Article

Assessment of Soil Redistribution Following Land Rehabilitation with an Apple Orchard in Hilly Regions of Central Iran

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Abstract: This study was executed to explore soil redistribution and soil quality changes induced by land degradation and then rehabilitation by orchard plantation in different slope positions in a semi-arid region in central Iran. A total of 72 surface soil samples (0–30 cm) were collected from three land uses (natural rangelands, dryland farming, and apple orchards) in four slope positions (shoulder, backslope, footslope, and toeslope). The soil physicochemical properties and magnetic parameters were measured, and soil redistribution was determined in the selected soil samples using the ¹³⁷Cs technique. The results showed that rangeland degradation and, subsequently, rainfed cultivation, led to a significant decline in the soil quality indicators, such as soil organic matter (SOM), total nitrogen (TN), available potassium (K_{ava}), and available phosphorous (P_{ava}), thus incurring further soil loss, as determined by the ¹³⁷Cs technique. Conversely, the conversion and rehabilitation of drylands to apple orchards cultivated on the contour terraces improved soil quality significantly and decreased soil loss ($p < 0.05$) and soil quality grade ($p < 0.01$). Additionally, the findings indicated that slope positions relative to land use change had a reasonable impact on the variability of soil properties and soil loss and deposition. The results of ¹³⁷Cs analysis showed that the drylands had the highest soil loss (185.3 t ha^{−1} yr^{−1}) and maximum sedimentation (182.5 t ha^{−1} yr^{−1}) in the shoulder and footslope positions, respectively. The random forest model applied between ¹³⁷Cs inventory and soil properties indicated that calcium carbonate equivalent (CCE), TN, P_{ava}, K_{ava}, and bulk density (ρ_b) could explain 75% of the total variability in ¹³⁷Cs inventory with high R² (0.94) and low RMSE (111.29). Magnetic measurements have shown great potential as a cost-effective and fast method for assessing soil redistribution in hilly regions, as confirmed by the findings of the ¹³⁷Cs analysis, which agreed well with the magnetic susceptibility at low frequency (χ_{lf}). Overall, the results confirmed that restoring abandoned dryland by orchard cultivation may improve soil quality and diminish soil loss in the semi-arid region of Iran. However, further research is required to assess other aspects of the ecosystem affected by this restoration.

Keywords: soil rehabilitation; ¹³⁷Cs technique; magnetic susceptibility; random forest; soil quality index

1. Introduction

Population expansion and increasing demand for land resources have placed significant pressure on ecosystems, such as natural rangelands, due to overgrazing in pursuit of more fresh meals. As a consequence, inappropriate cultivation practices such as plowing

along the slope gradient accelerate soil erosion, increase flood risk, and cause natural capital losses [1]. Rangeland degradation significantly reduces soil quality and incurs further soil loss. Several studies confirmed that overgrazing reduces soil quality indicators, including soil organic matter [2–4], soil nutrients [3,5], soil porosity [6], soil infiltration [6], and biomass production [5]. However, it increases bulk density [2,5], runoff, and soil loss [7,8].

Soil erosion is a natural incident that affects all landforms, especially undulating landscapes and hilly regions [9,10], which could impose enormous pressures on natural and agricultural ecosystems [11]. Slope steepness has a vital role in the degree of degradation or restoration of soil properties following rangeland degradation and soil erosion [2]. The hillslope positions have contributed significantly to the soil detachment variability at the landscape scale [12]. Therefore, knowledge about soil redistribution in the landscape is crucial for landowners and decision makers to choose the most proper management practices [13].

Numerous approaches have been developed to evaluate the quantity of soil loss or deposition at the landscape scale. The most important approaches for estimating soil loss/deposition are classified into various categories: direct measures, physical-based models, empirical models, conceptual models/hybrid models [14–16], and isotopic radionuclide models [17–19]. Isotopic techniques based on the use of fallout radionuclides such as Caesium-137 (^{137}Cs) have already been used successfully to estimate soil loss and deposition, especially over a mid-term period [18,20–22]. Zapata [23] and Lacoste et al. [24] showed that the ^{137}Cs can be a helpful approach to use tracing soil redistribution and erosion in different regions. Moreover, the ^{137}Cs inventory demonstrated a high correlation with soil properties and field measurement [12,24]. However, since the radionuclide method is costly and labor-consuming, new methods, such as magnetic susceptibility, have attracted the attention of researchers [9,25,26].

In recent decades, a significant portion of natural rangelands in central Iran, including the southern Isfahan province, has suffered from overgrazing and undergone dryland farming [2,27]. Changes of natural rangeland to dryland farming have led to several threats, such as severe soil erosion, calamitous floods accompanied by destructive consequences, and a decrease in the region's biodiversity. In some degraded areas and drylands, rehabilitation by apple orchards is being applied as an alternative land use. Some investigations have been conducted to determine the effects of rehabilitation of degraded lands on improving the ecosystem quality [28–31]. For instance, studying the rehabilitation of the degraded pasture in Minas Gerais, Brazil, by a secondary forest, Schiavon Lopes et al. [6] showed that the afforestation of the degraded land led to higher soil–water infiltration, larger macroporosity, and greater carbon storage compared to the pasture areas. To assess the impacts of land use conversion on soil quality indicators, soil quality indices (SQIs) are a widely used and simple method of quantifying soil quality [32–34]. The SQI assessment may help increase our knowledge of soil ecosystems and enable more effective management.

So far, few investigations have been conducted on the effects of the rehabilitation by orchards in arid and semi-arid regions. Knowledge about the effects of the land use change, especially orchard cultivation, on soil quality and soil redistribution in steep slopes is required for more efficient land use management. Therefore, the major objectives of this study were to (i) explore the effects of the land use change and the orchard cultivation on some soil quality parameters and magnetic properties in different slope positions, (ii) evaluate soil redistribution following the land use change using the ^{137}Cs technique, and (iii) examine relationships between soil quality properties and quantity of soil redistribution and erosion measured by ^{137}Cs in the semi-arid region in the south of Isfahan province, central Iran.

2. Materials and Methods

2.1. Description of the Study Area

The study area is located in central Iran in the southern part of Isfahan province, between $31^{\circ}25'$ and $31^{\circ}26'$ N latitudes, and between $51^{\circ}34'$ and $51^{\circ}35'$ E longitudes (Figure 1).

The average elevation of the studied site is 2400 m a.s.l. The mean annual precipitation and the mean annual temperature are 400 mm and 15.6 °C, respectively. The soil moisture and temperature regimes of the study area are Xeric and Mesic, respectively. Moreover, soils are classified as Typic Calcixerepts and Typic Xerorthents, according to Soil Survey Staff [35]. The studied hills have similar parent materials, including dissected, quaternary alluvial deposits for three land uses (i.e., natural rangeland, dryland farming, and apple orchards). Specifically, the major geological formation units in the study area consist of limestone, dolomite, marl, conglomerate, and silt- and sand- stone (Figure 1c).

Figure 1. Location of the study area. (a) Isfahan province among all the provinces in Iran, (b) location of the study area in the Semirom district, (c) geology map and the geological formations in the region, and (d) location of three land uses in the study area.

In the study area, the erosive evidence, including rill, sheet erosions, and the appearance of lime spots (carbonate calcium parent materials) in some places on the surface has been observed. As the study areas are a local site and cannot be illustrated by satellite images with high resolutions (for example, Landsat imagery 30 m × 30 m), there is no historical satellite imagery in the region. Thus, based on the personal correspondence with local residents and farmers, the rangelands were converted to dryland farming 50 years ago, and the apple orchard cultivation has reclaimed the abandoned drylands (or low-income drylands) in the last 20 years. Native vegetation in the rangelands predominantly comprises *Astragalus verus*, *Bromus tomentellus*, *Elymus gentry*, *Cousinia cylindracea*, and *Daphne mucronata*. Dryland farming is predominantly undertaken for barley and wheat production. Apple orchards (*Malus pumila*) are grown on the contour terraces (Banquet) upon application of traditional manure and administration of cultivation practices.

2.2. Soil Sampling

At three hillslopes corresponding to three land uses, four slope positions, namely shoulder, backslope, footslope, and toeslope, were identified (Figure 1c). The selected hillslopes were located at the southern aspect (see Figure 1), with similar slope gradients around 15–20%. Six soil samples were randomly collected from each slope position at a 0–30 cm depth. In order to demonstrate the soil sample distribution on the map, a three-dimensional representation of the sampling method is shown in Figure 2 as a typical

three-dimensional pattern. In total, 24 soil samples were collected from each land use. Thus, a total of 72 soil samples were sampled across the studied hillslopes. For the evaluation of soil loss/deposition using ^{137}Cs , a reference site was selected on flat slopes near the sites where the undisturbed rangelands were located, and the soil samples were collected from the depth intervals of 0–5, 5–10, 10–15, 15–20, 20–25, and 25–30 cm in the 20 m $\times$ 20 m area. All soil samples were air-dried, passed through a 2 mm sieve, and prepared for laboratory analyses.

Figure 2. Three-dimensional pattern of sampling scheme in the study area in different hillslope positions.

2.3. Laboratory Analyses

Particle size distribution, soil bulk density (ρ_b), soil organic matter (SOM) content, and calcium carbonate equivalent (CCE) were determined by the Bouyoucos hydrometer method [36], the core method, the Walkley and Black method [37], and Bernard's calcimetric method [38], respectively. Electrical conductivity (EC) and pH were measured in the soil/water extract ratio of 1:2.5. Total nitrogen (TN) was measured by the Kjeldahl method [39]. Available phosphorus (P_{ava}) and available potassium (K_{ava}) were measured by the methods proposed by Carter and Gregorich [40]. For magnetic measurements, after crushing, the Bartington MS2 dual-frequency sensor was used to measure soil magnetic susceptibility (χ) at low (0.47 kHz; χ_{lf}) and high frequencies (4.7 kHz, χ_{hf}) in all samples using approximately 20 g of soil held in a clear plastic vial (2.3 cm in diameter) [41]. The dependent frequency (χ_{fd}) was calculated using the following equation:

$$\chi_{\text{fd}} = \frac{(\chi_{\text{lf}} - \chi_{\text{hf}})}{\chi_{\text{lf}}} \times 100 \quad (1)$$

The ^{137}Cs inventory was measured in the samples after preparation. Accordingly, 500 g of the dried and sieved soils were placed in the Marinelli beakers and sealed for ^{137}Cs analyses. Gamma spectroscopy with a high-resolution germanium detector was used to measure the ^{137}Cs activity (Bq kg^{-1}) from the net area of a full-energy peak at 662 keV (ISO, 11929-1, 2000) in the Department of Physics, Isfahan University of Iran, during 2018–2019. The quality of the measurements was monitored using a reference material, no: IAEA-375, from the International Atomic Energy Agency (IAEA). The count time was nearly 150 min, and the counting error was preserved at the level of 10% and 95% confidence. The ^{137}Cs activities (Bq kg^{-1}) were turned to the area activities (Bq m^{-2}).

2.4. Soil Redistribution Assessment

Soil redistribution rate ($\text{t ha}^{-1} \text{ yr}^{-1}$) was assessed by the ^{137}Cs inventory at any location and compared with the reference site using the simplified mass balance model (SMBM) [42]. According to the SMBM, Equation (2) could be used for the eroded locations:

$$Y = 10\rho_b \times d / P \left(1 - \frac{X}{100} \right)^{\frac{1}{t-1963}} \quad (2)$$

$$X = \frac{^{137}\text{Cs}_{\text{reference site}} - ^{137}\text{Cs}_{\text{given point}}}{^{137}\text{Cs}_{\text{reference site}}} \times 100 \quad (3)$$

where Y = mean annual soil loss ($t \text{ ha}^{-1} \text{ yr}^{-1}$), ρ_b = bulk density (kg m^{-3}), d = depth of plow or cultivation layer (m), X = percent of loss or excess of ^{137}Cs inventory, and P = correction factor for particle size distribution.

The rate of soil deposition at the depositional sites (R'), where the ^{137}Cs inventory is higher than the reference site, was calculated by the following equation:

$$R' = \frac{A_{ex}(t)}{\int_{1963}^t C_d(t') e^{-\lambda(t-t')} dt'} = \frac{A(t) - A_{ref}}{\int_{1963}^t C_d(t') e^{-\lambda(t-t')} dt'} \quad (4)$$

where $A_{ex}(t)$ is the extra ^{137}Cs inventory in the sampling over the reference inventory in the year t' (defined as the inventory determined to be lower than the local reference inventory based on Bq m^{-2}), $C_d(t)$ is the ^{137}Cs concentration of the deposited sediment in the year t' based on Bq kg^{-1} , and λ is the constant of ^{137}Cs decay (yr^{-1}).

2.5. Soil Quality Index (SQI) Assessment

In this study, several soil properties (i.e., EC, pH, CCE, SOM, TN, P_{ava} , K_{ava} , and ρ_b) were considered as indicators of SQI assessment. The selected soil properties define soil health, productivity, fertility, soil degradation, and soil and water interaction.

The linear scoring method was used to transform soil properties into a dimensionless score (between 0.1 and 1) using the following functions: 'more is better' for soil properties including SOM, TN, P_{ava} , K_{ava} ; 'less is better' for CCE, ρ_b , and optimal range for pH and EC [33,34] (Table S1). The optimal values $0.2\text{--}2 \text{ dS m}^{-1}$ and 7 were used for EC and pH, respectively [32].

The Nemoro SQI (SQI_n) equation [30,31] is defined as the following equation:

$$SQI_n = \sqrt{\frac{P_{ave}^2 + P_{min}^2}{2}} \times \frac{n-1}{n} \quad (5)$$

where P_{ave} , P_{min} , and n are the average value, the minimum value for the scores attained for each sampling point, and the number of indicators, respectively. The SQI was divided into five categories, namely, very high (I), high (II), moderate (III), low (IV), and very low (V).

2.6. Statistical Analysis and Modeling

Descriptive statistics, including minimum, maximum, standard deviation, coefficient of variation (CV), and skewness, were determined by SPSS v. 19.0 (SPSS Inc. Chicago, IL, USA). The correlations between the studied variables were also computed using SPSS 19.0 [43]. A linear and non-linear relationship between ^{137}Cs and magnetic susceptibility (χ_{lf}) was constructed to understand better the relationship between χ_{lf} and the rate of soil loss/deposition. Additionally, a random forest model was used to predict the ^{137}Cs inventory as the dependent variable, with magnetic susceptibility and soil physicochemical properties as independent variables. Two user-defined parameters in the random forest model, namely, the number of trees in the forest (n_{tree}) and the number of environmental covariates in each random subset (m_{try}), were optimized based on the out-of-bag error [44]. The importance of the independent variables in the random forest was calculated based on the variable importance [45]. The ^{137}Cs inventory modeling performance was evaluated using ten-fold cross-validation with ten repetitions by the coefficient of determination (R^2), mean absolute error (MAE), and the root mean square error (RMSE). The random forest model was conducted in the R3.3.1 program using the 'caret' package [46].

A random block design was applied for the statistical analysis, and the data were examined using analysis of variance (ANOVA). The mean comparison was performed using the LSD method at the probability level of $p < 0.05$. All graphs were plotted in the Excel program (v. 2013).

3. Results and Discussion

3.1. Descriptive Statistics

The results of the descriptive analysis for the studied properties, including soil physicochemical properties, magnetic susceptibility, and ^{137}Cs inventory, are presented in Table 1. According to the results of the Kolmogorov–Smirnov test, all studied variables were normally distributed in three land uses (Table 1). The skewness values presented in Table 1 also confirmed the normal distribution of the variables (varied from -1.11 to $+1.10$). The coefficient of variation (CV) was used as the criterion to define the variability in the studied soil parameters in each land use. The results showed that, among the soil variables, TN values showed the highest CV values of 39.67, 64.10, and 38.14% for the rangelands, drylands, and apple orchards, respectively.

3.2. Soil Loss and Deposition Rates

The ^{137}Cs technique was used to assess soil loss and soil deposition (soil redistribution) in this study. The content of ^{137}Cs significantly differed among the land uses in four slope positions (Figure 5). The figure shows that the lowest and highest values for ^{137}Cs were observed in dryland farming land use's shoulder and toeslope positions (Figure 5a). The inventory of ^{137}Cs in the reference site, near the selected sites, was 2552 Bq m^{-2} . In western Iran, in the landscapes with comparable elevation, climate, and latitude, Afshar et al. [20] and Ayoubi et al. [47] reported ^{137}Cs equal to 2107 and 2130 Bq m^{-2} for the reference sites. By applying ^{137}Cs in the reference site and the ^{137}Cs loss in each location, soil loss/deposition was calculated using Equations (2) and (4). The soil loss/deposition results for three land uses in different slope positions are given in Figure 5b. The net soil loss occurred in the following order in the shoulder position: dryland > apple orchard > rangeland. The highest soil loss ($185.3 \text{ t ha}^{-1} \text{ yr}^{-1}$) in the shoulder position of dryland indicated the effects of tillage by the local farmers, especially in the direction of the slope gradient. Similarly, Rahimi et al. [21] demonstrated soil loss of $110 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the shoulder position after pasture degradation and intensive cultivation in the Fereydunshahr district in western Iran. Applying the simplified mass balance model (SMBM), Theocharopoulos et al. [78] reported the highest value for soil loss of $168.19 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the steep slope of the cultivated area in central Greece.

Similarly, Karchengani et al. [58] and Khormali et al. [48] reported higher CCE content after deforestation and clear-cutting of forests in Lordegan district, west of Iran, and northern Iran, respectively. The highest value of CCE content was observed in the apple orchards. Although lower CCE was expected in the orchards due to lower soil erosion, higher CCE in this land use might be attributed to deep tillage for tree cultivation (Figure 3a).

Figure 3b shows the variability of soil phosphorus (P_{ava}) in surface soils in three land uses and four slope positions. The highest P_{ava} values were observed in the apple orchards, which may be attributed to reducing soil loss and more fertilization by farmers. Moreover, the highest content was observed in the toeslope position, which was presumably ascribed to the transformation of phosphorus accompanied by the fine particles transported from higher to lower positions by runoff. The lowest phosphorous in the drylands confirmed the process of soil erosion and the depletion of the soil surface from the soil nutrients. Similar results were obtained for values of K_{ava} (Figure 3c) and TN (Figure 3d). Several studies confirmed that the reclamation of bare lands significantly affected the status of soil nutrients [31,59], which could be related to various factors, such as the rate of fertilization, the kinds of applied fertilizers, the modes of plant configuration, the tillage practices, and the kind of land use after reclamation in particular [31,60,61]. Additionally, the reclamation age is another important factor regulating soil nutrients [31]. In our study area, the reclamation by the orchards in contour terraces (Banquet), accompanied by relatively high fertilization employed by NPK fertilizers, made a significant contribution to the total amounts of nitrogen, phosphorous, and potassium (Figure 3).

Table 1. Descriptive statistics of studied variables in three selected land uses.

Variable (Unit)		Rangeland (n = 24)					Dryland Farming (n = 24)					Apple orchard (n = 24)					
		Min	Max	Mean	CV (%)	Skew	Min	Max	Mean	CV (%)	Skew	Min	Max	Mean	CV (%)	Skew	KS
Radionuclide property	^{137}CS (Bqm $^{-2}$)	1026	1782	1411.50	19.76	−0.06	509	2099.60	1166.80	26.61	0.51	619.50	1417.50	1000.8	24.61	0.12	0.14
Soil chemical properties	P _{ava} (mg kg $^{-1}$)	30.61	48.91	35.82	17.54	1.10	19.18	42.67	32.16	28.19	−0.15	45.27	83.24	65.43	18.10	0.02	0.12
	K _{ava} (mg kg $^{-1}$)	294.66	667.59	445.65	26.72	0.35	240.60	532.06	362.18	26.97	0.53	294.66	548.29	407.25	21.07	0.30	0.10
	EC (dS m $^{-1}$)	1.09	1.40	1.27	5.97	−0.56	1.02	1.50	1.19	13.26	0.63	0.98	1.33	1.15	10.34	0.26	0.19
	pH (−log[H $^{+}$])	7.60	7.80	7.70	0.81	0.13	7.60	7.74	7.64	0.67	0.71	7.50	7.71	7.60	1.16	0.01	0.20
	CCE (%)	17.50	35.50	27.99	20.13	−0.51	18	40.50	30.88	24.40	−0.43	23.50	45	35.39	21.45	−0.40	0.22
	SOM (%)	1.09	2.35	1.55	24	0.79	1.03	2.18	1.55	21.43	0.44	1.47	2.29	1.83	12.22	0.35	0.19
	TN (%)	0.09	0.30	0.20	39.67	0.02	0.05	0.30	0.16	64.10	0.37	0.12	0.40	0.28	38.14	−0.10	0.21
Soil physical properties	ρb (g cm $^{-3}$)	1.04	1.80	1.45	16.98	−0.19	1.20	1.88	1.60	14.39	−0.49	1.16	1.89	1.50	16.18	0.05	0.17
	Sand (%)	20.30	37.20	32.14	13.61	−1.11	19.22	37.90	26.46	21.97	0.51	18.54	36.88	28.83	17.18	0.42	0.10
	Clay (%)	42.25	66.65	53.20	13.99	0.60	40.38	58.04	46.65	9.20	0.57	38.46	59.50	46.72	10.35	0.93	0.11
	Silt (%)	10.66	27.18	17.45	26.30	0.81	9.14	38.48	26.89	28.73	−0.49	13.20	33.94	24.45	21.44	0.0041	0.10
Magnetic properties	χ _{lf} (10 $^{-8}$ m 3 kg $^{-1}$)	20.0	30.0	24.68	14.15	0.22	24.0	29.0	26.75	6.06	−0.34	22.0	29.50	26.69	6.62	−0.62	0.14
	χ _{hf} (10 $^{-8}$ m 3 kg $^{-1}$)	19.0	29.0	23.63	14.49	0.20	23.0	28.0	25.63	6.39	−0.17	20.0	28.0	25.33	7.05	−0.79	0.12

^{137}Cs : Caesium inventory; P_{ava}: available phosphorous; K_{ava}: available potassium; EC: Electrical conductivity; CCE: Calcium carbonate equivalent; TN: Total nitrogen; ρb: bulk density; χ_{lf}: magnetic susceptibility at low frequency; χ_{hf}: magnetic susceptibility at high frequency; Skew: Skewness. KS: Kolmogorov–Smirnov criteria.

Figure 3. Variability of some soil properties at a 0–30 cm depth in various land uses at four slope positions in the study area: (a) CCE (calcium carbonate equivalent), TN: total nitrogen; (b) P_{ava} (available phosphorus); (c) K_{ava} (available phosphorus), (d) TN (total nitrogen); (e) SOM (soil organic matter); (f) ρ_b (bulk density). Means ($n = 24$) with the same letter are significantly different using the least significant difference (LSD) test at $p < 0.01$.

The variability in SOM contents for the various land uses in four different slope positions is given in Figure 3e. The mean values for SOM among the land uses were 1.83, 1.55, and 1.55% for the apple orchards, rangelands, and dryland farming, respectively (Table 1, Figure 3). Both pasture degradation and conversion to dryland farming [62] decreased SOM contents (Figure 3). Following the change in the land use from the rangelands to the cultivated lands, the SOM values decreased to 20.4, 3.02, 3.05, and 2.01% in the shoulder, backslope, footslope, and toeslope positions, respectively (Figure 3). Ayoubi et al. [2], Li et al. [63], and Mohammed et al. [64] reported a decrease in the SOM values following grassland conversion to cultivated lands in the rangelands of western Iran and the pastures of Mongolia, respectively. Several studies indicated that cultivation can significantly reduce the SOC pools by breaking large aggregates into smaller aggregates and exposing SOM to oxidation processes and microbial decomposition [34,65–68].

The restoration of drylands by orchards increased SOM, particularly in the shoulder, backslope, and footslope positions (Figure 3e). The orchards' rehabilitation of degraded soils increased SOM values even higher than those of initial rangelands, which may be

due to the slow decomposition rate of orchard wood litters than grasslands and the nearby farmers' manure application (Figure 3e). Several scholars reported an increase in the SOM pools after recovering the degraded lands because of the decomposition of plants (especially perennials), animal bodies, and microorganisms [28,31]. Following the trend in SOM variability from shoulder to toeslope positions, the SOM values were the lowest and the highest in the shoulder and toeslope positions, respectively, in all land uses. Several investigations on the variability of SOM values in different slope positions indicated that the highest SOM values in the lower slope positions were due to soil redistribution and massive transportation of materials along the hillslopes [48,58].

The variations of bulk density (ρ_b) along the slope position in three land uses are given in Figure 3f. As Figure 3f shows, the land use conversion significantly influenced the bulk density. The highest ρ_b was observed in the drylands cultivated with the soils having a high rate of plowing and lower SOM values, which was consistent with the findings of other studies [65,69].

The comparison of the means and SQI assessment in different land uses and slope positions are shown in Tables 2 and 3, respectively. The results indicate that the mean values of SQIs among different land uses and slope positions showed significant differences ($p < 0.01$) (Table 3). Among different land uses, we found the highest and lowest SQIs in the apple orchard and dryland farming land uses, respectively (Table 3), which can directly be due to the higher values of SOM, P_{ava} , and TN (Figure 3). Apple orchard land use showed a high soil quality grade, whereas dryland farming and rangeland land uses had a moderate soil quality grade (Tables 2 and 3). Numerous research has shown that land use modification significantly affects soil qualities [2,27,33,34,48,67]. Moreover, the highest SQIs were found in the toeslope positions among different land uses (Table 3). In the rehabilitation of the degraded soils with apple orchards in footslope and toeslope positions, the SQIs showed a very high soil quality grade, mainly due to receiving the soil depositions with a high amount of SOM, P_{ava} , K_{ava} , and TN as positive soil indicators and less of the negative soil indicator (CCE) in the SQI assessment (Table 3 and Figure 3).

Table 2. Soil quality grade classification for indices and indicator methods.

Index	Indicator Method	SSF	Soil Quality Grades				
			I (Very High)	II (High)	III (Moderate)	IV (Low)	V (Very Low)
SQI_n	TDS	Linear	>0.459	0.400–0.459	0.341–0.400	0.281–0.341	<0.281

SQI_n : Nemoro soil quality index, SSF: standard scoring functions.

3.3. Variability in Magnetic Susceptibility

Figure 4a indicates the changes in magnetic susceptibility among the land uses in different slope positions. The lowest magnetic susceptibility was observed in the shoulder position in apple orchards, whereas the highest was found on the toeslope in apple orchards and dryland farming (Figure 4a). Several mechanisms have been suggested for enhancing the magnetic susceptibility of surface soils. The major sources include soil pedogenesis [70], inherited from the parent material [2], industrial and urbanization activities [71], and biogeochemical processes induced by petroleum hydrocarbon pollution [72,73]. As this study was carried out far away from pollution sources and all parent materials were limestones with low magnetic susceptibility, any increase in χ_{lf} was related to the pedogenic processes [74]. Furthermore, the high positive significant relationship between χ_{fd} and χ_{lf} ($r = 0.70$, $p < 0.01$; Figure 4b) confirmed that the magnetic susceptibility was increased by the pedogenic processes, including an increase in the super-paramagnetic particles and neoformation minerals (e.g., illite and chlorite clay minerals and goethite) [75]. Followed by the pedogenic formation of ferrimagnetic minerals, their distribution along the landscape was highly dependent on soil redistribution and mechanical processes. The higher χ_{lf} in the lower position was related to soil deposition, and the lower χ_{lf} in the upper position was related to soil loss (Figure 4a). During soil erosion processes, the fine materials associated with magnetic minerals were transferred from upper positions (i.e., shoulder) to lower

positions (i.e., toeslope) [25,58,76]. Lower magnetic susceptibility in the shoulder position of the apple orchards compared to drylands was unusual (Figure 4a), despite having lower soil loss in the apple orchards. It seems that lower magnetic susceptibility in the apple orchards in the shoulder position may be related to higher CCE as a diamagnetic mineral reducing magnetic susceptibility due to less soil erosion (Figures 3a and 4a) [77].

3.4. Soil Loss and Deposition Rates

The ^{137}Cs technique was used to assess soil loss and soil deposition (soil redistribution) in this study. The content of ^{137}Cs significantly differed among the land uses in four slope positions (Figure 5). The figure shows that the lowest and highest values for ^{137}Cs were observed in dryland farming land use's shoulder and toeslope positions (Figure 5a). The inventory of ^{137}Cs in the reference site, near the selected sites, was 2552 Bq m^{-2} . In western Iran, in the landscapes with comparable elevation, climate, and latitude, Afshar et al. [20] and Ayoubi et al. [47] reported ^{137}Cs equal to 2107 and 2130 Bq m^{-2} for the reference sites. By applying ^{137}Cs in the reference site and the ^{137}Cs loss in each location, soil loss/deposition was calculated using Equations (2) and (4). The soil loss/deposition results for three land uses in different slope positions are given in Figure 5b. The net soil loss occurred in the following order in the shoulder position: dryland > apple orchard > rangeland. The highest soil loss ($185.3 \text{ t ha}^{-1} \text{ yr}^{-1}$) in the shoulder position of dryland indicated the effects of tillage by the local farmers, especially in the direction of the slope gradient. Similarly, Rahimi et al. [21] demonstrated soil loss of $110 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the shoulder position after pasture degradation and intensive cultivation in the Fereydunshahr district in western Iran. Applying the simplified mass balance model (SMBM), Theocharopoulos et al. [78] reported the highest value for soil loss of $168.19 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the steep slope of the cultivated area in central Greece.

Table 3. Comparison of the mean values of soil quality indices in different land uses and slope positions.

Land Use		Rangeland (<i>n</i> = 24)				Dryland Farming (<i>n</i> = 24)				Apple Orchard (<i>n</i> = 24)				Pr > F
		0.372 b				0.336 b				0.429 a				0.0002 *
SQI _n	Shoulder	backslope	footslope	toeslope	Shoulder	backslope	footslope	toeslope	Shoulder	backslope	footslope	toeslope		
	0.306 ^c	0.326 ^c	0.399 ^b	0.458 ^a	0.267 ^c	0.276 ^c	0.369 ^b	0.432 ^a	0.345 ^b	0.372 ^b	0.499 ^a	0.498 ^a	0.0001 *	

* Significant at the 0.01. Means (*n* = 24) with the same letter are significantly different using the least significant difference (LSD) test at *p* < 0.01. SQI_n: Nemoro soil quality index.

a

b

Figure 4. Variability in magnetic susceptibility (χ_{lf}) at three land uses in four slope positions (**a**), the relationship between χ_{lf} and χ_{fd} for all studied soil samples (**b**). Means with the same letter are significantly different using the least significant difference (LSD) test at $p < 0.01$.

Figure 5. Variability in magnetic susceptibility (χ_{lf}) at three land uses in four slope positions, means with the same letter are significantly different using the least significant difference (LSD) test at $p < 0.01$ (a,b) the relationship between χ_{lf} and χ_{fd} for all studied soil samples.

3.5. Correlation Analysis and Modeling

The results of the correlation analysis among the studied variables, as the indicators of soil redistribution along the hillslopes, are presented in Table 4. According to the results, ^{137}Cs was significantly correlated with SOM ($0.87, p < 0.01$), K_{ava} ($0.85, p < 0.01$), TN ($0.95, p < 0.05$), P_{ava} ($0.89, p < 0.01$), ρ_b ($0.99, p < 0.05$), χ_{lf} ($0.47, p < 0.01$), and χ_{hf} ($0.52, p < 0.05$) (Table 4).

Table 4. Correlation coefficients among the soil properties in the studied sites at different land uses.

Variable	¹³⁷ Cs	SOM	K _{ava}	CCE	TN	ρ _b	P _{ava}	χ _{lf}
Apple orchard (n = 24)								
¹³⁷ Cs	1							
SOM	0.87 **	1						
K _{ava}	0.85 **	0.66 **	1					
CCE	−0.95 **	−0.87 **	−0.74 **	1				
TN	0.95 **	0.77 **	−0.83 **	−0.87 **	1			
ρ _b	0.99 **	0.86 **	0.91 **	−0.93 **	0.95 **	1		
P _{ava}	0.89 **	0.84 **	0.84 **	−0.94 **	0.94 **	0.98 **	1	*
χ _{lf}	0.42 **	0.26	0.84 **	−0.41 *	0.53 **	0.47 **	0.55 **	1
Dryland farming (n = 24)								
¹³⁷ Cs	1							
SOM	0.83 **	1						
K _{ava}	0.96 **	0.89 **	1					
CCE	−0.98 **	−0.85 **	−0.97 **	1				
TN	0.91 **	0.79 **	0.93 **	−0.93 **	1			
ρ _b	0.90 **	0.64 **	0.83 **	−0.90 **	0.83 **	1		
P _{ava}	0.93 **	0.71 **	0.90 **	−0.94 **	0.93 **	0.97 **	1	
χ _{lf}	0.47 *	0.39	0.44 *	−0.45 *	0.27	−0.43 *	0.33	1
Rangeland (n = 24)								
¹³⁷ Cs	1							
SOM	0.80 **	1						
K _{ava}	0.94 **	0.90 **	1					
CCE	−0.84 **	−0.87 **	−0.92 **	1				
TN	0.96 **	0.82 **	0.96 **	−0.85 **	1			
ρ _b	0.99 **	0.78 **	0.93 **	−0.83 **	0.96 **	1		
P _{ava}	0.82 **	0.84 **	0.88 **	−0.92 **	0.84 **	0.81 **	1	
χ _{lf}	0.42 *	0.3	0.34	0.37	0.35	0.38	0.44 *	1

*, **, Significant at 95 and 99% probability level. ¹³⁷Cs: Caesium inventory; SOM: Soil organic matter; K_{ava}: available potassium; P_{ava}: available phosphorous; CCE: calcium carbonate equivalent; TN: total nitrogen; ρ_b: bulk density; χ_{lf}: magnetic susceptibility at low frequency; χ_{hf}: magnetic susceptibility at high frequency.

The variability in the soil nutrients (K_{ava}, P_{ava}, and TN) was highly related to SOM, as shown in Table 4. The high and positive correlations found between SOM and these nutrients confirmed their connection. In the shoulder position with a high rate of soil erosion and lower ¹³⁷Cs (Figure 5), SOM was associated with nutrients detached and transported to the lower position (Figure 3e). Studying the forest soils in Germany, Fujiyoshi and Sawamura [82] reported a significant relationship between potassium and ¹³⁷Cs inventory ($r = 0.90$). The positive and significant relationship observed between ¹³⁷Cs and ρ_b confirmed that intensive cultivation practices were followed in the lower position, leading to the accumulation of more materials and ¹³⁷Cs. Moreover, ¹³⁷Cs inventory showed a negative correlation with CCE, indicating that a lower inventory of ¹³⁷Cs was excited in the steep slopes with the high content of CCE (Table 4). Overall, significant relationships between ¹³⁷Cs inventory and soil properties confirmed that erosional and hydrological processes can regulate soil variability in the hilly regions of the study area [18]. These findings were consistent with the results of Karchegnai et al. [18,21,47,80,83].

Relatively high and positive correlations were obtained between magnetic measures (χ_{lf}) and ¹³⁷Cs inventories in three land uses (Table 4). Magnetic susceptibility was previously utilized as a soil redistribution tracer [47]. Ferrimagnetic minerals, such as maghemite and magnetite, are associated with fine materials (i.e., clay particles); they have translocated from upper slopes to lower slopes through soil redistribution, leading to an increase in soil magnetic susceptibility in lower positions [9,21,76,84]. The non-linear relationship between ¹³⁷Cs and χ_{lf} was studied to understand better the relationship between χ_{lf} and the rate of soil loss/deposition. The results of this analysis for three land uses are shown in

Figure 6. As can be seen, non-linear correlations between ^{137}Cs and magnetic susceptibility were significantly higher than linear correlations. Similarly, in the Fereydunshahr district, Rahimi et al. [21] showed that non-linear relationships could explain 74% and 76% of the variability in ^{137}Cs in the pasture and cultivated soils, respectively. In Chelgerd district, Charmahal and Bakhtiari province, west of Iran, Ayoubi et al. [47] found $R^2 = 0.45$ for the non-linear relationships between ^{137}Cs and magnetic susceptibility.

Figure 6. Non-linear relationships between χ_{lf} and ^{137}Cs inventory in three land uses: (a) apple orchard; (b) dryland; (c) rangeland.

The ^{137}Cs inventory content was predicted using the random forest and soil properties to explore the contribution of the studied soil properties to explaining the variability in ^{137}Cs in the study area. The validation criteria and variable importance for predicting ^{137}Cs inventory by random forest model are shown in Table 5 and Figure 7, respectively. The best prediction accuracy (RMSE = 111.29 and $R^2 = 0.46$) for predicting ^{137}Cs inventory was achieved for the number of environmental covariates in each random subset (mtry = 13) and the number of trees in the forest (ntree = 500) (Table 5). Previous studies confirmed that the random forest model is a robust machine learning approach for predicting soil properties [45,85–87]. The variable importance analysis showed that soil properties, including CCE, TN, available phosphorous (P_{ava}), available potassium (K_{ava}), and pb, were the most important variables in random forest prediction, which, in total, can explain 75% of the variability in ^{137}Cs in the study area (Figure 7). Thus, this result confirmed the effects of erosional processes on the soil properties along the hillslopes. In the Chelgerd district of Iran, Ayoubi et al. [47] showed that soil properties such as K_{ava} and χ_{lf} were identified as the most important variables, explaining 61% of the variability in ^{137}Cs inventory.

Table 5. Random forest model results between ^{137}CS inventory as the dependent variable and soil properties as independent variables in the study area.

Variable	mtry	ntree	RMSE $\pm$ SD	$R^2 \pm$ SD	MAE $\pm$ SD
^{137}CS inventory	13	500	111.29 $\pm$ 26.85	0.94 $\pm$ 0.04	89.58 $\pm$ 23.75

mtry: number of variables in each random subset; ntree: number of trees in the forest; RMSE: root mean square error; R^2 : coefficient of determination; MAE: mean absolute error.

Figure 7. The variable importance analysis of soil properties in the prediction of ^{137}Cs inventory for the random forest model. CCE: calcium carbonate equivalent; TN: total nitrogen; P_{ava} : available phosphorous; K_{ava} : available potassium; pb: bulk density; EC: electrical conductivity; SOM: soil organic matter; χ_{lf} : magnetic susceptibility at low frequency; χ_{hf} : magnetic susceptibility at high frequency.

4. Conclusions

This study investigated the effects of land use changes (especially rehabilitation with an apple orchard) and slope positions on the variability of soil physicochemical and magnetic properties, and soil redistribution using the ^{137}Cs technique in three land uses. The main conclusions are:

1. Two factors, namely rangeland degradation and land conversion to dryland farming, have significantly changed the soil physicochemical properties in various slope positions during the past 50 years. CCE increased in the eroded positions (shoulder and backslope), whereas SOM, TN, K_{ava} , and P_{ava} decreased in these positions, especially in dryland farming, because of soil loss. The rehabilitation of the degraded soils with apple orchards significantly improved soil quality indicators.
2. The restoration of drylands by orchards improved SQIs in different slope positions. The apple orchards increased SQI values in footslope (0.499, very high) and toeslope (0.498, very high) positions compared to drylands (0.369, moderate for footslope; 0.432, high for toeslope).
3. Magnetic susceptibility is significantly reduced in dryland farming compared to rangeland due to soil erosion and deposition along the landscape. In the upper position, lower values for χ_{lf} were observed, whereas the highest χ_{lf} were found in the lower position due to the movement of magnetic particles associated with fine particles.
4. Applying SMBM on the ^{137}Cs inventory indicated the highest soil loss observed in the dryland and orchard cultivation regions. Thus, it can be concluded that land rehabilitation significantly decreased the soil loss rate in the recent two decades. In the steep slopes (i.e., shoulder and backslope) and the lower positions (i.e., footslope and toeslope) of three land uses, net soil loss and net deposition occurred, respectively.
5. The correlation analysis showed that ^{137}Cs well correlated with some soil properties known to be soil quality indicators (i.e., TN, K_{ava} , P_{ava} , SOM, bulk density, and CCE). The good agreement between ^{137}Cs inventory and χ_{lf} confirmed the high potential of magnetic susceptibility, as an indicator, for evaluating soil redistribution along the hillslope. Additionally, the random forest models revealed that CCE, TN, K_{ava} , P_{ava} , and ρ_b were the most important variables, explaining 75% of the variability of ^{137}Cs inventory in the study area.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy12020451/s1>, Table S1: Standard scoring functions and indicators parameters in the study area (SSF Equations were adopted from Zeraatpisheh et al. [34]).

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