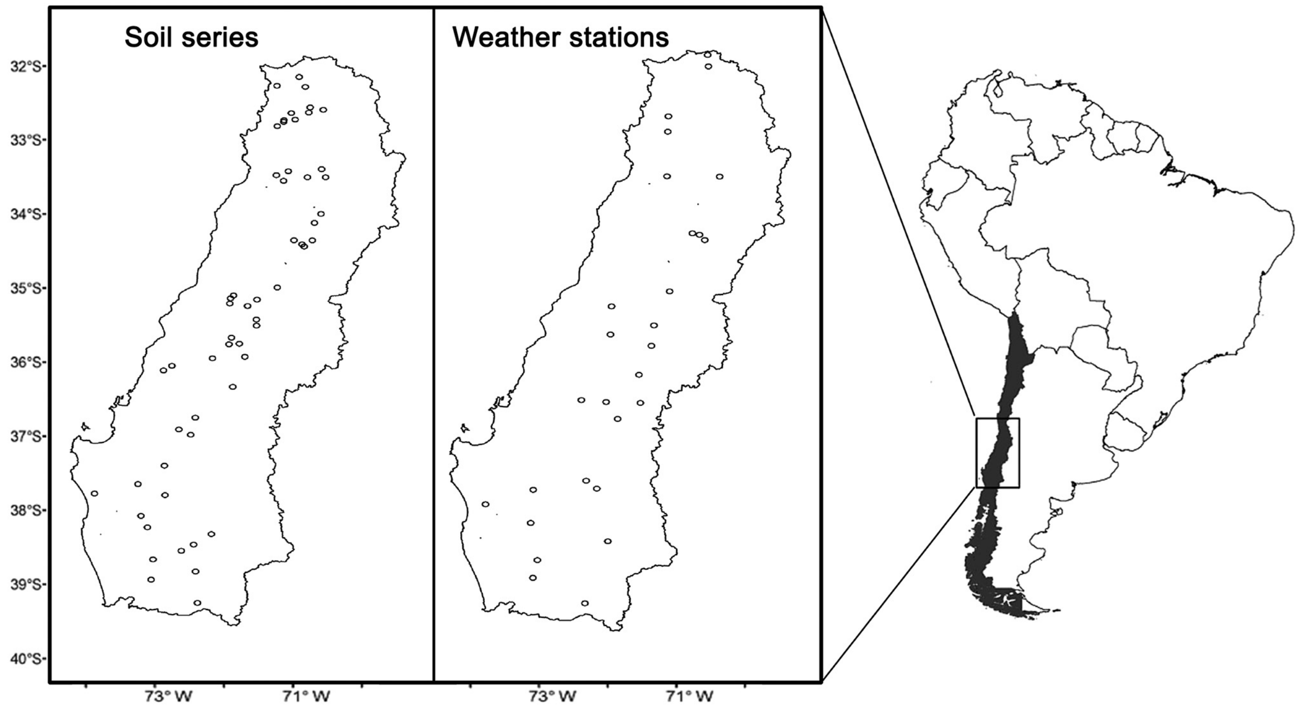

Fig. 1. Spatial distribution of the soil and climate data.

soil loss estimates with little environmental information (Spaeth et al., 2003; Amore et al., 2004; Kinnell, 2010). On the other hand, process-based soil loss models such as the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989) use validated process-based equations that simulate soil loss (Tiwari et al., 2000). WEPP is one of the most widely used and validated process-based models (Flanagan et al., 2012), as it includes erosion, plant growth, residue, water use, hydraulic and soil processes (Laflen et al., 1991). Thus, WEPP is a site-independent model that can be used with confidence when process-based equations are applicable (Pieri et al., 2007). Moreover, unlike RUSLE, WEPP can be used for predicting event-based soil loss estimates (Yu, 2002), which is necessary for accurately designing soil conservation practices intended to increase soil and water quality (Nearing et al., 1999). However, because of its complexity and extensive input variable requirements, some of which are difficult or expensive to measure, it is not a suitable alternative when resources are scarce (Mankin, 2000).

RUSLE computes the average annual erosion expected on field slopes as the product of five factors. The equation is thus:

$$A = K \times R \times LS \times C \times P \quad (1)$$

where A is the soil loss of the event (t ha^{-1}), K is the soil erodibility (t h MJ^{-1} mm^{-1}), R is the rainfall erosivity of the event (MJ mm ha^{-1} h^{-1}) and LS, C and P are dimensionless factors that account for the effects of hillslope geometry, vegetation and management practices, respectively (Renard et al., 1991; Kinnell, 2010). This model has proven to be reliable for predicting long-term annual soil loss estimates (Kinnell, 2010), but not for estimating the soil loss associated with individual events, as soil properties change between rainfall events (Schmalz et al., 2013; Mirus and Loague, 2013; Gitika and Ranjan, 2014).

Another advantage of WEPP over RUSLE is that it accounts for both deposition and detachment processes (Polyakov and Nearing, 2003), whereas RUSLE only predicts soil detachment (Renard et al., 1991). For uniform hillslopes with small slope gradients, this is not a major issue, as deposition is typically small compared to detachment (Proffitt et al., 1991). However, for complex hillslopes, where deposition is a significant process (Bonilla et al., 2007, 2008), this disadvantage is of major relevance, as deposition is a critical variable for determining sediment delivery, sediment composition and hence, water quality (Pimentel et al., 1995; González et al., 2016). In addition, RUSLE does not account for sediment enrichment and aggregate breakdown and transport, both of which are predicted with WEPP (Foster et al., 1995). This is crucial when modeling the transport of pollutants, as pollutant adsorption relates to the specific surface area of the sediment (Horowitz and Elrick, 1987).

Estimating sediment delivery and sediment composition is necessary for designing effective soil conservation practices; however, no widely used empirical models, such as the RUSLE, exist for such purpose. Thus, the objective of this study was to provide a first attempt in developing a model based on the RUSLE, but that addresses three of its critical shortcomings: (i) it is designed to predict daily soil loss estimates; (ii) it accounts for soil deposition; and (iii) it breaks down the sediment into sand, silt, and clay fractions. For this purpose, the main variables controlling soil loss at the event scale were identified from a WEPP-simulated soil loss data that used measured soil and climate data from Central Chile. Moreover, the model incorporates the effect of two management practices on sediment delivery, which can be used for effective soil conservation planning. Simple models such as this provide an alternative for designing soil conservation practices when technical and/or economic resources are scarce, and contribute to a more sustainable land use.

2. Materials and methods

2.1. Study area, soil and climate data

This study focuses on Central Chile between latitudes 32°04′ S and 39°47′ S (Fig. 1). Soil and climate data for 83 sites were collected from the databases of the Information Center of Natural Resources (CIREN) and the General Directorate of Water Resources (DGA). Fifty-six soil series were used according to their areas of influence as representatives of the soils found in Central Chile (Fig. 1). Each soil series was coupled with one or more of the 28 weather stations shown in Fig. 1 based on the proximity between the soil and the stations. Tables 1 and 2 show the main soil and rainfall characteristics for each site. The hourly rainfall data ranged from 3 to 28 years, with 418 years of data and more than

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