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Effects of land use change on soil splash erosion in the semi-arid region of Iran

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ABSTRACT

Land use change may escalate the process of splash erosion as the primary mechanism causing water erosion. The objective of this study was to investigate the impacts of different management practices and land uses on splash erosion in a semiarid region in Iran. The major land uses in the area were pasture, degraded pasture, dry land farming, and irrigated farming. For the purposes of this study, soil properties including organic matter, $CaCO_3$, surface shear strength (SSS), particle size distribution, mean weight diameter (MWD), and the topographic attributes were measured. Soil splash erosion was measured at 80 different locations under the following four conditions comprising different values of slope (S:%) and rainfall intensity (RI:mm·h^{-1}): 5–50, 5–80, 15–50, and 15–80, respectively, using the multiple splash sets (MSS) especially designed and tailored for the purposes of this study. A completely randomized design was used in which soil texture and the land use systems were independently analyzed. The fuzzy linear regression (FLR) was used and compared with the multiple-linear regression (MLR) analysis. It was found that the splash erosion in the study region was mainly influenced by landuse and soil management practices rather than by intrinsic soil properties like tested textures. The average splash erosion values among landuse types are: degraded pasture > cultivated farming > pasture; this is claimed to be associated with the lower organic matter content and shear strength due to overgrazing and untimely grazing. The FLR models outperformed the MLR ones ($p > 0.01$). MWD and SSS attributes were the most effective variables in estimating soil splash, indicating the structural susceptibility of the soils to management practices. Based on the results obtained, MWD and SSS may be regarded as important indices of splash erosion.

1. Introduction

Soil erosion is one of the most serious environmental problems threatening many ecosystems in (semi-)arid regions of the world. More specifically, disturbed areas in these regions exhibit a greater potential for soil detachability and transportability (Saygın et al., 2011). The main impacts of these disturbances include reduced vegetation, loss of surface cover by decaying vegetation, and soil compaction (Ravi et al., 2009). Disturbed lands in Iran include forests and pastures that have been disturbed by such human activities as overgrazing, untimely grazing, shrub burning, and tillage (Khalilmoghadam et al., 2009). Soil erosion rate in Iran is estimated at 25 Mg per hectare per year which is four times greater than its world average (Abbaszadeh Afshar et al., 2010; Jalalian et al., 1996). What adds to this undesirable situation is the high rate of land use change from pasture to dry land farming which is estimated at 400 m^2 per second (Abbaszadeh Afshar et al., 2010).

Land use/cover affects the occurrence and the intensity of runoff and soil erosion (Chen et al., 2001; Wei et al., 2007). Proper management of land use/land cover patterns may greatly improve soil properties, leading to reduced soil erosion to the recommended threshold limits (Fu, 1989; Chen et al., 2003). Improved physical soil properties can also positively affect the establishment of vegetation (Kosmas et al., 2000). Different land uses and/or cover systems might lead to changes in a number of soil properties and soil erosion processes (Costa et al., 2003). Different models have been widely used to study and simulate the effects of landuse changes on surface runoff and sediment yield (Wendt and Corey, 1980; Lorup et al., 1998; Raclot and Albergel, 2006; Yuan et al., 2007; Yu et al., 2009; Xiaoming et al., 2010). Schiettecatte et al. (2008) showed that spatial differences in erosion rates within the watershed are mainly caused by differences in topography and landuse. Wei et al. (2007) reported that the runoff coefficient and erosion modulus of shrubland were lowest followed by grassland and woodland in an increasing order. Pastureland was found to have an adverse effect on erosion control, which was slightly weaker than cropland but far greater than the other three land use types.

The absence of vegetation cover in disturbed lands accelerates splash erosion rates by as much as several folds compared to undisturbed sites (Lal, 2001; Thomaz and Luiz, 2012). The detachment of soil particles by splash depends on several raindrop characteristics,

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including raindrop size and mass, drop velocity, kinetic energy, and water drop impact angle (Sharma et al., 1993; Singer and Le Bissonnais, 1998; Cruse et al., 2000; Bhattacharyya et al., 2010). Detachment rate is strongly influenced by soil properties, including soil texture and thickness of the water layer at the soil surface (De Ploey and Savat, 1968; Moss and Green, 1983; Sharma et al., 1991; Kinnell, 1991; Jomaa et al., 2010), soil strength, bulk density, cohesion, soil organic matter content, moisture content, infiltration capacity (Nearing et al., 1988; Owoputi, 1994; Morgan et al., 1998; Planchon et al., 2000; Ghahramani et al., 2011), soil initial water content, surface compaction and roughness (Planchon et al., 2000), the nature of soil aggregates and crust, porosity, capacity of ionic interchange, and clay content (Poesen and Torri, 1988). Several studies have shown that splash detachment rate is mainly related to surface rock fragments in soils with sparse vegetation cover (Jomaa et al., 2012).

Soil particle size distribution plays an important role in splash erosion (Woodburn, 1948) as smaller particles are splashed over longer distances than larger ones and fine sands have a higher detachability than coarse sands (Poesen and Savat, 1981). Wainwright (1996) observed that soil conditions before a rainfall event and their changes during the event might control splash conditions. Le Bissonnais (1996) classified 17 Mediterranean soils into two groups and found that seal formation was the main factor involved in splash and wash erosion. Luk (1979) and Ekwue (1991) showed that large aggregate sizes and high organic matter content (OM) protect soils against splash detachment. Singer and Le Bissonnais (1998) observed that differences in OM among the three soils they studied were small, and that the differences in soil texture did not lead to significant differences in splash. Legout et al. (2005) observed that the size distribution of splashed fragments was comparable to the size distribution of fragments resulting from aggregate breakdown rather than the original soil matrix. They concluded that the size distribution of splashed fragments depended indirectly on the size distribution of aggregate breakdown products but directly on their size.

The multiple-linear regression (MLR) method (Mayr and Jarvis, 1999; Tomasella et al., 2000) and the fuzzy linear regression (FLR) (Tran et al., 2002) are the two most common methods used for developing soil spatial prediction functions (SSPFs) and pedo-transfer functions (PTFs). Compared to MLR, the FLR method might be more appropriate when: 1) data are not sufficient to perform the statistical regression; 2) the assumptions about the statistical distribution cannot be justified; 3) the relationship between input(s) and output is vague; and 4) imprecise human judgments are involved (Tran et al., 2002). Since its development by Zadeh (1965), the fuzzy set theory has been successfully used in solving problems dealing with vague expert knowledge, uncertainty, or imprecise/insufficient data. Recently, there has been a variety of studies applying the theory to different areas of soil and soil erosion studies (Mitra et al., 1998; Changying and Junzheng, 2000; Kumar et al., 2000; Lark, 2000; Oberthur et al., 2000; Jian-guo et al., 2001; Ahamed et al., 2000; Tayfur et al., 2003; Hodza, 2010).

Although most previous studies on splash erosion have focused on impacts of soil, climate, topography, and ground cover characteristics, to the best of the authors' knowledge, no study has of yet been reported on the effects of different management systems and land use changes on soil splash erosion. Therefore, this study was conducted in the central Zagros region, Iran: i) to investigate the impact of different management systems and land use changes from pasture to degraded pasture and cultivated lands on soil splash erosion, and ii) to compare the predictive power of the fuzzy linear regression (FLR) and that of multiple linear regressions (MLR) in estimating soil splash erosion.

2. Materials and methods

2.1. General site description

This study was conducted in part of the central Zagros, Iran (50°15′–51°51′ N and 31° 20′–32°53′ E) covering an area of approximately 27,500 ha (Fig. 1). The region is characterized by a long term average rainfall of 600 mm, a mean temperature of 14 °C, an elevation of 1870 to 1980 m above mean sea level, and a hilly topography. Within the study area, there are seven geological units: Asemari formation (M_{as}^{lm}), Agha-Jari formation (M_{aj}^{c}), Alluvial Fan and old terrace (Q_1^t), Alluvial Fan and new terrace (Q_2^t), silt and clay flats (Q_3^t), Mishan formation (M_{mn}^{m}), and Gachsaran formation (M_{gs}^{mg}) with moderate weathering and sensitivity to erosion (Iranian Geological Organization, 2006). The soils include *Calcic Haploxerolls*, *Typic Calciaquolls*, *Pachic Calcixerolls*, *Calcic Haploxeralfs*, *Calcic Haploxeralfs*, *Fluventic Haploxerepts*, and *Typic Calcixerepts* (Soil Survey Staff, 2010) as well as *Haplic Fluvisols*, *Haplic Calcisols*, *Fulvic Cambisols*, *Calcic Luvisols*, *Luvic Calcisols*, *Calcic Kastanozems*, and *Luvic Calcic Kastanozems* (World soil resources reports, 2006). The major land uses are pasture (*Astragalus* sp. and *Bromus* sp.), degraded pasture (*Bromus* sp.), dryland farming, and irrigated farming. Winter wheat (*Triticum aestivum*) is mostly cultivated on the dry farmed lands and clover (*Trifolium resupinatum*) is generally cultivated on irrigated fields. Conventional tillage (i.e., moldboard plowing and disking by MF285 tractors) is used in dryland and irrigated farming. The degraded pasture area was under intensive sheep overgrazing (i.e., four to eight times greater than its normal capacity) during late May to early September. All the cover crops (*Bromus* sp.) on the degraded pasture lands are consumed by livestock during grazing.

2.2. Experimental design

The study area was initially divided into similar Land Unit Tracts (LUT). LUT is defined as an area of land where the attribute values are sufficiently uniform and distinct from those of the neighboring areas to justify its delineation in a map or an image (Gunn and Aldrick, 1988). The attributes included soil, geology, topography, and land use attributes. The stratifying procedure was conducted using a geology map with a resolution of 1:100,000, a topography map at 1:50,000, a land use map at 1:250,000, and a land capability map at 1:250,000. GIS9.3 environment was used for analyzing the data and for producing the thematic map layers so that a total number of 25 LUT layers was generated. Supervised random sampling was used to collect samples in every land unit. A total number of 80 samples was collected in order to produce a measure of diversity in soil properties within each LUT (13 from pasture lands, 13 from degraded pasture lands, 30 from dry land farms, and 24 from irrigated farms) from the A horizons of the soil. The positions of the points were identified by GPS for reference purposes.

2.3. Soil attributes

Particle size distributions of the soils were determined by sieving and sedimentation (Gee and Bauder, 1986), the organic matter and calcium carbonate contents were measured using the Walkley–Black procedure (Nelson and Sommers, 1986), titration was accomplished using NaOH (Nelson, 1982) and aggregate stability was determined by the wet sieving method (Chepil, 1962). A shear vane was used to make shear strength measurements in the saturation condition. The procedure used in this study was to push the vane into the soil surface until the blades were covered (about 8 mm deep), and a clockwise rotation rate was then applied to ensure that failure developed within 5 to 10 s. The maximum stress value was recorded on a dial at the top of the vane driver. Vanes with a stress range between 0 and 100 kPa were used in all the cases to induce shear failure. A non-return pointer assisted readings.

2.4. Topographic attributes

A 10-m by 10-m DEM (National Cartographic Center, 2009) was used to characterize the topographic attributes of slope, wetness

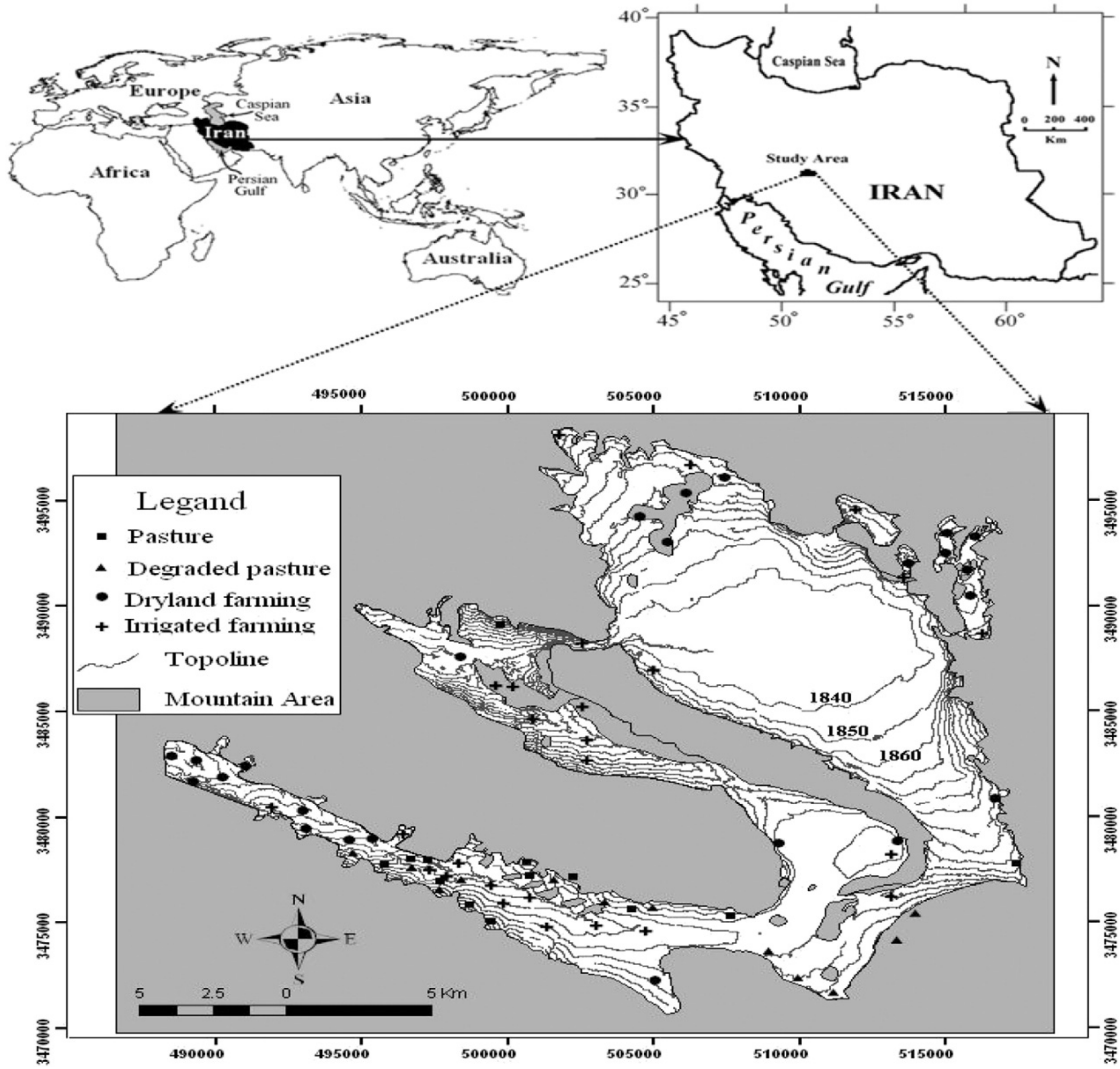

Fig. 1. Locations of the study area and soil sampling/measurement.

index, stream power index, and elevation of the representative points (Table 1) using the standard commands of the ILWIS 3.4 and ArcGIS 9.3 GRID module.

2.5. Multi splash set (MSS)

Numerous laboratory and field investigations have been carried out in recent years aimed at measuring soil splash erosion. But, without field evidence to support them, the validity of the results of these studies remains questionable (Morgan, 1981). In this study, soil splash erosion was measured under the following four different conditions during 30 min of slope (S: %) and rainfall intensity (RI: $mm \cdot h^{-1}$): 5–50, 5–80, 15–50, and 15–80, respectively, using the multi splash set (MSS) in each sample (with three replicates). MSS were developed based on the archetype of Morgan's field splash cup (Morgan, 1981) and field portable drop-former rainfall simulator (Fernández-Gálvez et al., 2008) for laboratory experiments. The objectives of the modification were to construct a splash cup that would ensure a high replication rate with variable soils, slopes, and rainfall rates. The MSS (Fig. 2) consisted of two parts: a rainfall simulator and a splash set. The rainfall simulator was made for use over an area of 30 cm in diameter and consisted essentially of a drop forming chamber supported by a metal

Table 1
DEM attributes, definitions, abbreviations and units.

Attribute	Abbreviation	Description	Unit
Slope	S	The first derivative along the steepest slope or the rate of change of elevation in the direction of the steepest descent	%
Elevation	E	Elevation above sea level	m
Wetness index	WI	A measure of topographic control over soil wetness or the ratio between the catchment area and slope to reflect flow accumulation	–
Power index	PI	The topographic index for stream forming power of flow or time rate energy expenditure per unit of contour width	–
Sediment index	SI	A measure of topographic control over sediment transport (USLE's LS factor)	–

structure at a certain height above the soil core. The drop-former chamber was connected to a water reservoir which supplied water by a pump at an adjustable constant rate (Fernández-Gálvez et al., 2008). The splash set consisted of an inner stainless steel hollow cylinder, 110 mm long and 100 mm in diameter, which was filled with soil (disturbed/undisturbed) and installed on a plate connected to an electromotor. The inner stainless cylinder, which was partitioned into upslope and downslope compartments, was surrounded by a catching tray 300 mm in diameter with a boundary wall 300 mm high. An electromotor (5 rpm, 20 W) turned the soil cylinder at different rotations per minute to isolate soil splash against the effects of sediment movement by overland flow. A slope-meter system changed the slope of the soil cylinder from 0 to 45%. The entire structure was supported by a triangular base with three legs 40 cm high at each corner. Runoff and sediment transported across the bottom holes (upslope and downslope) of the tray were funneled into two bottles placed at the outlet. The detached soils from the upslope and the downslope compartments of the catching tray were collected separately to be dried and weighed. The combined upslope and downslope weights form a measure of splash detachment. The downslope weight minus the upslope weight is a measure of the net downslope splash transport. Finally, splash erosion rate was calculated using Eq. (1):

$$S_t = \frac{S_u + S_d}{T * A} \tag{1}$$

where, S_t is the splash erosion rate ($g \cdot min^{-1} \cdot m^2$), S_u is the upslope splash soil (g), S_d is the downslope splash soil (g), A is the soil sample area (m^2), and T is the duration of the fall (min).

2.6. Statistical analyses

The data were analyzed using a completely random design with different land use systems as the main treatments. Statistical analyses were performed using the generalized linear model (GLM) procedure in SAS (version 9.2). Mean comparisons were performed using the least significant difference (LSD) test at $p > 0.01$. The impacts of land use on soil splash erosion and other topographic attributes (slope, elevation, power, sediment, and wetness index) and soil properties including particle size distribution (PSD), mean weight diameter (MWD), organic matter (OM), and calcium carbonate were evaluated. In an additional analysis, the effect of soil textural class on splash erosion was investigated using a similar experimental design.

Four conditions (slope and rainfall intensity) of splash erosion measurement were selected as dependent inputs versus independent available data of soil properties and topographic attributes for the four multiple linear regression analysis models. In the multiple linear regression (MLR) analysis, four models were tested for each land use. The

Table 2
Inputs used for fuzzy linear regression (FLR) at different models for developing PTFs and SSPFs 1: splash erosion in %5 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 2: splash erosion in %15 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 3: splash erosion in %5 slope and 80 $mm \cdot h^{-1}$ rainfall intensity; 4: splash erosion in %15 slope and 80 $mm \cdot h^{-1}$ rainfall intensity.

landuse	Model	Variables	Converted Y(soil splash erosion)
Pasture	1	OM-WI-CoSilt-PI	$Y^{0.1}$
	2	SI-OM	$Y^{0.1}$
	3	MWD	$Y^{0.2}$
	4	SSS	$Y^{0.2}$
Degraded pasture	1	SSS	$Y^{0.1}$
	2	CaCO3–OM	$Y^{0.1}$
	3	MWD-clay	$Y^{0.2}$
	4	MWD	$Y^{0.2}$
Dryland farming	1	MWD-VCoSand–CoSand	$Y^{0.1}$
	2	MWD-VFSand–FSand-Slope	$Y^{0.1}$
	3	MWD-VFSand	$Y^{0.1}$
	4	MWD	$Y^{0.1}$
Irrigated farming	1	MWD-CoSilt-PI	$Y^{0.1}$
	2	MWD-WI	$Y^{0.1}$
	3	SSS-OM	$Y^{0.1}$
	4	MWD-F& M Silt	$Y^{0.1}$

MWD: mean weight diameter; VCoSand: very coarse sand; CoSand: coarse sand; VFSand: very fine sand; FSand: fine sand; CoSilt: coarse silt; SSS: surface shear strength; OM: organic matter; PI: power index; WI: wetness index; SI: sediment index; F & M Silt: fine and medium silt.
PTFs: pedotransfer functions; SSPFs: soil spatial prediction functions.
Converted Y: normalized soil splash erosion values.

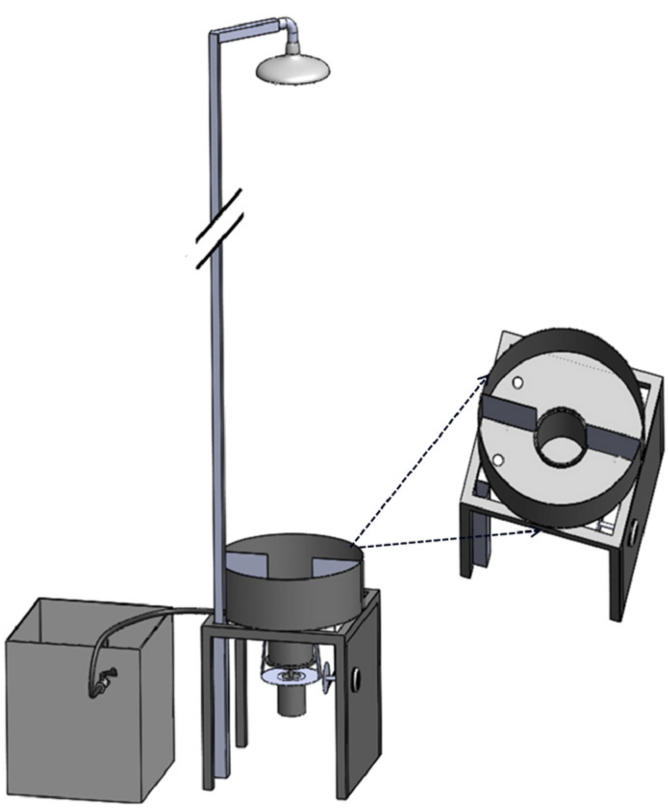

Fig. 2. A general perspective view of multiple splash set(MSS).

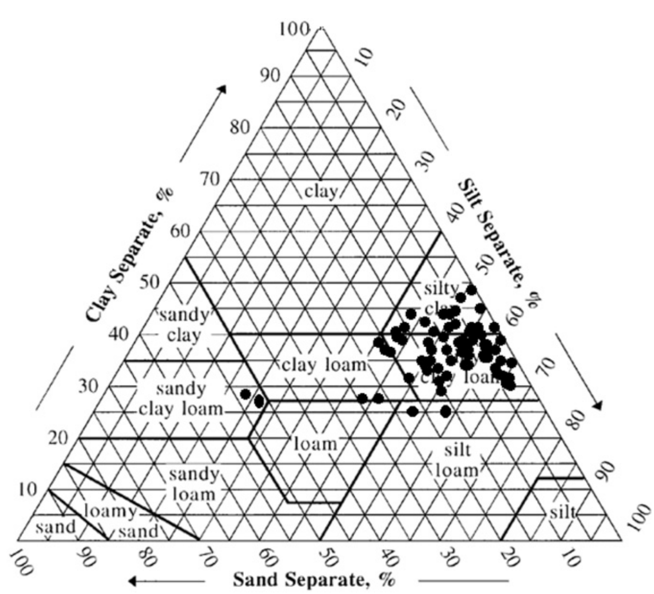

Fig. 3. Soil textures of the study area.

Table 3
Mean comparisons of splash erosion rate (g min^{-1} m^{-2}) values in different conditions of Slope (S) and rainfall intensity (RI) as affected by soil textural class.[a,b]

Texture class	RI 1 & S1	RI 1 & S2	RI 2 & S1	RI 2 & S2
Silty clay(20)[c]	3.37a	11.08a	29.70a	45.83a
Silty clay loam(44)	3.88a	12.21a	30.25a	51.10a
Clay loam(10)	2.67a	8.13a	23.75a	45.02a

[a] RI 1& S1: rainfall intensity(50 mm·h^{-1}) & slope (5%); RI 1& S2: rainfall intensity(50 mm·h^{-1}) & slope (15%); RI 2& S1: rainfall intensity (80 mm·h^{-1}) & slope (5%); RI 2& S2: rainfall intensity (80 mm·h^{-1}) & slope (15%).
[b] Figures followed by similar letters in each column are not significantly different at $p < 0.05$ (LSD).
[c] Numbers in the parentheses stand for the number of soils (locations) in a soil textural class.

stepwise regression method was used to identify the most sensitive variables using the statistical analysis system (SAS, 1999). Based on this regression analysis, four separate sets of inputs were then used in the fuzzy linear regression models for each land use. The inputs selected in the regression analysis of models 1 to 4 were used for models 1 to 4 (Table 2) in the fuzzy linear regression, respectively.

2.7. Fuzzy Linear regression (FLR)

The fuzzy linear regression model, proposed by Tanaka et al. (1982) and Tanaka (1987), is based on the idea of a fuzzy function (Dubois and Prade, 1980; Zimmer mann, 1985) given in a linear form as follows:

$$Y = A_1x_1 + \cdots + A_mx_m = Ax \tag{2}$$

where, x is the independent variable vector, and A represents the fuzzy sets representing model parameters.

In this model, the fuzzy parameters are used in the form of triangular fuzzy numbers rather than crisp values (i.e., single-valued parameters) on which statistical inferences may be drawn in the case of classical linear regression:

$$A_j(aj) = \begin{cases} 1-\dfrac{\left|a_j-a_j\right|}{c_j} & \text{if } a_j-c_j \le a_j \le a_j+c_j \\ 0 \quad \text{otherwise} & \end{cases} \tag{3}$$

where, $A_j(a_j)$ is the membership function of the fuzzy set which represents the parameter a_j; α_j is the center of the fuzzy number, also called a modal value; and c_j is the width or spread around the center of the fuzzy number.

These triangular fuzzy numbers have an interesting interpretation; namely, the modal value describes the most possible value of the parameter, while the spread reflects the precision of the parameter. Using the fuzzy parameter A_j in the form of triangular fuzzy numbers and then applying the extension principle, it becomes clear that the membership function of Y in Eq. (2) is given as:

$$Y(y) \begin{cases} 1-\dfrac{\left|y-x^t a\right|}{c^t|x|} & \text{for} \quad x = 0 \\ & \text{for} \quad x = 0, \quad y \neq 0 \\ 1 & \text{for} \quad x = 0, \quad y = 0 \\ 0 & \end{cases} \tag{4}$$

where, the superscript t denotes the transpiration operation. Here, c and α denote the vectors of model values and spreads for all model parameters.

Finally, the method uses the criterion of minimizing the total vagueness, s, defined as the sum of individual spreads of the fuzzy parameters of the model.

$$\text{Minimize} \quad s = c_1 + c_2 + \cdots + c_m.$$

Simultaneously, the condition that the membership value of each observation y_i should be greater than an imposed threshold, h ϵ [0, 1], is taken into account. This criterion simply expresses the fact that the fuzzy output of the model should 'cover' all the data points y_1, y_2, …y_N

Table 5
Summary of statistics (maximum, minimum, average and coefficient of variations, CV) for soil chemical and physical properties among the land uses.

Landuse	Statistics	$CaCO_3$ (%)	OM (%)	MWD (mm)	SSS (kPa)
Pasture	Max	37.20	4.16	3.54	18.67
	Min	12.00	2.10	2.08	11.23
	Ave	23.60^{a}	2.58^{a}	2.78^{a}	14.77^{a}
	CV	0.34	0.23	0.15	0.16
Degraded pasture	Max	30.14	1.92	2.80	15.55
	Min	0.57	1.00	1.58	8.50
	Ave	15.62^{a}	1.60^{b}	2.17^{b}	12.41^{b}
	CV	0.59	0.19	0.18	0.17
Dry land farming	Max	55.00	2.86	15.34	9.93
	Min	1.62	1.02	1.81	9.50
	Ave	20.23^{a}	1.83^{b}	2.34^{b}	12.29^{b}
	CV	0.66	0.26	0.15	0.12
Irrigated farming	Max	36.00	4.30	3.62	22.56
	Min	3.40	0.48	1.12	9.00
	Ave	19.62^{a}	1.94^{b}	2.38^{b}	13.82^{ab}
	CV	0.48	0.47	0.26	0.23

Figures followed by similar letters in each column are not significantly different at $p < 0.05$ (LSD).

Table 4
Summary of statistics (maximum, minimum, average and coefficient of variations, CV) for soil properties and topographic attributes among the land uses.

Parameter	Pasture				Degraded pasture				Dryland farming				Irrigated farming			
	Max	Min	Ave	CV	Max	Min	Ave	CV	Max	Min	Ave	CV	Max	Min	Ave	CV
Clay (%)	43.50	27.00	36.00^{ab}	0.14	46.50	31.50	38.64^{a}	0.11	43.50	27.00	35.15^{b}	0.11	48.00	28.50	37.72^{ab}	0.12
F & M Silt (%)	43.00	26.00	35.04^{a}	0.15	50.50	28.50	37.32^{a}	0.19	40.00	19.00	32.68^{a}	0.16	45.00	22.50	34.22^{a}	0.19
CoSilt (%)	21.98	12.92	18.00^{ab}	0.14	22.89	2.55	15.00^{b}	0.37	37.88	10.36	20.44^{a}	0.34	31.53	12.15	19.51^{a}	0.24
VCoSand (%)	5.46	0.18	2.16^{a}	0.86	5.85	0.05	1.47^{ab}	1.22	3.49	0.04	1.42^{ab}	0.69	4.28	0.06	1.06^{b}	0.99
CoSand (%)	4.25	0.26	2.01^{a}	0.72	6.65	0.07	1.83^{a}	1.07	4.20	0.10	2.00^{a}	0.70	5.45	0.08	1.47^{a}	0.86
MSand (%)	3.02	0.11	1.72^{a}	0.58	4.52	0.07	1.56^{a}	0.88	4.46	0.20	1.95^{a}	0.68	4.57	0.14	1.46^{a}	0.84
FSand (%)	4.75	0.07	1.53^{a}	0.78	2.56	0.14	1.22^{a}	0.66	6.32	0.15	2.08^{a}	0.81	3.25	0.17	1.30^{a}	0.75
VFSand (%)	13.48	0.95	3.55^{a}	0.92	7.48	1.18	2.97^{a}	0.58	14.29	1.57	4.29^{a}	0.74	6.74	0.91	3.27^{a}	0.51
Elevation (m)	2071.43	1881.34	1993.94^{a}	0.03	2126.33	1901.45	2010.03^{a}	0.03	2054.86	1698.21	1920.70^{b}	0.06	2042.86	1800	1981.75^{a}	0.03
Slope (%)	16.60	5.92	10.20^{a}	0.31	12.82	1.69	7.71^{ab}	0.45	30.73	1.53	8.48^{ab}	0.88	17.06	1.66	6.21^{b}	0.60
Power index	46.42	4.01	53.00^{a}	2.46	295.10	4.47	90.00^{a}	1.06	815.43	1.22	100.00^{a}	1.85	267.53	5.66	107.93^{a}	4.96
Sediment index	119.99	0.10	21.29^{a}	1.53	19.99	0.94	8.38^{a}	0.77	40.25	0.05	6.02^{a}	1.75	1084.06	0.12	48.52^{a}	4.45
Wetness index	17.99	8.64	10.93^{ab}	0.25	11.26	7.71	9.27^{b}	0.13	17.14	7.12	12.72^{a}	0.26	17.95	8.06	12.19^{a}	0.29

Figures followed by similar letters in each row are not significantly different at $p < 0.05$ (LSD).
VCoSand: very coarse sand; CoSand: coarse sand; Msand: medium sand; VFSand: very fine sand; FSand: fine sand; CoSilt: coarse silt; FSilt: fine and medium silt.

Table 6
Summary of statistics (maximum, minimum, average and coefficient of variations, CV) for soil splash erosion in different rainfall intensity (RI) and slope (S) among the land uses.

Landuse	Statistics	RI 1 & S1	RI 1& S2	RI 2 & S1	RI 2& S2
Pasture	Max	4.02	14.82	34.10	59.50
	Min	0.55	2.03	7.24	23.9
	Ave	2.15[b]	8.72[b]	21.14[b]	43.63[b]
	CV	0.55	0.44	0.42	0.26
Degraded pasture	Max	7.55	48.00	58.70	79.40
	Min	1.77	4.98	16.20	38.6
	Ave	4.29[a]	15.46[a]	36.59[a]	58.12[a]
	CV	0.42	0.80	0.33	0.22
Dry land farming	Max	9.93	23.50	57.30	74.70
	Min	1.03	4.33	13.2	29.4
	Ave	3.82[ab]	11.19[ab]	31.99[a]	51.08[ab]
	CV	0.63	0.42	0.33	0.22
Irrigated farming	Max	13.34	44.53	51.70	74.40
	Min	0.82	2.7	7.07	13.45
	Ave	3.93[ab]	11.48[ab]	28.48[ab]	46.35[b]
	CV	0.73	0.70	0.47	0.34

RI 1& S1: rainfall intensity (50 $mm \cdot h^{-1}$) & slope (5%); RI 1& S2: rainfall intensity (50 $mm \cdot h^{-1}$) & slope (15%); RI 2& S1: rainfall intensity (80 $mm \cdot h^{-1}$) & slope (5%); RI 2& S2: rainfall intensity (80 $mm \cdot h^{-1}$) & slope (15%).
Figures followed by similar letters in each column are not significantly different at $p < 0.05$ (LSD).

to a certain degree, h. A choice of h value then influences the widths c_j of the fuzzy parameters.

$$\mathrm{Y(yi)} \geq \mathrm{h} \quad \text{for all} \quad i = 1, 2, \ldots, \mathrm{N}. \tag{5}$$

The index i refers to the number of non-fuzzy data (N) used for constructing the model. Using the expression of the membership function (4), the threshold conditioning inequalities can be rewritten as:

$$(1-h)c^t|x| - \left|y - x^t a\right| \geq 0, \qquad x \neq 0. \tag{6}$$

The conditioning inequalities ensuring satisfaction of the minimum threshold value and simple vagueness criterion are linear with respect to the unknown parameters, i.e., their center points and spreads. With the objective function defined in Eq. (5) and the constraints in Eq. (6), Tanaka et al. (1982) and Tanaka (1987) formulated the problem of finding the fuzzy regression parameters as in the following linear programming problem:

$$\begin{aligned} &\text{Minimize} \quad s = \sum\nolimits_{j=1}^{m} c_j \\ &\text{Subject to} \quad (1-h)\sum\nolimits_{j=1}^{m} c_j \left|x_{ij}\right| + x_i^t a \geq y_i, \\ &(h-1)\sum\nolimits_{j=1}^{m} c_j \left|x_{ij}\right| + x_i^t a \geq y_i, \\ &c \geq 0, \qquad \text{for all} \quad i = 1, 2, \ldots, \mathrm{N}, \end{aligned} \tag{7}$$

where, c and α are vectors of unknown variables and s is the total vagueness as previously defined.

Attention must be drawn at this juncture to the point that α does not show up in the objective function and that only the increase in spreads penalizes the chosen criterion. This can explain why an added input–data point satisfying the threshold membership value of the model identified without that particular point does not cause a change in the model. In other words, the model is sensitive to all new data points satisfying the constraints of the model previously established. This, is turn, underscores the significance of the proper choice of the threshold level, h; too low values of h could make the model very robust but simultaneously not highly specific.

2.8. Evaluation criteria

The index of confidence (IC) and mean square error (MSE) between the measured and the estimated values were used to judge the performance of the different models.

$$\mathrm{IC} = 1 - \frac{\mathrm{SSE}}{\mathrm{SST}} \tag{8}$$

$$\mathrm{SSE} = 2\sum_{i=1}^{m} \left(y_i - \hat{Y}_j^c\right)^2 \tag{9}$$

$$\mathrm{SST} = \sum\nolimits_{i=1}^{m} \left(y_i - \hat{Y}_j^L\right)^2 + \sum\nolimits_{i=1}^{m} \left(\hat{Y}_j^R - y_j\right)^2 \tag{10}$$

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} \left(y_i - \hat{Y}_i\right)^2}{n} \tag{11}$$

Table 7
Performance of different multiple linear regression (MLR) models (1 to 4) in predicting soil splash erosion in landuses.[a]

Parameter	Pasture				Degraded pasture				Dryland farming				Irrigated farming			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Intercept	1.53	1.40	2.83	2.65	1.43	1.60	2.36	2.72	1.32	1.50779	1.62	1.62	1.26	1.40	1.65	1.70
MWD			−0.36				−0.31	−0.22	−0.08	−0.0981	−0.08	−0.06	−0.09	−0.08		−0.08
VCoSand									0.04							
CoSand									−0.03							
VFSand										−0.0084	−0.003					
FSand										0.01766						
Slope																
CoSilt	−0.01												0.004			
F&M Silt																−0.01
PI	−0.00002									−0.0214			−0.00003			
WI	−0.01													0.005		
$CaCO_3$						−0.01										
SSS				−0.04	−0.02										−0.01	
OM	−0.06	−0.06				−0.13									−0.03	
Clay							0.01									
SI		−0.002														
MSE	0.001	0.002	0.010	0.006	0.002	0.002	0.005	0.005	0.003	0.001	0.001	0.001	0.001	0.002	0.001	0.001
IC	0.92	0.67	0.72	0.55	0.59	0.73	0.75	0.64	0.57	0.80	0.53	0.54	0.77	0.66	0.84	0.75

MWD: mean weight diameter; VCoSand: very coarse sand; CoSand: medium and coarse sand; VFSand: very fine sand; FSand: fine sand; CoSilt: coarse silt; SSS: surface shear strength; OM: organic matter; PI: power index; WI: wetness index; SI: sediment index; F & M Silt: fine and medium silt.
[a] 1: splash erosion in %5 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 2: splash erosion in %15 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 3: splash erosion in %5 slope and 80 $mm \cdot h^{-1}$ rainfall intensity; 4: splash erosion in %15 slope and 80 $mm \cdot h^{-1}$ rainfall intensity.

Table 8
Performance of different fuzzy linear regression (FLR) models (1 to 4) in predicting soil splash erosion in landuses.[a]

Parameter	Pasture				Degraded pasture				Dryland farming				Irrigated farming			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Intercept	1.58 (0.167)	1.42 (0.158)	3.20 (0.652)	2.84 (0.370)	1.48 (0.032)	1.63 (−0.141)	2.47 (−0.27)	2.62 (0.551)	1.35 (−0.33)	1.53 (0.153)	1.72 (0.104)	1.66 (0.01)	1.33 (−0.130)	1.27 (0.12)	1.63 (0.20)	1.68 (−0.012)
MWD			−0.50 (−0.125)				−0.29 (0.044)	−0.17 (−0.15)	−0.09 (−0.08)	−0.11 (−0.02)	−0.12 (0.008)	−0.09 (0.045)	−0.12 (0.028)	−0.08 (−0.04)		−0.08 (0.028)
VCoSand									0.03 (−0.04)							
CoSand									−0.03 (0.032)							
VFSand										−0.01 (−0.002)	−0.01 (−0.004)					
FSand										0.02 (−0.012)						
Slope										−0.003 (−0.001)						
CoSilt	−0.01 (0.002)												0.003 (0.009)			
F&M Silt																−0.001 (0.001)
PI	−0.00002 (−0.00001)												−0.00003 (−0.005)			
WI	−0.02 (−0.003)													0.02 (−0.012)		
$CaCO_3$						−0.01 (0.003)										
SSS				−0.05 (−0.009)	−0.03 (0.008)										−0.01 (−0.001)	
OM	−0.06 (−0.034)	−0.06 (−0.006)				−0.15 (0.137)									−0.03 (−0.043)	
Clay							0.01 (0.010)									
SI		−0.003 (0.002)														
h	0.5	0.7	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
S	0.83	2.39	3.87	3.06	1.73	1.58	2.48	2.85	3.46	1.64	2.84	2.60	3.38	5.45	3.40	2.60
MSE	0.001	0.003	0.013	0.007	0.002	0.002	0.006	0.005	0.003	0.001	0.002	0.001	0.002	0.005	0.001	0.001
IC	0.91	0.93	0.89	0.90	0.92	0.91	0.90	0.92	0.91	0.90	0.90	0.91	0.91	0.90	0.94	0.90

MWD: mean weight diameter; VCoSand: very coarse sand; CoSand: medium and coarse sand; VFSand: very fine sand; FSand: fine sand; CoSilt: coarse silt; SSS: surface shear strength; OM: organic matter; PI: power index; WI: wetness index; SI: sediment index; F & M Silt: fine and medium silt. Numbers in the parentheses stand for the width around the center.

[a] 1: splash erosion in %5 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 2: splash erosion in %15 slope and 50 $mm \cdot h^{-1}$ rainfall intensity; 3: splash erosion in %5 slope and 80 $mm \cdot h^{-1}$ rainfall intensity; 4: splash erosion in %15 slope and 80 $mm \cdot h^{-1}$ rainfall intensity.

where, y_i denotes the measured value, $\hat{Y}_i$ is the predicted value, and $\hat{Y}_i^c$ and $\hat{Y}_j^L, \hat{Y}_j^R$ are the predicted values in the center, on the left, and on the right of the fuzzy number, respectively. In addition, the analysis of variance (ANOVA) was performed using SAS (SAS, 1999) to determine whether the differences between FLR and MLR were significant in predicting soil splash erosion.

3. Results and discussion

According to US Soil Taxonomy, the dominant soil textures are clay loam, silty clay, and silty clay loam (Fig. 3). In this area, however, silt loam and sandy clay loam soil classes were also identified, but neither was included in the statistical analysis due to the low number of samples (replications). Distribution of the 74 soils in the land uses followed the order: 13 in pasture, 12 in degraded pastures, 23 in dry land farming, and 26 in irrigated farming (Table 3).

Additional statistical analysis showed that the average values of soil splash erosion were not significantly affected by soil texture class (Table 3). This indicates that the soil splash erosion property mainly varied on the average with land use independently of tested soil textures in the region. As shown in Table 3, soil splash erosion decreased with fineness of the soil texture. This result is in agreement with the findings of Legout et al. (2005). They indicated that the greatest amount of splash was measured with sand, followed by silt loam and clay soils. They also reported that size distribution of splashed fragments depends indirectly on the size distribution of aggregate breakdown products but directly on the size selectivity of movement initiation.

3.1. Soil physical and chemical properties as affected by land use

The results of statistical analysis for the particle size distribution and topographic attributes among the land uses are summarized in Table 4. None of the soil particle fractions including sand (very fine, fine, medium, coarse, very coarse), silt (fine & medium) and clay, except for coarse silt, exhibited any significant differences among the different land use systems investigated (Table 4). Slopes in the area varied in each case between 5.92–16.60, 1.69–12.82, 1.53–30.73, and 1.66–17.06%, respectively, in pasture lands, degraded pasture lands, dry land farms, and irrigated farms. In the same way, the mean values of topographic attributes including wetness, sediment, and power indexes were 10.93, 9.27, 12.72, 12.92; 21.29, 8.38, 6.02, 48.52; 53.6, 90, 100, and 107.93. Unlike the power and sediment index, a low spatial variability was observed in the wetness index in the region.

Table 5 presents the comparisons of the mean values obtained for land use impacts on selected soil physical and chemical properties. As expected, the soils in the Zagros region have a high calcium carbonate ($CaCO_3$) content, with average values varying in each case between 23.61, 15.62, 20.23, and 19.62% in pasture, degraded pasture, dry land farming, and irrigated farming land uses, respectively. Soil organic matter (OM) for the same land uses exhibited mean values of 2.58, 1.60, 1.83, and 1.94%. In the pasture land use, OM recorded a larger value because of its higher vegetation cover density than in the degraded pasture or cultivated land uses. For the same land uses, the mean values of mean weight diameter (MWD) were 2.78, 2.17, 2.34, and 2.38, and those for surface shear strength (SSS) were 14.77, 12.41, 12.29, and 13.82 in this region. The pasture land use significantly affected soil OM; consequently, the high values observed for MWD and SSS were mainly due to the high percentage of shrub vegetation cover and low grazing. In contrast, the low values of OM, MWD, and SSS observed for the degraded pasture soils might have been due to untimely grazing, overgrazing, and shrub burning. The pastures in the region are mainly covered by *Astragalus* sp. and *Bromus* sp. with low grazing, but degraded pastures are covered by *Bromus* sp. almost all of which is consumed by the livestock during intensive grazing. In this situation, no considerable amounts of litter or *Bromus* sp. residues were added to the soils. However, when degraded pastures were converted to cultivated farms, the values of OM, MWD, and SSS significantly increased (Table 5) mainly because the initial average value of OM in the degraded pasture soils was not high and the wheat (dryland farming) and clover (irrigated farming) residues left after the harvest in cultivated farming led to a sudden increase. This finding is in agreement with those of Kelishadi et al. (2014) who reported that not only the reduced tillage by traditional tools but also the greater input of high-quality (with low C/N ratio) residues in cultivated farming more or less preserved the soil OM content in the Zagros region (Kelishadi et al., 2014). Grandy et al. (2002) maintains that structural soil degradation occurs mostly due to reduced soil organic matter caused by excessive soil cultivation.

3.2. Soil splash erosion as affected by land use

The mean values of soil splash erosion (Table 6) varied in each case between 2.15–43.63, 4.29–58.12, 3.82–51.08, and 3.93–46.35 ($g \cdot min^{-1} \cdot m^{-2}$), in pastures, degraded pastures, dry land farms, and irrigated farms, respectively. Under experimental conditions, our results demonstrated that soil splash erosion was very severe in the Zagros region with calcareous soils. Mermut et al. (1997) also found that the splash loss of calcareous loess was higher than gray luvisol.

Compared to lands with a slope of 5%, on those with a slope of 15%, the average value of soil splash erosion for RI 2 (80 $mm \cdot h^{-1}$) and RI 1 (50 $mm \cdot h^{-1}$) varied in each case between 2.06–4.05, 1.58–3.6, 1.59–2.92, and 1.62–2.92 times greater than those obtained for pastures, degraded pastures, dry land farms, and irrigated farms, respectively. The results of this study demonstrated that slope had a significant effect on soil splash erosion, which is consistent with the findings of Fu et al. (2011). They reported that splash erosion components increased with slope gradient but declined after a maximum value was reached. The average value of soil splash erosion (Table 6) for a rainfall intensity of 80 $mm \cdot h^{-1}$ for S2 (%15) and S1(%5) varied in each case between 5–9.83, 3.75–8.52, 4.56–8.37, 4.03–7.24 times greater than those obtained for pastures, dry land farms, and irrigated farms, respectively, with a rainfall intensity of 50 $mm–h^{-1}$.

Land use significantly affected soil splash erosion (Table 6). This indicates that the average values of soil splash erosion mainly varied with land use independently of soil texture in this region. Almost all the coefficients of variation (CVs) for soil splash erosion were greater than 36%, showing a relatively high spatial variability according to Wilding's (1985) categorization (Table 6). The results reported by Wei et al. (2007) indicate that erosion processes are strongly influenced by such plant characteristics as aboveground structure morphology, litter cover, organic matter components, and root network (Gyssels et al., 2005; Wei et al., 2007).

Soil splash erosion was significantly greater in the degraded pasture land uses than those in other land uses investigated. The intermediate values of this parameter belonged to cultivated farms, which was not significantly different from those of pasture land use (Table 6). This trend is interpretable by considering the fact that soil splash erosion is positively related to organic matter, surface shear strength, and mean weight diameter. OM, SSS, and MWD were lower in the degraded pasture soils resulting in higher values of soil splash erosion. The lowest values of soil splash erosion belonged to the pasture land as a result of its high levels of OM, MWD, and SSS (Table 5). The presence of soil organic matter (Van Oost et al., 2007; Kuhn et al., 2009) and chemical fertilizers may have a strong effect on particle bindings (dry compaction) and crust formation, and thereby on increased SSS. Mouzai and Bouhadef (2011) reported that persistent soil compaction caused by farm vehicles during cultivation (soil compacted by tractor wheels) could affect splash and, further, that the degree of dry soil compaction, as an individual property, may reflect soil resistance to splash erosion. They also demonstrated that mechanical soil compaction reduces the number of voids between particles and increases SSS.

The differences in soil splash erosion became greater among the land uses in RI 2 (Table 6). Soil splash erosion of dry land farms was

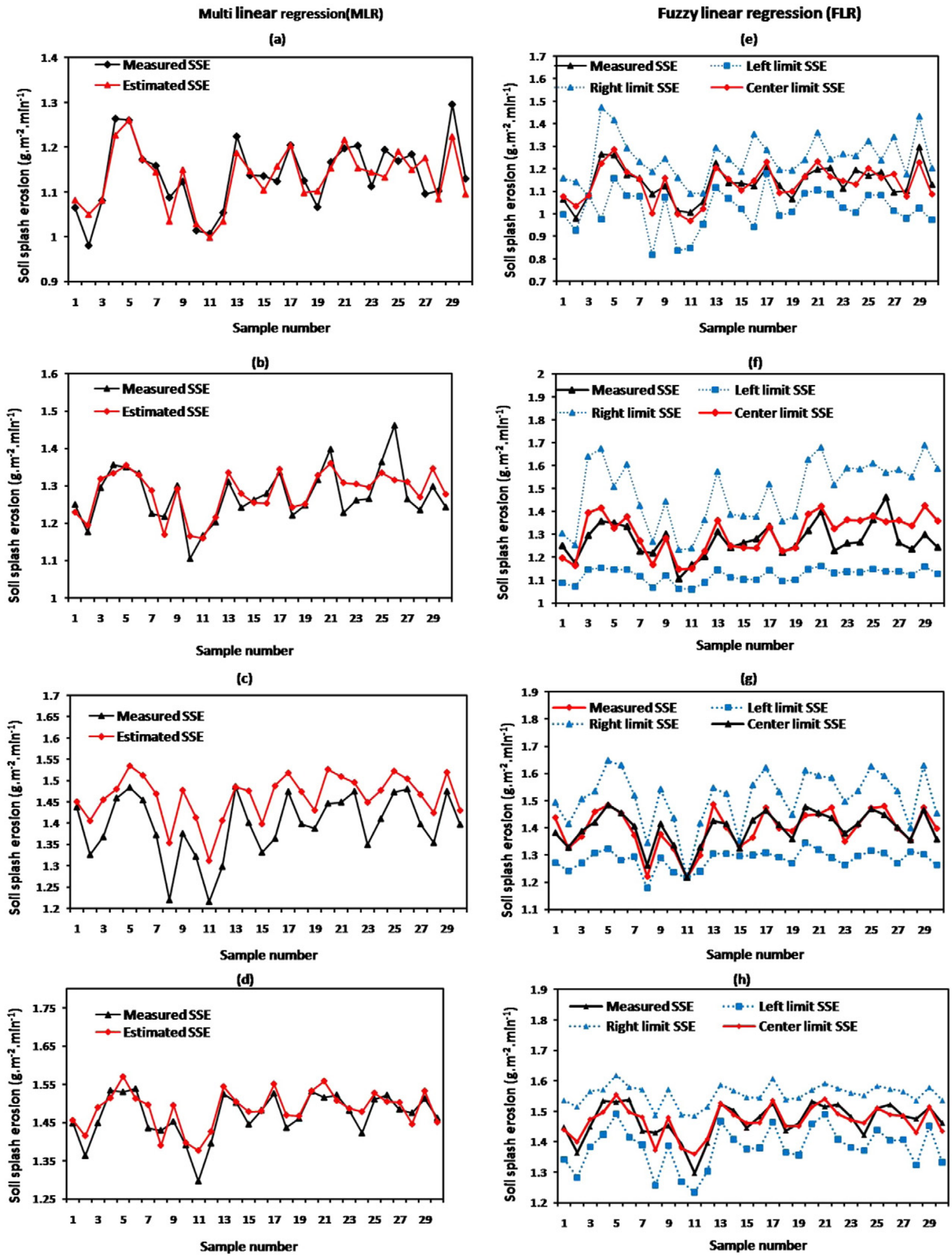

Fig. 4. Comparison of the measured and estimated soil splash erosion (SSE) for four models: Model 1 (splash erosion in %5 slope and 50 mm·h^{-1} rainfall intensity), Model 2 (splash erosion in %15 slope and 50 mm·h^{-1} rainfall intensity), Model 3 (splash erosion in %5 slope and 80 mm·h^{-1} rainfall intensity) and Model 4 (splash erosion in %15 slope and 80 mm·h^{-1} rainfall intensity) in irrigated farming. Multi-linear regression (left) and fuzzy linear regression (right) results are shown.

significantly greater than that of pasture land in R2 S1 (Table 6). The significant difference was, however, observed between degraded pasture land and irrigated farm in R2 S2. This might be due to the differences in surface shear strength among land uses (Table 5). This is consistent with the findings of Agassi and Bradford (1999) who reported that SSS is about the only soil variable that consistently correlates with rainfall detachment and that this parameter should perhaps be included in splash distribution models. Based on our previous study in the Zagros region (Khalilmoghadam et al., 2009), reduced surface soil shear strength in degraded pastures, as compared to pasture lands, might be due to the disruption of soil aggregates and the reduction of organic carbon and root network (resulting from untimely grazing, overgrazing, and shrub burning). Surface shear strength is the key soil mechanical property influencing its splash detachment processes (Nearing and Bradford, 1985; Watson and Lafflen, 1986; Brunori et al., 1989).

3.3. Comparison of fuzzy and multiple linear regressions

Soil splash erosion values estimated by MLR and FLR are presented in Tables 7 and 8, respectively. The MLR models accounted for 55–92, 59–75, 53–80, and 66–84% of the splash erosion variability and resulted in MSE values between 0.006–0.10, 0.002–0.005, 0.001–0.003, and 0.001–0.003 in the pasture land, degraded pasture land, dry farms, and irrigated farms, respectively. Similarly, the FLR models developed for simulating soil splash erosion explained 89–91, 90–92, 90–91, and 90–94% of the soil splash variability in the same land uses (Table 8).

Based on the values of evaluation indices (IC and MSE) presented in Tables 7 and 8, it appears that MLR models had a lower efficiency in predicting soil splash erosion than did the FLR models. In general, FLR outperformed the regression model in predicting soil splash erosion (Fig. 4). The differences between the FLR and the MLR models were statistically significant ($p > 0.01$) such that the latter were not able to predict a large proportion of the total variability in soil splash erosion, presumably because the effects of the predictors on the dependent variables might be vague in nature. Similarly, comparing the fuzzy linear regression pedotransfer functions (PTFs) and the MLR pedotransfer functions, Tran et al. (2002) reported that FLR models generally outperformed regression ones in the development of data sets. Contrary to these findings, Sadatinejad et al. (2009) reported that the FLR method is not a suitable method for reconstructing monthly discharge data in their studied river basin.

The most important soil and topographic parameters, which showed linear relationships between these variables and soil splash erosion, are presented in Table 7. Comparison of the impacts of different soil and topographic attributes on soil splash erosion indicates that MWD and SSS are more suitable than others for monitoring the soil splash erosion behavior. Angulo-Martínez et al. (2012) reported that the best predictor for splashed mass is the MWD. A relationship has also been established between splash detachment and SSS by Cruse and Larson (1977), Al-Durrah and Bradford (1981), Poesen (1981), and Al-Durrah and Bradford (1982a, 1982b). The soil friction angle (Nearing and Bradford, 1985) and the stable aggregate particle size distribution (Torri, 1987; Torri et al., 1987) have also been implicated in this relationship. A polynomial function between the mass weighted average radial distance, as a dependent variable, and SSS, as an independent variable, was found by Mouzai and Bouhadef (2011). They reported that the relationship between detachment rate and SSS representing the degrees of compaction is best described by a second degree polynomial regression.

4. Conclusion

The influence of land use change on soil splash erosion was investigated based on simulated rainfall on disturbed soils using the multi splash set (MSS) under experimental conditions. The findings of this study demonstrated that a considerable amount of soil splash erosion occurred in the study region which is characterized by low OM and vegetation cover. The soil splash erosion in the region was found to be highly variable exhibiting different responses to land use changes depending on the management practices employed, soil properties, topographic attributes, and rainfall characteristics. On average, soil splash erosion was significantly affected in the central Zagros region, Iran, by the land use system (i.e., soil structure and management practices) rather than by the tested soil textures. Soil splash erosion was higher in degraded pasture soils than in the other land uses; this was attributed to the lower soil organic matter content, MWD, and surface shear strength. Low soil organic matter content in the degraded pasture land is probably caused by livestock overgrazing and ultimately grazing. The study also revealed that compared to low slopes, changing land use from pasture to degraded pasture on steep slopes with a high precipitation led to accelerated splash erosion by as much as several times. Pasture land use was found to have the best conditions in terms of soil properties; hence, its superior soil splash erosion control. These effects were argued to stem from the preservation of organic matter by controlled livestock grazing. Finally, the FLR method was found to yield better estimates of soil splash erosion than the MLR method, as the former significantly improved estimation accuracy while it also took account of the uncertainty in the predictions.

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