Estimating erosion rates using ^{137}Cs measurements and WATEM/SEDEM in a Mediterranean cultivated field

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Abstract

The loss of fertile topsoil is one of the principal soil degradation problems in agricultural landscapes worldwide. Mediterranean agroecosystems are particularly threatened to soil degradation because of the climate, a higher sensitivity to soil erosion and the intensification of human activities and agricultural practices during centuries. The severity of this problem and the expected increasing risk of soil erosion in Mediterranean cultivated landscapes as a consequence of climate change have generated a demand for estimations of soil redistribution rates and soil loss monitoring.

In this study, a representative cultivated field of mountain Mediterranean agroecosystems was selected to estimate ^{137}Cs derived soil redistribution rates using a ^{137}Cs mass balance model. Besides numeric simulation was performed using the WATEM/SEDEM model to estimate spatially-distributed soil redistribution rates. A detailed topographic survey was done to obtain a high-resolution digital elevation model (2.5 m) of the study field and ^{137}Cs derived soil redistribution rates were used to calibrate the model. In the study field, soil erosion predominated over soil deposition. Mean values of ^{137}Cs derived soil erosion and deposition rates were $19.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$

and $12.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively. Water erosion was the predominant process of soil redistribution whereas tillage erosion was not significant. The rates obtained with WATEM/SEDEM model were lower; mean erosion was $3.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and mean deposition rates that occurred in 35% of the grid cells was of $5.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The use of spatially-distributed models is required to better quantify soil redistribution processes and to evaluate superficial soil distribution. However, point-estimates of soil redistribution such as those provided by ^{137}Cs are required to allow calibration of the models. The knowledge about the spatial distribution of erosion processes is a useful tool for the application of effective soil erosion control and prevention strategies on water and tillage erosion on agroecosystems.

Keywords: ^{137}Cs fallout; ^{137}Cs conversion models; MBM III; WATEM/SEDEM; soil redistribution processes; cultivated soils; Mediterranean agroecosystems.

1. Introduction

The impact of soil erosion on Mediterranean agroecosystems has received increasing attention due to the vulnerability of Mediterranean soils to erosion, which is the main cause of land degradation. The climatic conditions in Mediterranean areas, which are characterized by scarce and heavy rainfall events (Alpert et al., 2002) and drought summer followed by autumn rainfalls, together with soil characteristics such as poor development, thin soil profiles and low soil organic matter intensify soil erosion in these agricultural landscapes. Furthermore, the long agricultural history in the Mediterranean region including deforestation, overgrazing and extensive agriculture leads to consider tillage erosion. The concerns on soil erosion have led to explore methods to quantify and predict soil redistribution rates. Soil erosion surveys using radiotracers and modelling approaches offer a considerable potential to study soil erosion processes and

quantify soil redistribution rates (Porto et al., 2003; Gaspar et al., 2013). The radioactive fallout Caesium-137 (^{137}Cs) has been successfully applied in different environments (Ritchie et al., 2007; Ritchie and McHenry, 1990). In Mediterranean agroecosystems ^{137}Cs fallout has been established as an effective and reliable tool to estimate soil redistribution (Navas et al., 2005; Sadiki et al., 2007; Porto and Walling, 2012; Benmansour et al., 2013; Mabit et al., 2013). The advantage of this technique is the potential to provide medium term spatially distributed soil redistribution rates by both water and tillage erosion that represent mean annual values for the past 50 years. One of the key issues of using ^{137}Cs inventories is to establish relationships between ^{137}Cs loss and gain or percentage residuals for each sampling point and the rates of soil redistribution. Navas and Walling (1992) highlighted that the estimation of soil redistribution rates in Mediterranean soils was affected by the high stone content because similar ^{137}Cs profiles exhibited very diverse total inventories. This fact was taken into account in the models of ^{137}Cs profile activity and mass balance by Soto and Navas (2004, 2008) that estimate soil erosion and deposition rates for uncultivated and cultivated soils, respectively. Other well-known mass balance models used to quantify soil redistribution rates by water and tillage is the Mass Balance Model III (MBM III) by Walling and He (1997). These models simulate the ^{137}Cs transference in soil profiles during the time in which soil is exposed to erosion processes and relate soil loss and ^{137}Cs loss to calculate soil redistribution rates at each sampling point.

Over the last years there has been a remarkable progress in the development of techniques for soil erosion assessment complementary to the existing methods such as distributed, process based models to represent soil redistribution processes. WATEM/SEDEM is a spatially distributed soil erosion and sediment delivery model that has been applied in different landscapes. Verstraeten et al. (2002) applied

WATEM/SEDEM to three agricultural catchments in the Loess area of central Belgium to evaluate the effectiveness of a variety of soil conservation and sediment control measures. In Alpine mountain catchments Van Rompaey et al., (2005) indicated that the model concept of WATEM/SEDEM was not suitable for an accurate assessment of the sediment delivery processes. However, Verstraeten et al. (2007) found a good performance of WATEM/SEDEM in the Southeastern Uplands of Australia suggesting that the model accounted well for gully erosion. Krasa et al. (2010) reported that WATEM/SEDEM was useful for assessing both soil erosion and its offsite impacts in several mountain catchments of the Czech Republic. Alatorre et al., (2012) applied WATEM/SEDEM to simulate soil redistribution in an experimental catchment in the Central Spanish Pyrenees under current, past, and hypothetical future land use/land cover conditions. Model calibration was performed based on ^{137}Cs derived soil redistribution rates and good agreement was found between modeled and measured annual sediment yield values at the catchment outlet.

Model validation and calibration are the most important steps in model performance to detect failures in the model implementation or in the parameterization process. Results of the physically based, spatially distributed erosion models need to be validated, which requires detailed field information that can be compared with model outputs. Generally, the spatial variation of erosion and deposition within catchments has been validated by runoff data and sediment loads collected at catchment outlets. Soil redistribution rates derived from ^{137}Cs have been used for validating the results of spatially distributed soil erosion models including WATEM/SEDEM (Alatorre et al., 2011). However, there is a lack of reliable spatial validation of distributed models due to the absence of spatially distributed soil erosion data. Model calibration of WATEM/SEDEM is usually done with sediment yield data (Zhao et al., 2015). Studies at detailed scale using spatially

distributed data of ^{137}Cs estimates are scarce (Di Stefano et al., 2000a, 2000b; 2005). Alatorre et al. (2012) pointed out that in order to identifying an optimal combination of the transport capacity parameters through a process of inverse-modelling (calibration) using WATEM/SEDEM, a set of reliable point-estimates of soil redistribution processes, as those provided by ^{137}Cs , was required.

The combination of the spatially distributed models with ^{137}Cs derived rates can be of value to identify suitable locations for implementing soil conservation strategies in Mediterranean agroecosystems. To this purpose a representative Mediterranean cultivated field located at the lower end of the slope was selected to conduct this study. We aim to: i) assess soil redistribution rates estimated from ^{137}Cs inventories in the study field using a model developed for cultivated soils by Soto and Navas (2008) for the period comprised between 1959 and 2010, ii) assess soil redistribution rates by tillage derived from ^{137}Cs measurements by applying on two selected transects a mass balance model by Walling and He (1997) (MBM III), iii) apply the WATEM/SEDEM model at the field scale and calibrate it with ^{137}Cs derived soil redistribution rates for finding an optimal set of input parameters, and iv) examine the effect of soil redistribution processes on the spatial variability of soil properties in the study field. Medium and long-term soil erosion models could be useful tools to simulate and analyse soil redistribution processes in Mediterranean mountain agroecosystems.

2. Materials and methods

2.1 Study area

The study area is a rain-fed cultivated field (1.6 ha) located in the central part of the Ebro Basin (northeast Spain) (Fig. 1a). The field was selected because changes in the topography, manmade structures and past agricultural practices are well documented

(Quijano et al., 2013, 2016). Conventional tillage practices have been carried out in the study field from 1950 to 1995 using a mouldboard with tractor at a ploughing depth between 25 and 30 cm. For the last 15 years (1995–2010) minimum tillage has been implemented using chisel with tractor at a ploughing depth between 15 and 20 cm and during the soil survey and sampling the field has remained fallow. Crop rotation has not been done in the field and the main crop is winter barley (*Hordeum vulgare*) and occasionally wheat (*Triticum aestivum* L.). The average altitude of the study area is 630 ± 3.2 m a.s.l ranging from 622 to 636 m and the mean slope is 7.4% ranging from 1.1 to 19%. Soils were classified as Calcisols, which are developed on Quaternary deposits that are mainly formed by alluvial deposits (Quijano et al., 2014). The climate is continental Mediterranean, characterized by cold winters and hot and dry summers. The rainfall events mainly occur in spring (April and May) and autumn (September and October). The mean annual rainfall is around 500 mm and the mean annual temperature is 13.4 °C. The study field is delimited by manmade infrastructures in the north and west parts whereas an ephemeral stream flows at the eastern limit of the field (Fig. 1b). The vegetation bordering the field is a bottomland forest typical of riparian systems in Mediterranean ecosystems with *Quercus coccifera*, *Quercus ilex* and *Populus alba*.

The drainage of the study field is not homogeneous; the observed flow lines show two main different directions of northeast and southeast components. Furthermore, according to field observations and topographical surveys four hydrological units were identified and delineated within the study field. The limits of the hydrologic units were coincident with convex zones where there was divergent flow (Fig. 1c). The hydrological units U1 and U2 were located upslope with a mean elevation of 632.2 m and 632.1 m respectively. Both units had higher mean slope values (8.5% and 9.2%, respectively), compared to U3 and U4 units located downslope. The U3 and U4 units

had lower mean elevations, 631 m and 627 m, respectively, and lower mean slope values of 7.2% and 5.7%, respectively. The topography at the northern unit U2 was characterized by a contrasting morphology of the land surface related to the development of a gully system, however the southern part was relatively flat. The three northern hydrological units (U1, U2 and U3) drained into the main ephemeral stream. These three units had a flow with a northeast component whereas the south hydrological unit (U4) had flow lines with south component draining into a single outlet point (Fig. 1c). In the south limit of the study field, there is a 20-30 cm deep furrow bordering the edge of the field caused by continuous tillage. These practices along the years have caused compaction of the soil surface leading to a general decrease of the current level of soil together with a progressive soil accumulation along the tillage furrow (Quijano et al., 2016).

Fig. 1 (a) Location of the study field in the central part of the Ebro basin (NE Spain). (b) 3D view of the study area including the reference site (RS) and the study field (SF). (c) Sampling points on a 10x10 m grid (n=156) and limits between hydrological units with flow lines. (d) Sampling points of the elevation dataset (n=666). (e) Digital elevation model of the study field with the four hydrological units.

2.2 Digital elevation model

A digital elevation model (DEM) of the study field was generated to characterize the land surface. The elevation of a total of 617 points was measured on a 5x5 m regular grid using a Geodolite 506 total station with an angular precision of 6'' and a distance accuracy of $\pm 5\text{mm} + 5\text{ppm}$ to capture the topography in detail at field scale and generate a DEM with high spatial resolution. Moreover, elevation was measured using a Geodolite 506 total station around the limits of the study field to avoid interpolation edge effects on 49 points (Fig. 1d). Therefore, a total of 666 elevation data points were used. The *Topo to Raster* tool in ArcGIS 10.2.1 was used to generate the DEM, because it is an interpolation method specifically designed for the creation of hydrologically correct DEMs with a connected drainage structure. This tool is based on the ANUDEM methodology from the Australian National University. The latest version of the ANUDEM program developed by Hutchinson (1988) is included in the Spatial Analyst toolbox (Liu et al, 2009) within ArcGIS 10.2.1.

The effect of cell size on the representation of the land surface and modelling was examined systematically because the DEM grid cell size affected significantly a range of hydrological and topographic parameters (Florinsky and Kuryakova, 2000; Lacroix et al., 2002). The choice of the more accurate grid cell size for spot interpolated digital elevation model was done by producing DEMs at resolutions of 5, 2.5, 2.0, 1.5 and 1 m using the same input data and interpolation algorithm. The derived slope gradient and flow accumulation maps derived from the DEMs were visually compared to determine the optimum grid cell size. It was found that there was no improvement in the information of the interpolated DEMs when increasing the resolution beyond 2.5 m (half the grid size of the original topographic data), because artifacts and anomalies in slope gradient and flow accumulation maps appeared with finer DEM resolutions. The

DEM with a 2.5 m resolution created with *Topo to Raster* (Fig. 1e) was therefore used in the remaining of the study.

2.3 Sampling sites and soil analysis

A total of 156 soil samples were collected on a 10 x 10 m grid (Fig. 1c) using a 7 cm diameter automatic core driller. The sampling depth up to 30 cm included the depth of ploughing. If according to field observations the sampling point was a depositional site, the sampling depth was extended up to 50 cm to ensure the total depth of the ^{137}Cs profile was collected.

Two downslope transects located in the southern hydrological unit U4 (Fig. 1c) were established to estimate soil redistribution by tillage applying MBM III (Walling and He, 1997). The two transects were selected because the observed flow lines of runoff along the slope paralleled the sampling points. From the border of the field a total of 6 sampling points on each transect were selected from the 10 x 10 m grid ensuring that soil redistribution by tillage from upslope to downslope could be examined.

Two reference sites were selected to establish the reference inventory for the study field. One is adjacent to the study field (Fig.1b) and the other is separated 2 km. Both reference sites are on flat undisturbed areas under typical Mediterranean forest vegetation with *Quercus coccifera* and *Q. ilex* and are not affected by erosion or deposition processes. A total of 21 soil profiles were sampled up to 40 cm using a 7 cm diameter automatic core driller to establish the reference inventory of ^{137}Cs for the study area. Of these 5 soil profiles were sectioned at 5 cm increment in order to examine the vertical distribution of ^{137}Cs .

Soil samples were packed, weighed, labelled and stored prior to laboratory analysis. Samples were passed through a 2-mm sieve to separate and weight the coarse (>2 mm)

and fine (<2 mm) fractions. The fine fraction was used for ^{137}Cs and soil analyses. The grain size of different fractions was analysed by Coulter laser granulometer after elimination of organic matter with 10% H_2O_2 at 80 °C, stirred 24 h to facilitate particle dispersion and subjected to ultrasound during the analyses. The soil organic matter (SOM) content was determined by dichromate oxidation and subsequent titration with ferrous ammonium sulphate using a Mettler Toledo titrimeter and an electrode (Guitian and Carballas, 1976).

2.4 ^{137}Cs measurements and modelling

The ^{137}Cs massic activities (Bq kg^{-1}) were measured using high resolution, low background, low energy, hyperpure germanium, coaxial gamma-ray detector coupled to an amplifier and multichannel analyser (Canberra industries, Inc, USA). The detector has an efficiency of 50% and a 1.9 keV resolution (shielded to reduce background). The detector was calibrated using standard soil samples with the same geometry as the measured samples. Soil subsamples of 50 g of the fine fraction were transferred into plastic containers and sealed for gamma-ray analysis with counting times over 30000 s and an analytical precision of the measurements of <5% (95% level of confidence) (Navas et al., 2005). The ^{137}Cs massic activity (Bq kg^{-1}) was converted into activity per unit area or inventory (Bq m^{-2}) using the mass of the fine fraction and the cross section of the core sampler.

Estimates of soil redistribution rates are based on a comparison of the ^{137}Cs inventory for an individual sampling point and the ^{137}Cs reference inventory. Lower ^{137}Cs inventories than the reference inventory indicating loss of radionuclide thus soil loss. Similarly, the values of ^{137}Cs inventories higher than the reference ones indicating soil deposition (Walling and He, 1999).

In this study, we selected the model proposed by Soto and Navas (2008) for cultivated soils specially developed for Mediterranean stony soils and tested in a nearby mountain area with similar soil and rainfall characteristics (Navas et al., 2012, 2014). An improved version of this mass balance model in which the numerical solution has been ameliorated by using a second order equation is applied to the grid sampling points to calculate soil redistribution rates derived from ^{137}Cs measurements. The model assumes a temporary evolution of the ^{137}Cs concentration within the soil. It was considered a total inventory of ^{137}Cs equal to zero before 1954, increasing the ^{137}Cs inventory from this year in a quantity equal to the corresponding atmospheric deposit. Although the tests of nuclear weapons commenced in the early 1950s, the detectable quantities of ^{137}Cs in soils began in 1954 (Ritchie and McHenry., 1973). Moreover, the model considers just one compartment, which extends from the soil surface to the cultivation depth “ H ” (cm). Soil within this compartment is composed by two soil fractions, the coarse (>2 mm) and fine fractions (<2 mm). Both are characterized by its mass, volume and density. Since the ^{137}Cs radionuclide is fixed in the fine fraction (Quine et al., 1994), the model takes into account a volume factor, which is the volume for fixing ^{137}Cs . The effective volume (V_f , dimensionless) is the relation between the volume occupied by the fine fraction and the total volume of the compartment. The effective volume is important since the existing models do not take into account soil factors as the stoniness (Soto and Navas, 2004) which may have a relevant role in limiting soil loss in Mediterranean environments (Cerdan et al., 2010).

Tillage mixes soil thoroughly thus ^{137}Cs concentration is uniformly distributed within the plough layer (25–30 cm in the study area) (Gaspar and Navas, 2013). Thus, if $C(t)$ is the total inventory in a given t moment (Bq m^{-2}), $C(t - 1)$ is the total inventory in the

previous moment (Bq m^{-2}), and $D(t)$ is the atmospheric ^{137}Cs deposition in that interval of time (Bq m^{-2}). Then the total inventory in a given t is:

$$C(t) = C(t-1) + D(t) \quad (1)$$

The model assigns the thickness of the soil layer that is lost per unit of time “ E ” (cm per month). Thus, the total inventory in a given moment decreases due to the loss by soil erosion as follows:

$$C(t) = C(t-1)(1 - (E / H * V_f)) \quad (2)$$

Similarly, the increases of ^{137}Cs inventory in the compartment for depositional sites, “ F ” is the material deposited per unit of time (cm per month). The model assumes that the deposited material comes from a short distance and has similar ^{137}Cs concentration than that of the sampling point.

$$C(t) = C(t-1)(1 + (F / H * V_f)) \quad (3)$$

In addition to the ^{137}Cs downward migration and the ^{137}Cs deposition, the model also takes into account the decrease of ^{137}Cs activity as a result of radioactive decay.

The mass balance model III (MBM III) developed by Walling and He (1997) was used to estimate soil redistribution rates along the two selected transects located in the southern hydrological unit (Fig. 1c). The MBM III model simulations have been carried out using a PC-compatible software package developed by Walling and He (2001).

The MBM III incorporates the effect of soil redistribution introduced by tillage and the remaining component of soil redistribution that corresponds to water erosion. The effect of tillage on soil redistribution can be represented by a downslope sediment flux (F_Q) (Govers et al., 1996) and the downslope sediment flux ($\text{kg m}^{-1} \text{yr}^{-1}$) from a unit contour length is:

$$F_Q = \phi \sin \beta \quad (4)$$

Where β ($^{\circ}$) is the slope angle and ϕ ($\text{kg m}^{-1} \text{yr}^{-1}$), is a site specific constant.

The flow line down slope is divided into several sections and each section can be approximated as a straight line, the net soil redistribution induced by tillage (R_t) expressed in $\text{kg m}^{-2} \text{yr}^{-1}$ can be expressed as:

$$R_t = (F_{Q,out} - F_{Q,in}) / L_i = \phi(\sin \beta_i - \sin \beta_{i-1}) / L_i = R_{t,out} - R_{t,in} \quad (5)$$

Where L_i (m) is the slope length of the i th segment and $R_{t,out}$ and $R_{t,in}$ are defined as follow:

$$R_{t,out} = \phi \sin \beta_i / L_i \quad (6)$$

$$R_{t,in} = \phi \sin \beta_{i-1} / L_i \quad (7)$$

The net erosion rate (R , $\text{kg m}^{-2} \text{yr}^{-1}$) is:

$$R = R_{t,out} - R_{t,in} + R_w \quad (8)$$

Where R_t is the soil redistribution rare by water expressed in $\text{kg m}^{-2} \text{yr}^{-1}$.

2.5 WATEM/SEDEM

The WATEM/SEDEM model is an empirical, spatially distributed model (Van Oost et al., 2000a; Van Rompaey et al., 2001; Verstraeten et al., 2002) of soil erosion, transport and deposition, which is used to estimate long-term mean annual soil erosion rates. WATEM/SEDEM is a combined version of two previous soil erosion models, WATEM (Water and Tillage Erosion Model; Van Oost et al., 2000b) and SEDEM (Sediment Delivery model; Van Rompaey et al., 2001). It can be applied at different scales from small areas to large regional scales under a wide range of environmental conditions (Verstraeten and Prosser, 2008). The main aim of the model is to simulate transport and deposition within a drainage basin and to predict sediment delivery to river channels. The model consists of two components, one simulating water erosion and another one

simulating tillage erosion. The water erosion component is based on the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1991, 1997a). The RUSLE model calculates potential average soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) as the product of a rainfall erosivity factor (R , $\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$), a soil erodibility factor (K , $\text{Mg h MJ}^{-1} \text{ mm}^{-1}$), a slope length factor (L , dimensionless), a slope steepness factor (S , dimensionless), a cover and management factor (C , dimensionless) and a conservation support practice factor (P , dimensionless). The sediment generated is then routed downslope according to the topography until a stream cell is reached. Sediment transport by overland runoff is modeled according to a transport capacity equation (TC , $\text{T ha}^{-1} \text{ yr}^{-1}$):

$$TC = k_{tc} RK (LS - 4.1S_g^{0.8}) \quad (9)$$

Where k_{tc} comprises the transport capacity coefficient, R , K , S and L are RUSLE factors and S_g is the slope gradient. For a specific raster cell, sediment deposition occurs when the transport capacity of the cell is smaller than the amount of sediment that reaches the cell; otherwise, the sediment generated is redistributed during transportation (Verstraeten et al., 2007).

Tillage erosion refers to the downslope transport of soil as a result of ploughing (Govers et al., 1999) and is modelled as a diffusion-like process. Tillage erosion is controlled by the change of the slope gradient, so erosion takes place on convex areas while soil accumulation occurs mainly on concave zones. A tillage transport coefficient (k_{till}) controls the intensity of tillage erosion. The net soil flux caused by tillage on a hillslope of infinitesimal length and unit width is proportional to the local slope gradient (Govers et al., 1994):

$$Q_{s,t=k_{till}S} = -k_{till} dh/dx \quad (10)$$

Where $Q_{s,t}$ represents the net downslope flux due to tillage translocation ($\text{kg m}^{-1} \text{yr}^{-1}$), k_{till} is the tillage transport coefficient ($\text{kg m}^{-1} \text{yr}^{-1}$), S is the local slope gradient (m m^{-1}), h is the height at a given point of the hillslope (m) and x is the horizontal distance (m).

The transport capacity parameters k_{till} and k_{tc} depend on the land cover and are site-specific. Therefore, they need to be calibrated based on local data for each implementation of the model.

2.5.1 Model input

The main input data required to run WATEM/SEDEM are the DEM of the study field and the parameters of the RUSLE model. These were supplied in the form of IDRISI GIS (Clark Labs Inc.) raster layers. The length slope factor (LS -factor) was obtained from the DEM using the RUSLE algorithm proposed by McCool et al. (1989). The rainfall erosivity factor (R -factor) is the average annual summation of individual rainstorm erosive index (EI) which was calculated by multiplying the kinetic energy per unit area by the maximum rainfall intensity during a period of 30-minutes for each rainstorm. Rainstorms less than 12.7 mm are not included in the erosivity computations unless at least 6.35 mm of rain fell in 15 min (Renard et al. 1997b). The value of R -factor was the average of the R -factors calculated annually for the period 2005–2014, using a database of rainfall series at a time resolution of 15 min from the SAIH system of the Hydrographic Confederation of the Ebro River. Data were not available before 2005. A constant value of R -factor was considered for the study field because the WATEM/SEDEM model assumes that the spatial variability of the R -factor is uniform for small areas. The R -factor was $881 \text{ MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ that agrees with an estimated value for the area of $730\text{--}900 \text{ MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ obtained from the high resolution (1 km grid cell) rainfall erosivity map for Europe (Panagos et al., 2015). In addition,

annual rainfall for the period 2005–2014 was recorded after each rainfall event from a pluviometer located 1.4 km far from the study field. This dataset was compared with rainfall data from the Vigas station. To determine whether the period 2005–2014 was representative of normal, wet or dry conditions a methodology as the developed by Serrano-Notivoli et al. (2014) was applied to reconstruct a long term precipitation dataset for the 1940–2012 period. Reconstruction was done through regression relations from daily precipitation dataset of nearest weather stations to the rain gauge, which is located in Castiliscar, 7 km far from the study field. The *K*-factor was calculated using the equation by Wischmeier and Smith (1978), which takes into account the contents of clay, silt and SOM. For the study field the mean value of *K*-factor was $0.035 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$. The *C*-factor for arable land was estimated from the literature (NS Department of Agriculture and Fisheries, 2001). As arable land is a mixture both in space and time of two crops, a long-term average value was computed by taking the average of the *C*-factor values for winter wheat and barley. The *C*-factor was set to 0.2. The support practice factor (*P*-factor) was considered 1.0 (Wall et al., 2002).

2.5.2 Model calibration

A single execution of the WATEM/SEDEM model has been applied to the study field assuming uniform soil and land use and management conditions for the study period. The WATEM/SEDEM model implementation in agricultural landscapes requires the calibration of the transport capacity coefficients (*k_{tc}*) and the tillage transport coefficient (*k_{till}*). The transport capacity coefficients are dependent on land use the lowest *k_{tc}* (*k_{tc} min*) is for well vegetated surfaces such as forest, grassland and pasture, while the high *k_{tc}* (*k_{tc} max*) is for poorly vegetated surfaces. The transport capacity is the maximum sediment mass that can be transported by the overland flow. If the

sediment production is higher than the transport capacity, sediment will be deposited. Thus, the higher the transport capacity coefficient, the more sediment can be transported downslope. The original model was calibrated using observed data on sediment yield from 21 catchments in Belgium (Verstraeten et al., 2001). The optimal WATEM/SEDEM parameters depend on the quality and the resolution of the input data (Van Rompaey et al., 2001). Therefore the combined erosion–transport model can only be calibrated for a specific combination of grid size and routing method. As the study field consisted on a cultivated field, only k_{tc} max and k_{till} parameters were calibrated. The calibration procedure consisted on an inverse-modelling approach. A systematic sampling of the pair of parameters (k_{tc} max and k_{till}) at discrete steps within a pre-defined range of values was undertaken, and simulations were run with each pair of values, as described in Alatorre et al. (2010). For each combination of parameters soil erosion and deposition rates were computed for each 2.5x2.5 m grid cell, allowing comparison of the values predicted by WATEM/SEDEM with point soil redistribution rates derived from ^{137}Cs .

The Nash–Sutcliffe model efficiency (NS, Nash and Sutcliffe, 1970) was used for assessing the goodness of fit of the model results, according to the following equation:

$$NS = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O_{mean})^2} \quad (11)$$

Where O_i is the observed value, P_i the predicted value, O_{mean} the mean observed value and n is the number of observations. NS can range from $-\infty$ to 1, and represents the proportion of the initial variance accounted for the model. The closer the value of NS is to 1, the more efficient is the model, whereas $NS \leq 0$ indicates that the observed mean is a better predictor than NS model efficiency.

Plate spline interpolation was used for creating a smooth, fine-resolution representation of the error surface, allowing finding the optimum pair of parameters as those that yielded the highest possible NS with a great precision. This method was the same used by Alatorre et al. (2012), who demonstrated that the error surface of WATEM/SEDEM transport parameters was smooth and allowed such an interpolation with very little error, provided that the sampling of the parameters was dense enough.

Two calibration procedures were carried out one considering the entire study field and the other considering each hydrological unit individually.

2.6 Statistical analysis

Data were analysed using SPSS 19.0 (Chicago, IL, USA). The relationships between soil redistribution rates and physiographic factors and soil properties were assessed using the Pearson's correlation coefficients and linear regression analyses. Furthermore, one-way analysis of variance (ANOVA) was performed to assess the statistical significance of the effects of soil redistribution (eroded and depositional points) on soil properties.

The spatial distribution of physiographic factors and soil properties were derived by ordinary kriging, using a spherical semivariogram model with trend. All the output maps and interpolations were performed using ESRI ArcGIS 10.2.1 software.

Confusion matrices were computed by comparing the results from ^{137}Cs derived soil redistribution rates and those simulated from WATEM/SEDEM. The ^{137}Cs sampling points were classified as eroded or depositional according to the two methods, and the number of true positives, true negatives, false positives and false negatives were computed assuming that the ^{137}Cs values were the truth. The confusion matrix allows

computing a number of useful prediction statistics when applied to simulation model output (Beguería, 2006).

Statistical analysis of NS model efficiency and linear regression were carried out using R Statistical Software v.3.1.2 (R Core Team, 2014). Plots were created using the R package ggplot2 (Wickham, 2009).

3. Results

3.1 Soil properties

The predominant grain size within the field was less than 0.05 mm (Table 1). Most soil samples (71%) had <0.05 mm fraction content higher than 70%. Only 4% of the soil samples had contents of the sand fraction (between 0.05 and 2 mm) higher than 50%. The coarse fraction (>2 mm) was higher than 1% in 30% of the soil samples.

Table 1 Basic statistics of the soil and topographic properties in the study field.

n = 156	Mean	Median	S.D.	CV %	Min	Max
>2 mm (%)	1.09	0.44	2.19	201.16	0.00	16.85
2 - 0.05 mm (%)	23.42	20.45	13.31	56.84	3.50	74.30
<0.05 mm (%)	76.58	79.55	13.31	17.38	25.70	96.50
SOM (%)	1.15	1.16	0.28	24.50	0.46	2.59
elevation (m)	629.95	630.28	3.21	0.51	622.60	635.40
slope (%)	7.41	7.10	3.13	42.21	1.10	19.00

S.D. standard deviation; CV coefficient of variation

Sampling points located upslope (636–632 m) had higher and significant ($p \leq 0.05$) percentage of the <0.05 mm fraction (mean= $83 \pm 10.3\%$) compared to middle slope (632–629 m) and bottom slope (629–622 m) positions with mean values of the <0.05 mm fraction of $75 \pm 14.8\%$ and $72 \pm 12.1\%$, respectively. The <0.05 mm fraction decreased from northwest to southeast as did elevation in coincidence with the SOM pattern (Fig. 2). Higher and significant ($p \leq 0.05$) SOM content was found upslope (mean= $1.3 \pm 0.27\%$) compared to middle slope (mean= $1.1 \pm 0.26\%$) and bottom slope

(mean=1.0±0.20%) positions. However, lower and significant ($p \leq 0.05$) sand content (mean=17±10.3%) was found upslope compared to middle slope (mean=25±14.8%) and bottom slope (mean=28±12.1%) positions. Furthermore, the highest coarse fraction and sand contents were found at the end of the gully in the northeast part of the study field (Fig. 2) with mean values of 13±3.7% and 70±5.5% of the coarse and sand fractions, respectively.

Fig. 2 Spatial distributions of the topographic attributes (slope and curvature), grain size fractions and SOM content in the study field.

There were moderate and significant correlations between grain size fractions, SOM and topographic attributes such as elevation and slope (Table 2). Contents of SOM and <0.05 mm fraction were directly and significantly correlated ($p \leq 0.01$) but inversely correlated with the percentages of coarse and sand fractions. Moreover, SOM was

directly correlated ($p \leq 0.01$) with elevation and slope, as it was the <0.05 mm fraction whereas coarse and sand fractions were inversely correlated with elevation and slope.

Table 2 Pearson's correlation coefficients between soil and topographic properties.

	>2 mm	2 - 0.05 mm	<0.05 mm	SOM	Elevation
n=156	(%)	(%)	(%)	(%)	(m)
2 - 0.05 mm (%)	0.621				
<0.05 mm (%)	-0.621	-1.000			
SOM (%)	-0.308	-0.498	0.498		
Elevation (m)	-0.062	-0.307	0.307	0.484	
Slope (%)	-0.237	-0.292	0.292	0.270	0.532

Bold numbers indicate statistical significance at $p \leq 0.01$ level

3.2 ^{137}Cs soil redistribution rates

The values of ^{137}Cs massic activity in the study field showed high spatial variability (CV=39%) ranging between below the detection limit ($<0.3 \text{ Bq kg}^{-1}$) and 5.7 Bq kg^{-1} with a mean value of $2.5 \pm 0.96 \text{ Bq kg}^{-1}$. Similarly, the ^{137}Cs inventories also varied largely ranging from 0 to 4094 Bq m^{-2} (CV=48.6%) with a mean value of $1374 \pm 668.5 \text{ Bq m}^{-2}$.

Based on the 21 ^{137}Cs inventories at the reference sites, it was established that the ^{137}Cs reference inventory for the study field was $1507 \pm 92.0 \text{ Bq m}^{-2}$. This reference inventory is similar to values found in nearby study catchments (Gaspar et al., 2013; Navas et al., 2012, 2014) and falls within the range of $1475\text{--}2288 \text{ Bq m}^{-2}$ estimated for the region by Legarda et al. (2011) and Caro et al. (2013). Figure 3a shows the depth distribution of the ^{137}Cs massic activity and inventories at the reference sites. In the reference soil profiles, ^{137}Cs was not detected below 35 cm and $>80\%$ of the total ^{137}Cs was found in the first 10 cm concentrated in the upper soil layers. The exponential decrease of ^{137}Cs with depth confirmed that soils were undisturbed.

According to the ^{137}Cs reference inventory, sampling points were divided into eroded points with ^{137}Cs inventories less than 1450 Bq m^{-2} , stable points in which ^{137}Cs inventory ranged between 1450 and 1550 Bq m^{-2} and depositional points with ^{137}Cs inventories above 1550 Bq m^{-2} . As much as 63% of the sampling points in the study field had inventories lower than the reference inventory indicating a predominance of ^{137}Cs loss. The values of ^{137}Cs inventories between 1200 and 1450 Bq m^{-2} were the most frequent ($n=29$). Only 5% of the sampling points had stable soil conditions and in 50 sampling points, ^{137}Cs inventories exceeded the value from the reference sites indicating that these sampling points have experienced gain of ^{137}Cs and thus soil accumulation.

The estimated soil redistribution rates ranged from a maximum value of erosion rate of $171 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ to a maximum deposition rate of $90 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Most sampling points ($n=101$) experienced soil erosion with a mean value of $19.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ whereas soil deposition occurred in 35% of the study field with a mean value of $12.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The mean value of curvature was of -0.5 m^{-1} (i.e. concave) for the depositional points and of 0.2 m^{-1} for the eroded points (Table 3).

Table 3 Means of soil and topographic parameters in the study field by soil redistribution.

	Eroded points n=101	Depositional points n=55
>2 mm (%)	0.75±1.37a	1.71±3.12b
2 - 0.05 mm (%)	21.85±12.43a	26.30±14.46b
<0.05 mm (%)	78.15±12.43a	73.70±14.46b
SOM (%)	1.15±0.29a	1.16±0.26a
^{137}Cs (Bq kg^{-1})	1.98±0.70a	3.31±0.74b
^{137}Cs (Bq m^{-2})	1011.21±334.72a	2039.42±613.87b
Soil redistribution rates ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	-19.73±35.88a	12.58±18.75b
Elevation (m)	630.00±3.14a	629.85±3.35a
Slope (%)	7.82±3.11a	6.67±3.05b
Curvature (m m^{-2})	0.16±1.93a	-0.47±2.17b

Different letters indicate significant differences at $p \leq 0.05$ level

The deposition rates higher than $30 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ were found along the gully in the north part of the field while in the south part deposition was found along the tillage furrow with most rates ranging between 20 and $24 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Soil erosion rates higher than $50 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ were found in areas of concentrated runoff related to the gully system near the field boundaries (Fig. 3a).

Fig. 3 (a) Soil redistribution rates (SRr) derived from ^{137}Cs measurements (point estimated and spatial ordinary kriging), depth distribution of ^{137}Cs mass activity and boxplots of 5 ^{137}Cs inventory profiles at the reference site. (b) Simulated soil redistribution rates (SRr) with WATEM/SEDEM for the entire study field and c) for the hydrological unit U2.

The soil redistribution rates estimated with the MBM III model along the two selected transects T1 and T2 are shown in Figure 4a. The mean erosion rates by water were 12.3 and $12.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ranging between 5.5 and $19.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and between 6.2 to $16.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for T1 and T2, respectively. The mean deposition rate by water in T1 was $4.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ranging from 2.9 to $7.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, whereas in transect T2 only one sampling point accumulated soil at a rate of $7.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. The mean soil erosion rates by tillage were 0.12 and $0.10 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ranging between 0.03 and $0.26 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and between 0.05 to $0.12 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for T1 and T2, respectively. The mean

deposition rates by tillage in T1 and T2 were 0.28 and 0.43 $\text{Mg ha}^{-1} \text{yr}^{-1}$ ranging from 0.17 to 0.35 $\text{Mg ha}^{-1} \text{yr}^{-1}$ and from 0.40 to 0.45 $\text{Mg ha}^{-1} \text{yr}^{-1}$, respectively. High Pearson's correlation coefficients were found between ^{137}Cs derived soil redistribution rates using the model by Soto and Navas (2008) and that derived from MBM III (Walling and He, 1997) for transects T1 ($r = 0.998$, $p \leq 0.01$) and T2 ($r = 0.997$, $p \leq 0.01$) (Fig.4b).

Comparing eroded and depositional sampling points, the mean of the <0.05 mm fraction was lower and significantly different ($p \leq 0.05$) at depositional points than at eroded ones whereas the mean value of the coarse fraction was higher and significantly different in depositional points than in the eroded ones (Table 3). Furthermore, it was found a lack of significant correlations between soil and topographic properties and soil redistribution rates apart from the direct and significant correlation between SOM content and soil erosion rates ($r=0.243$, $p \leq 0.05$), and the negative correlation between elevation and soil deposition rates ($r=-0.277$, $p \leq 0.05$).

Fig. 4. (a) Boxplots of the soil redistribution rates (SRr) by water and tillage from MBM III model for the two transects ($n=12$). (b) Linear regressions between soil redistribution rates (SRr) from MBM III and Soto and Navas (2008) models for the transects T1 and T2.

3.3 Model calibration

The calibration of WATEM/SEDEM was carried out performing a high number of simulations ($n=874$). A preliminary calibration was done with k_{tc} values ranging from 0 to 100 m, in combination with values of k_{till} ranging from 0 to 1000 kg m^{-1} ($n=200$). These first simulations showed that the optimal combination of k_{tc} max and k_{till} , according to the NS statistic, ranged between 0–5 and 0–10, respectively. Therefore, the

model was run with values of ktc max and ktill within those limits (n=674). Figure 5a show the results of the NS statistic for the entire study field and Figure 6 for each one of the four hydrological units separately. In Table 4 are shown some statistics commonly used in model calibration. A rather poor result was obtained for the field as a whole, as shown by the comparison between WATEM/SEDEM and ^{137}Cs estimates on Figure 5b and by the low NS (0.11) and low R^2 (0.14). The mean absolute error (11.28 $\text{Mg ha}^{-1} \text{yr}^{-1}$) was also high (Table 4). The optimum parameters where ktc max=1.28 and ktill=0, i.e. very low values (Figure 5a).

Fig. 5. (a) Calibration of ktc max and ktill parameters using ^{137}Cs derived soil redistribution rates for the entire study field: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross). (b) Linear regression between soil redistribution rates from WATEM/SEDEM and ^{137}Cs measurements for the entire study field.

Table 4 Model evaluation statistics (ME: mean error; MAE: mean absolute error; PBIAS: percent bias; NS: Nash-Stucliffe efficiency) for the study field and the four hydrological units.

	Field	U1	U2	U3	U4
ME	3.60	10.08	0.44	0.89	3.83
MAE	11.28	11.59	9.72	6.40	14.42
PBIAS %	-104.40	-100.80	57.60	-164.20	-85.60
NS	0.11	-0.29	0.49	0.00	-0.11
R^2	0.14	0.04	0.55	0.11	0.01

When the four hydrological units were considered separately, it was found that only good results could be obtained for the U2 unit (NS=0.49, $R^2=0.55$) (Table 4). The optimum parameter values were ktc max=1.92 and ktill=0 (Figs. 6 and 7).

Fig. 6. Calibration of ktc max and ktill parameters using ^{137}Cs derived soil redistribution rates for the four hydrological units: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross).

Fig. 7 Linear regressions between soil redistribution rates from WATEM/SEDEM and ^{137}Cs estimates for the four hydrological units.

New simulations were performed using the calibrated parameters of ktc max and ktill for the entire field and the U2 unit (Figs. 3b and c). Despite the lower NS value for the entire study field, the spatial pattern of erosion and deposition rates predicted by WATEM/SEDEM model was comparable to the patterns of soil redistribution rates derived from ^{137}Cs measurements. Figure 3a shows the simulated soil redistribution rates obtained by ^{137}Cs (point estimated and spatial ordinary kriging interpolation) and figure 3b shows the spatial distribution of soil redistribution rates predicted by WATEM/SEDEM for the entire field. The model estimates ranged from a maximum value of erosion of $15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ to a maximum deposition of $42 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Most sampling points ($n=102$) experienced soil erosion, with a mean value of $3.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, whereas soil deposition occurred in 35% of the grid cells and was concentrated within the gully and in the southern tillage furrow, with a mean value of $5.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Figure 3c shows the modelled rates by WATEM/SEDEM for the hydrological unit U2. There was a high spatial congruence between simulated and measured erosion and deposition sites. High deposition rates ($>20 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) were found along the gully whereas moderate to high erosion rates characterized the surrounding convex areas. Individual simulations were not performed on the rest of hydrological units due to the poor calibration results.

The confusion matrices in Table 5 show the ^{137}Cs sampling points classified as erosion or deposition rates, considering the entire field and the unit U2. According to ^{137}Cs derived soil redistribution rates most sampling points ($n=101$) experienced soil erosion, while soil deposition occurred in 55 sampling points. In unit U2, soil erosion occurred in 22 sampling points whereas soil deposition was found in 18 points. Considering the WATEM/SEDEM derived rates, it was found that for the entire study field 102 sampling points were simulated as eroded points and 54 as depositional ones. In unit

U2, 25 sampling points were simulated as eroded and 15 as depositional points. The overall accuracy of the model for classifying eroded and depositional points was high (70% and 80% for the entire study field and unit U2, respectively). Furthermore, the proportion of erosion cases correctly predicted (true positive rate, or model sensitivity) was high (75% and 72%, respectively). The proportion of deposition cases correctly predicted (true negative rate, or model's specificity) was medium to high (53% and 72%, respectively) (Table 6).

Table 5 Confusion matrices on calibration dataset for the entire study field and unit U2.

WATEM/SEDEM soil redistribution rates	Field		Unit U2	
	¹³⁷ Cs derived soil redistribution rates		¹³⁷ Cs derived soil redistribution rates	
	Erosion rates	Deposition rates	Erosion rates	Deposition rates
Erosion rates	76	26	20	5
Deposition rates	25	29	2	13

Table 6 Statistics of the model calibration dataset for the entire study field and unit U2.

	Field	Unit U2
Sensitivity	0.75	0.91
Specificity	0.53	0.72
False positive rate	0.47	0.28
False negative rate	0.25	0.09
Overall accuracy	0.67	0.83

4. Discussion

The decrease of the thin (<0.05 mm) fraction and the corresponding increase of the coarse (>2 mm) fraction at lower topographic positions in the gully is related to the exportation out of the study field of the finer grain size particles to the main stream evidenced by the positive and direct correlations between the <0.05 mm fraction, elevation and slope and the negative and inverse correlation between elevation, slope and >2 mm fraction (Table 2). The spatial distribution of grain size particles within the study field is related to soil movement from upslope to bottom slope positions by soil

redistribution processes. The predominant direction of water flow within the field is determined by the slope and curvature. Alba (2003) also found, in cultivated soils, that the distribution of soil texture was influenced by runoff.

A sorting process occurs during the transport phase implying that the lighter soil particles are removed as eroded material and washed out of the field while the coarser and heavier particles remain. Similar spatial patterns are observed for SOM, which is primarily mobilized in association with the finer fraction. As found by Beguería et al., (2015) lighter soil particles and organic matter are removed with preference by raindrop splash and runoff in agricultural fields.

For exceptional rainfall events the field is drained by the functional gully in the hydrological unit U2 as reported by López-Vicente et al. (2015), who studied a 3-day exceptional rainfall event (~235 mm). After repeated pulses of rainfall events the gully system activates the exportation of sediment out of the field to the ephemeral stream through several outlets. As a consequence there is a relative enrichment of coarse and sand fractions in this depositional area located within the main flow line and bordering the east edge of the study field, where an alluvial fan forms after extreme events. The channel depth of the ephemeral gully in unit U2 had mean and maximum values of 11 and 23 cm, respectively. The widening of the ephemeral gully downslope may lead to accelerate water erosion, in agreement with Valentin et al. (2005).

The general pattern of soil erosion and deposition from ^{137}Cs estimates showed a predominance of erosion over deposition within the study field. The mean soil erosion ($19.7 \text{ Mg ha}^{-1} \text{ y}^{-1}$) and deposition ($12.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$) rates compared well with average soil redistribution rates (ca. $20 \text{ Mg ha}^{-1} \text{ y}^{-1}$) reported in agricultural mountain fields in central Ebro basin by Navas et al. (2014) and Gaspar and Navas (2013). The most frequent values of soil erosion rates (56%) varied between 10 and $25 \text{ Mg ha}^{-1} \text{ y}^{-1}$ and for

soil deposition rates (23%) ranged between 0 and 10 Mg ha⁻¹ y⁻¹. The magnitude of the most frequent soil redistribution rates recorded (79%) was consistent with the soil loss rates found in Mediterranean rainfed crops by Kosmas et al. (1997) who indicated that sediment losses ranged from 15 to 90 Mg ha⁻¹ y⁻¹ for rainfalls greater than 380 mm.

Soil loss occurred in convex shoulder positions and soil accumulation in concave areas at bottom slope positions as also observed by Schumacher et al. (2005) in a field of central Iowa. Removal of finer soil particles (<0.05 mm) by rainfall events in association with ¹³⁷Cs that occurred at the end of the gully and at some points along the edge of the field close to the main stream is linked to higher soil erosion rates found in the north part of the study field (30–171 Mg ha⁻¹ yr⁻¹). A previous study in the field by López-Vicente et al. (2015) during exceptional rainfalls recorded important soil losses for just one single event. The lower contents of finer soil particles are related to lower ¹³⁷Cs inventories as the strong fixation of ¹³⁷Cs occurs into the frayed edge of clays (Gaspar et al., 2014). Higher deposition rates (up to 90 Mg ha⁻¹ yr⁻¹) are recorded in concave areas in the north part of the field within the hydrological unit U2 along the gully and along the edges in the south part of the field.

The calibration and evaluation procedures of the modelling performance have been treated as a single-criteria optimization problem using the NS efficiency because generally the analysis as a multi-objective problem using different efficiency criterion place emphasis on different systematic and/or dynamic behavioral errors making it difficult to clearly assess model performance (Krause et al., 2005). Furthermore, when using multiple criteria in evaluation it has to be considered that some of these are mathematically related (Weglarczyk, 1998) for example, the mean squared error criterion and its related normalization the NS efficiency (Gupta et al., 2009). Consequently in the study case using related efficiency criteria to estimate the error

between the simulated and observed variable may not have any advantages over single efficiency criteria.

As reported by Alatorre et al., (2010) it is not possible to find a single set of parameters that optimize the error function unless a distributed set of point estimates of soil redistribution rates, such as those provided by ^{137}Cs , are used. Otherwise, there is a range of possible parameter combinations that yield equally good results, represented as a 'ridge' in the NS plot. The model performed well in the hydrological unit U2 with a NS value of 0.49, whereas the simulation was poor for the entire field (NS=0.11) and especially in the hydrological units U1, U3, U4 (NS $\leq$ 0). Anthropogenic changes done in the study field based on the information given by the owner and field observations might explain the poor fit in units U1, U3 and U4 obtained using WATEM/SEDEM which is a topographically driven model. On one hand these anthropogenic changes included filling a steep bank between the U3 and U4 units. In addition, the hydrological unit U1 was an alternative entry to the field where the repeated transit of heavy machinery led to a significant impact on the soil that might have affected the patterns of soil movement. The calibrated and best model performance was obtained for the hydrological unit U2. This is the unit with the steepest and better-defined topography, including a gully, and also the least altered by human activity compared to the other three units in which apart from cultivation practices there was an impact produced by the farm machinery modifying the topography and soil surface characteristics by disturbance and compaction. The contrasted topography of the U2 in comparison to U1, U3 and U4 units, allowed for a higher runoff concentration that was well captured by the model.

Water erosion is the main erosion process within the field after comparing the simulated soil redistribution rates and ^{137}Cs derived rates whereas the contribution of tillage to soil

redistribution was almost negligible. It could be associated to the relevant influence of rainfall both amount and distribution. Most runoff events occurred in the period from early October to late February. During this period rains are of high intensity and long duration (López-Vicente et al., 2008), while the vegetation cover is still not sufficient to protect soil from raindrop impact. Rainfall extreme events recorded in the study activates the ephemeral gully system within the study field thus intensifying water erosion processes over tillage erosion (López-Vicente et al., 2015). Moreover, the specific topography of the study field together with the slope that in some parts reaches up to 19 % seems to have also an effect on the predominance of water erosion over tillage erosion. In our study field, soil erosion and deposition is driven mainly by water erosion. This fact was confirmed by the calibrated k_{till} parameter and by the estimation of soil redistribution rates by tillage using MBM III along the two selected transects. The impact of the recent land management change from mouldboard to chisel with a difference of 5 cm in the plough layer might not be so relevant in the overall soil redistribution rates for the last 50 years. Moreover, the estimated soil erosion rates by water with MBM III were substantially higher than the soil deposition rates, indicating the predominance of soil loss over soil accumulation along the transects.

Soil redistribution rates estimated from ^{137}Cs inventory conversion models were higher than those from WATEM/SEDEM at most sampling points. Underestimation of soil redistribution rates is related to the poor results of the model during calibration, which resulted in very low parameter values in order to maintain the mean error low (here measured by the NS statistic). This may be seen as a sign of WATEM/SEDEM not being capable of offering an adequate description of the processes taking place on the study field. For example, the fact that the model assumes a homogenous sediment

mixture along the whole erosion/transport/deposition process, while evidences were found of sediment sorting processes taking place, may have affected the model ability.

At present the current version of the WATEM/SEDEM model does not allow including temporal changes in land management or soil properties as bulk density for a study period. Similarly, ^{137}Cs mass balance models do not implement temporal changes related to land management. To overcome this limitation, model simulations were carried out assuming average values of the RUSLE factors as C-factor for the study period.

In addition, difficulties were found for estimating some model parameters. This was notably the case of the rainfall erosivity factor, for which only data at high-resolution was available for the period 2005–2014. A precise assessment of *R*-factor values requires an accurate computation of the rainfall erosivity of each storm as well as high resolution rainfall measurements at a small time step (Diodato, 2004) from 1 to 60 min for a period of at least several years (Panagos et al., 2015). In addition records from Vigas station can underestimate real rainfall in the study field. Comparing the annual precipitation data at Vigas station for the last 10 years with the annual record with a pluviometer the former was on average 24% lower than that recorded in the study field. Soil losses from cultivated fields are directly proportional to rainfall erosivity (Renard et al., 1997a) because *R*-factor is a numerical descriptor of the ability of rainfall to erode soil (Wischmeier and Smith, 1959) and depends on both the amount and intensity of the precipitation (Keesstra et al. 2009), therefore the relative lower values of precipitation recorded at Vigas station could explain the underestimated soil redistribution rates from WATEM/SEDEM model. Furthermore, the reconstructed long term precipitation dataset for the 1940–2012 period showed that the average precipitation for the period 2005–2012 from the Vigas station was lower (367 mm) than the average for the

reference precipitation dataset (495 mm), indicating that the available records of precipitation at 15 min resolution from Vigas station in 2005–2014 correspond to a dry period. However, although the used value for the R factor may have been underestimated, it could be expected that this underestimation could be superseded during calibration by increasing the transport capacity coefficients accordingly.

In the study area the comparison between the simulated soil redistribution rates from the WATEM/SEDEM model with the derived ^{137}Cs rates provides a reliable spatial distributed dataset to examine the uncertainties associated with different models as also found by Li et al. (2007) in a cultivated field of 2.7 ha in North America.

The uncertainty related to the comparison of point measurements with area-averaged model estimations has not been assessed, thus we assumed that the point measurements were representative of the 2.5 x 2.5 cells. To evaluate the sensitivity of the simulation to changes in the R and C -factors we carried out 674 new simulations using R -factor= 1000 MJ mm ha⁻¹h⁻¹yr⁻¹ and C -factor=0.20 as model input parameters, and 674 new simulations with R -factor= 881 MJ mm ha⁻¹h⁻¹yr⁻¹ and C -factor=0.18. The results (included as additional online material) show that the simulations are relatively insensitive to changes in R and C -factors, when k_{tc} max and k_{till} are calibrated as recommended in the WATEM/SEDEM manual. After calibration, k_{tc} max and k_{till} were slightly modified in order to accommodate to the changes in R and C -factors, resulting in fairly similar soil redistribution rates than those computed before.

Visual comparison of the spatial variability of simulated soil redistribution rates from WATEM/SEDEM and ^{137}Cs estimates evidence similar spatial patterns, which are also closely linked to the topography of the field (i.e. deposition at concave areas and erosion at convex areas). Similar results were found by Schumacher et al. (2005), who compared the spatial patterns of tillage and water erosion estimates from

WATEM/SEDEM with total soil erosion ^{137}Cs estimates in a field cultivated since 1957. WATEM/SEDEM focuses on the spatial and to a lesser degree the temporal variability of the relevant processes (Shi et al., 2012). In agreement with Feng et al. (2010), although WATEM/SEDEM model underestimated the soil redistribution rates for each raster cell, it was found to be a reliable tool for predicting the spatial pattern of soil erosion and deposition within the study field. Here we found that WATEM/SEDEM allowed for a highly precise classification of the sampled points as eroded or depositional sites.

5. Conclusions

Soil redistribution rates estimated from ^{137}Cs estimates suggest a predominance of erosion over deposition. After repeated pulses of rainfall, the exportation of finer soil particles to the ephemeral stream at the end of the gully enriched depositional sediment in coarse and sand fractions at the bottom slope due to the wash off of the finer and relatively rich organic fractions. These events have important implications on soil redistribution within the field accelerating erosion by water which is the major factor controlling soil redistribution within the study field. Much lower soil redistribution rates by tillage estimated using MBM III along two selected transects were in line with the tillage rates obtained from WATEM/SEDEM model.

Simulations with topography WATEM/SEDEM model based on DEM are highly dependent on resolution. The efficiency of simulations depends on the quality of the representation of the digital elevation data and is sensitive to noise and artifacts in landscape characterization from DEM. Furthermore, simulated soil redistribution rates were found to be more reliable considering each hydrological unit separately than the entire study field. The good WATEM/SEDEM performance was found in hydrological

unit U2 which showed a contrasted topography in comparison to U1, U3 and U4 units where there was a limited correspondence between ^{137}Cs derived soil redistribution rates and estimates from WATEM/SEDEM model. Lower performance of WATEM/SEDEM with optimal model parameters in three of the four hydrological units might be related with topographic changes from human activity and impact of heavy machinery. This study points out that topographic changes in agricultural fields which are not directly related to water and/or tillage soil redistribution processes may not allow the successful implementation of topography driven model as WATEM/SEDEM.

This study confirms the potential of using medium term soil redistribution rates derived from ^{137}Cs estimates to examine and reduce uncertainties in WATEM/SEDEM model calibration. However uncertainties of using spatially distributed models in areas with historical land use transformation remains to be better understood. Further research is required for evaluating the effect of temporal changes in land management and the effect of averaging the input parameter values related to land management as well as possible changes in topography due to the human activity in model simulation.

Results of the present study highlight that a combination of anthropogenic changes on topography and water erosion were the main drivers of soil movement, which influenced the soil redistribution within the study field. Because the location and the particular topography of the study field is a common feature of the agricultural fields in the area the results of this study could be extrapolated to similar agricultural systems.

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Supplementary material for on-line publication

The WATEM/SEDEM simulations ($n=674$) were performed using $R\text{-factor} = 1000 \text{ MJ mm ha}^{-1}\text{h}^{-1}\text{yr}^{-1}$ and $C\text{-factor} = 0.20$ (Figs. 1, 2 and 3) and 674 WATEM/SEDEM simulations using $R\text{-factor} = 881 \text{ MJ mm ha}^{-1}\text{h}^{-1}\text{yr}^{-1}$ and $C\text{-factor} = 0.18$ (Figs. 4, 5 and 6).

Fig. 1. (a) Calibration of $ktc\ max$ and $ktill$ parameters using ^{137}Cs derived soil redistribution rates for the entire study field: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross). **(b)** Linear regression between soil redistribution rates from WATEM/SEDEM and ^{137}Cs measurements for the entire study field.

Fig. 2. Calibration of ktc_{max} and $ktill$ parameters using ^{137}Cs derived soil redistribution rates for the four hydrological units: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross).

Fig. 3. Linear regressions between soil redistribution rates from WATEM/SEDEM and ^{137}Cs estimates for the four hydrological units.

Fig. 4. (a) Calibration of ktc_{max} and $ktill$ parameters using ^{137}Cs derived soil redistribution rates for the entire study field: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross). **(b)** Linear regression between soil redistribution rates from WATEM/SEDEM and ^{137}Cs measurements for the entire study field.

Fig. 5. Calibration of ktc_{max} and $ktill$ parameters using ^{137}Cs derived soil redistribution rates for the four hydrological units: values of the NS goodness-of-fit statistic (colour scale and contour lines, interpolated), pairs of parameter values (grey dots) and best parameter combination (cross).

Fig. 6. Linear regressions between soil redistribution rates from WATEM/SEDEM and ^{137}Cs estimates for the four hydrological units.

Table 1 Model evaluation statistics (NS: Nash-Stucliffe efficiency) for the study field and the four hydrological units using $R\text{-factor} = 1000 \text{ MJ mm ha}^{-1}\text{h}^{-1}\text{yr}^{-1}$ and $C\text{-factor} = 0.20$.

	Field	U1	U2	U3	U4
NS	0.11	-0.29	0.53	0.10	-0.04

Table 2 Model evaluation statistics (NS: Nash-Stucliffe efficiency) for the study field and the four hydrological units using $R\text{-factor} = 881 \text{ MJ mm ha}^{-1}\text{h}^{-1}\text{yr}^{-1}$ and $C\text{-factor} = 0.18$.

	Field	U1	U2	U3	U4
NS	0.10	-0.28	0.50	0.09	-0.04