The effects of cropping systems on soil erosion risks and crop productivity using ImpelERO model and GIS in northeast of Iran

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Abstract Soil erosion is a severe problem worldwide, and controlling it will be a major challenge in the future. Neural networks, as an artificial intelligence technology, have grown rapidly over the past few years and have an ability to deal with nonlinear multivariate systems. An integrated Model to Predict European Land use named ImpelERO is a decision trees/neural network hybrid model. The overall approach of ImpelERO was applied in 49 selected sites from Mashhad–Chenaran plain to quantify the soil erosion features including soil vulnerability index, soil loss rate, erosion risk class and soil depth reduction by sugar beet cultivation under conventional and conservational management practices. Our results revealed that the soil vulnerability indexes ranged from 0.12 to 0.54 and 0.1 to 0.44 by conventional and conservational practices, respectively. The values of soil losses in the study area varied between 4 to 59.7 t ha⁻¹ year and 3.4 to 38.7 t ha⁻¹ year with an average of 11.72 and 7.83 t ha⁻¹ year by conventional and conservation management practices, respectively. The mean values of erosion risk classes ranged from V3 in conventional to V2 in conservational practices which categorize the region as accepted tolerable to sensitive to erosion. The long term soil productivity reduction for time horizons 2020, 2050 and 2100 revealed that the conservational practices have greater contribution on preventing productivity reduction than conventional management practices.

Keywords Vulnerability index · Soil loss · Erosion · ImplEro model · Productivity · Sugar beet · GIS

Introduction

Soil erosion, defined as the detachment and displacement of soil particles from the surface to another location (Govers et al. 1990; Flanagan 2002), continues to be a primary cause of soil degradation throughout the world (Fu and Gulinck 1994), and has become an issue of significant and severe societal and environmental concern (Elsen et al. 2003; Singha et al. 2006). The main causes of soil erosion are inappropriate agricultural practices, deforestation, overgrazing, land abandonment, forest fires and construction activities (Grimm et al. 2002; Yassoglou et al. 1998). Conservation tillage, i.e. the use of tillage techniques which seek to reduce soil disturbance and to maximize soil cover by residues, is primarily used as a means to protect soils from erosion and compaction or to conserve soil moisture. Other reasons for introduction of conservation techniques, e.g. improvement of soil quality and reduction of erosion and top soil loss (López et al. 2000; Machado et al. 2007; Cantero-Martinez et al. 2007; Fuentes et al. 2009) or higher soil moisture and efficiency of water usage (Verch et al. 2009). Conservation tillage, i.e. any form of (reduced) tillage that specifically intends to reduce soil disturbance during seedbed preparation with the objective to maintain soil cover, to improve soil structure and stability while maintaining a viable crop is known to be an effective tool to reduce erosion (Uri et al. 1998; Sisti et al. 2004). Several studies have shown that conservation tillage can significantly reduce erosion: a recent overview of results can be found in Montgomery (2007). However, the degree of reduction in erosion reduction that is reported

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varies significantly from study to study. Numerous studies showed that no tillage practices, with crop residues left on the soil surface increase soil organic carbon (SOC), improve soil aggregation, and preserve the nutrients for plant and soil microorganisms (Hendrix et al. 1998; Jacobs et al. 2009). Conservation tillage is intrinsically linked to residue management, i.e. full, partial or stubble-only retention. Thus, the net effect of any conservation tillage system depends on the integration of the system itself in relation to crop rotation and residue management. Indeed, surface residues accumulated due to conservation tillage were shown to promote higher soil organic C, microbial biomass N and C, potential N mineralization and total N (Salinas-Garcia et al. 2002). Conventional tillage practices including post-harvest residue removal and moldboard ploughing operations accelerate soil organic matter (SOM) oxidation, disrupt soil aggregate stability, and increase soil erosion due to frequent soil disturbance (Frey et al. 1999; Govaerts et al. 2006). Intensive tillage management has caused a significant loss of SOM and serious soil degradation (Liu et al. 2010). Reduced tillage leads to changes in many of the soil's physical properties. Soil bulk density often increases in the 0.1–0.2 m soil layer in the absence of ploughing. This leads to reduced air-filled pore space and higher water contents. With appropriate crop management, the long-term yields achieved from NT/RT can be at least as high as those achieved from conventionally tilled soils (Grandy et al. 2006; Soane et al. 2012). The soil is more susceptible to water erosion between the beginning of autumn and the end of spring, either because it is unprotected (before sowing) or only partially protected (before the crop reaches full canopy coverage). Therefore, a no-tillage system, in which crop residues are left on the ground surface, has been proposed to control water erosion (Unger et al. 1991). Residue retention in no tillage systems also favours infiltration (Baumhardt and Lascan 1996; Govaerts et al. 2007). Land use and soil cover are considered as the most important factors affecting the intensity and frequency of runoff and surface erosion (García-Ruiz 2010; Kosmas et al. 1997; Mitchell 1990??). The Middle East region is particularly fragile due to soil and climatic constraints (Kassam 1981). Drought is a constant feature of the region, with considerable annual and inter-annual variation in rainfall. Hence, farming systems have evolved to cope with drought such as wheat (*Triticum aestivum*) as dominant crop in cultivation (Cooper et al. 1987). Over the last few decades conservation tillage systems, such as shallow cultivation, reduced- or no-till, have been adopted extensively in Iran. This was largely due to labor and energy savings, reduced soil erosion and better soil moisture conservation (Blevins and Frye 1993; Derpsch et al. 2010). The aim of the present study was to assess the effects of cropping management systems including conventional and

conservation practices on the values of soil losses, soil vulnerability, erosion risk class and the depth of soil reduction by sugar beet cultivation using neural network based ImpelERO model and GIS in Mashhad plain, northeast of Iran.

Materials and methods

General characteristics of the study area

The present study was conducted in Mashhad plain with an area of 6,131 km², Khorasan-e-Razavi province, northeast Iran (Fig. 1). The study area is located between latitude 35°59' to 37°04'N and longitude 58°22' to 60°07'E including lands less than 1500 m above sea level (asl). The topographical elevation values of the study area vary between 900 and 1500 m asl, while the main topographical elevation range over 1200 m asl. The general physiographic trend of the plain extends in a NW–SE direction with an average of 160 km length surrounded between two mountainous zones of Kopetdagh at northward and Binaloud at southward based on visual interpretation of satellite image and field observations (Fig. 2).

Geologically, main alluvial nature of the plain has been developed into a thick sediment dominated environment belongs to quaternary period. The main land use practice at the study area is irrigated farming around Kashaf-rud River. The study area has a semi-arid climate with mean annual precipitation of 222.1 mm and mean annual temperature of 15.8 °C. The rainiest month is March (44.8 mm) and the driest month is September (1.2 mm). The soil profiles dataset including 49 selected sites were used for the study, where each selected site represents a land unit. Dataset files on climate data for meteorological stations closer to the selected sites including monthly means of temperature and precipitation correspond to 1981–2010 period were compiled from the Iran Meteorological Organization. The soil physical and chemical characteristics and the land terrain of the selected sites have been presented in Tables 1 and 2. The following cropping systems were considered on the selected application sites: Sugar beet under conventional practice and conservational practice. Table 3 summarizes for each cropping system, the agronomic practices which were assumed for all the sites and used as input data in the ImpelERO model application. The baseline and estimated yields were used to derive the productivity level. The tillage implements sequence, along with the number of times applied and the workability consideration by the farmer, were also established. These management practices, with special reference to the tillage operations, are frequently applied for sugar beet in irrigated condition.

Fig. 1 Location and geographical position of the study area

Fig. 2 Satellite image of the study area

Soil erosion estimation

Soil erosion parameters were calculated on the basis of the expert system/neural networks structure of the ImpelERO model (De la Rosa et al. 1999). This model was developed as a Universal Soil Loss Equation-type model following traditional land evaluation analysis and advanced empirical

modeling techniques. Using expert-decision trees, soil survey information and expert knowledge of the soil erosion process were combined with land and management qualities. An artificial neural networks approach was then applied to capture the interactions between the land and different management practices for winter sugar beet production in order to predict the vulnerability index to soil

Table 1 Soil physical and chemical characteristics of the study area

Site	Longitude	Latitude	Sand	Silt	Clay	Texture	ESP (%)	OM (%)	Bulk density
1	59.745	36.111	32	50	18	Silt loam/loam	14.1	1.07	1.407
2	59.683	36.214	39	45	16	Loam	4.41	1.26	1.438
3	59.757	36.147	21	57	22	Silt loam	10.5	1.1	1.357
4	59.684	36.349	14	56	30	Silty clay loam	5.76	1.34	1.298
5	59.835	36.144	45	41	14	Loam	21.8	0.52	1.469
6	59.751	36.208	17	61	22	Silt loam	5.09	0.88	1.349
7	59.839	36.207	25	64	11	Silt loam	2.04	0.67	1.466
8	59.843	36.270	39	33	28	Clay loam	10.5	0.95	1.356
9	59.770	36.336	33	41	26	Loam	5.63	0.76	1.355
10	59.608	36.350	32	54	14	Silt loam	2.18	0.88	1.444
11	59.618	36.406	41	47	12	Loam	0.58	0.67	1.484
12	59.699	36.400	39	49	12	Loam	0.43	0.47	1.48
13	59.540	36.410	34	52	14	Silt loam	5.49	1.03	1.448
14	59.466	36.476	33	53	14	Silt loam	4.96	0.59	1.446
15	59.544	36.473	37	49	14	Loam	0.88	0.48	1.454
16	59.629	36.470	41	40	19	Loam	2.61	0.6	1.416
17	59.700	36.466	33	47	20	Loam	0.73	0.48	1.394
18	59.392	36.482	54	34	12	Sandy loam	2.75	0.72	1.509
19	59.215	36.506	64	26	10	Sandy loam	1.46	0.78	1.555
20	59.316	36.553	15	53	32	Silty clay loam	4.41	1.43	1.29
21	59.392	36.538	30	49	21	Loam	3.59	1.17	1.381
22	59.470	36.538	43	40	17	Loam	3.73	1.17	1.437
23	59.549	36.535	22	53	25	Silt loam	12.8	1.02	1.34
24	59.627	36.532	30	51	19	Silt loam	2.18	0.84	1.395
25	59.236	36.597	24	50	26	Silt loam/loam	3.31	2.34	1.338
26	59.318	36.608	26	59	15	Silt loam	10.1	0.93	1.422
27	59.396	36.605	32	47	21	Loam	1.75	0.48	1.385
28	59.475	36.602	33	47	20	Loam	1.31	0.22	1.394
29	59.084	36.618	32	55	13	Silt loam	2.18	1.03	1.455
30	59.010	36.684	26	62	12	Silt loam	0.88	0.81	1.455
31	59.088	36.681	28	50	22	Silt loam/loam	3.45	2.78	1.37
32	59.166	36.677	24	58	18	Silt loam	3.17	1.6	1.392
33	59.322	36.671	25	51	24	Silt loam	0.58	1	1.352
34	59.394	36.670	32	51	17	Silt loam	0.88	0.52	1.416
35	58.935	36.749	14	58	28	Silty clay loam	6.02	1.91	1.308
36	59.013	36.746	36	60	4	Silt loam	7.71	1.09	1.636
37	59.092	36.743	44	31	25	Loam	59.8	0.91	1.382
38	59.170	36.740	58	31	11	Sandy loam	0.58	0.41	1.53
39	58.782	36.818	34	48	18	Loam	0.88	0.62	1.411
40	58.861	36.815	26	48	26	Loam	12.2	0.72	1.342
41	58.939	36.812	25	48	27	Clay loam/loam	8.59	1.03	1.334
42	58.707	36.884	34	56	10	Silt loam	0.58	0.93	1.497
43	58.786	36.881	29	49	22	Loam	13.3	0.59	1.372
44	58.554	36.953	32	52	16	Silt loam	0.43	0.86	1.425
45	58.633	36.950	48	40	12	Loam	0.58	0.88	1.498
46	58.711	36.947	25	52	23	Silt loam	6.42	1.84	1.358
47	58.558	37.016	32	54	14	Silt loam	0.43	1	1.444
48	58.636	37.013	30	52	18	Silt loam	0.58	0.59	1.403
49	58.697	37.012	24	58	18	Silt loam	0.29	0.76	1.392

Table 2 Land terrain values of the study area

Site	Slope		Aspect degree	Sub soil stoniness class ^b	Internal drainage ^c
	%	Class ^a			
1	1.00	F	3.00	C	M
2	1.00	F	3.00	C	M
3	1.00	F	3.00	C	M
4	2.00	A	7.00	F	V
5	2.00	A	3.00	C	M
6	1.00	F	3.00	C	M
7	4.00	G	3.00	F	M
8	1.00	F	7.00	F	V
9	1.00	F	7.00	F	M
10	4.00	G	3.00	F	M
11	2.00	A	7.00	F	M
12	4.00	G	5.00	F	M
13	2.00	A	3.00	F	M
14	2.00	A	3.00	F	M
15	2.00	A	7.00	F	M
16	1.00	F	5.00	F	M
17	2.00	A	7.00	F	M
18	2.00	A	3.00	F	H
19	2.00	A	3.00	C	H
20	2.00	A	3.00	F	V
21	2.00	A	3.00	F	M
22	5.00	G	5.00	F	M
23	1.00	F	7.00	F	M
24	2.00	A	7.00	F	M
25	1.00	F	3.00	C	M
26	1.00	F	7.00	F	M
27	2.00	A	7.00	F	M
28	1.00	F	7.00	F	M
29	2.00	A	3.00	C	M
30	2.00	A	3.00	C	M
31	1.00	F	3.00	C	M
32	1.00	F	3.00	F	M
33	2.00	A	7.00	F	M
34	2.00	A	7.00	F	M
35	1.00	F	3.00	C	V
36	2.00	A	3.00	C	M
37	2.00	A	7.00	F	M
38	2.00	A	7.00	F	H
39	1.00	F	5.00	C	M
40	1.00	F	3.00	F	M
41	2.00	A	7.00	F	V
42	1.00	F	3.00	F	M
43	1.00	F	5.00	F	M
44	2.00	A	3.00	F	M
45	2.00	A	3.00	F	M
46	2.00	A	7.00	F	M
47	2.00	A	3.00	F	M
48	2.00	A	7.00	F	M
49	7.00	U	7.00	F	M

^a Slope class: *F* flat, *A* almost flat, *G* gently undul, *U* undul^b Sub soil stoniness class: *F* few, *C* common^c Internal drainage: *H* rapid, *M* moderate, *V* very slow

Table 3 Agricultural management practices for sugar beet cultivation, and assumed to be used in the selected sites

Crop type	Management	Residue treatment	Tillage system	Row spacing (m)	Baseline yield (t ha ⁻¹) ^a	Estimated yield (t ha ⁻¹) ^b	Tillage operation		
							Implement	Time ^c	Workability ^d
Spring crop	Convention	Grazing	Traditional	0.6	36	38.5	Plow Moldboard	2	Yes
							Drill deep furrow	1	Yes
							Disc cultivator	3	Yes
							Harrow-roller	4	Yes
							Planter row	1	Yes
							Spray implement	4	Yes
							Fertilizer applicator	3	Yes
Spring crop	Conservation	Nil	Conservation	0.6	40.5	42	Drill conventional, no till	1	Yes
							Disc cultivator	2	Yes
							Harrow-roller	2	Yes
							Planter row	1	Yes
							Spray implement	4	Yes
							Fertilizer applicator	3	Yes

^a Baseline yield is the actual value of crop production from statistical sources

^b Estimated yield is the predicted value of crop production by using simulation models

^c Number of times that an implement is used

^d Workability status makes reference if (yes or no) the optimum soil water content for each tillage operation is considered by the farmer

erosion, erosion risk class, soil loss rate and soil depth reduction.

Results and discussion

Soil vulnerability Index

The values of soil vulnerability indexes ranged from 0.12 to 0.54 by conventional and 0.1 to 0.44 by conservation management practices for sugar beet cultivation. It was revealed that the index values of soil vulnerability by conventional managements in the study area were higher than the corresponding values by conservation management practices (Table 4). Undulated slopes, southward aspects, fine and/or silty soil texture and low drainage classes were found the most important factors affecting soil vulnerability index by conventional management practices; however, the effects of these parameters was reduced to 22.3 % in average by shifting to conservation management practices. The most vulnerable soils to erosion were found in some areas at southeast, middle and northwest of the plain, while the effect of conservation practices by reduced tillage and using soil stabilizers restricted the vulnerable areas to small parts in the middle and northwest of the study area (Fig. 3). García-Orenes et al. (2009) found that straw mulch was able to significantly improve soil properties after a 16 months study period in a Mediterranean farming area. Mulumba and Lal (2008) found that straw

application as soil stabilizer increased total porosity and soil aggregation with increasing mulching rates resulted in lower vulnerability to soil erosion. Similar positive relationships between organic matter and aggregate stability indices were found by García-Orenes et al. (2005) and Zornoza et al. (2007).

Soil loss estimation

The values of soil losses in the study area varied between 4 to 59.7 t ha⁻¹ year and 3.4 to 38.7 t ha⁻¹ year with an average of 11.72 and 7.83 t ha⁻¹ year by conventional and conservation management practices, respectively. The mean values of erosion risk classes ranged from V3 in conventional to V2 in conservational practices which categorize the region as accepted tolerable to sensitive to erosion (Table 4; Fig. 6). As expected the values of soil losses by conventional practices of sugar beet cultivation were higher than the corresponding values by conservation management practices (Table 4). According to the Technical Working Group on Erosion as part of European Union Soil Thematic Strategy (Jones et al. 2004) an average annual soil loss of more than 1 t ha⁻¹ can be considered as irreversible within a time span of 50–100 years. When the definition considers the maximum permissible rate at which soil fertility can be maintained, tolerable rates have a much larger range, 1 t ha⁻¹ year (Schaub and Prasuhn 1998) to as much as 15–20 t ha⁻¹ year where soils are deeper (Schertz 1983). A mean annual

Table 4 Soil erosion parameters by conventional and conservational practices for sugar beet cultivation

Conventional practices					Conservational practices			
Site	Vulnerability index (0.00–1.00)	Risk class (V1–V5)	Soil loss rate ($\text{t ha}^{-1} \text{ year}^{-1}$)	Soil depth reduction (cm year^{-1})	Vulnerability index (0.00–1.00)	Risk class (V1–V5)	Soil loss rate ($\text{t ha}^{-1} \text{ year}^{-1}$)	Soil depth reduction (cm year^{-1})
1	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
2	0.22	V2	7.3	0.05	0.18	V2	5.9	0.04
3	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
4	0.38	V3	25.1	0.19	0.3	V2	9.8	0.08
5	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
6	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
7	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
8	0.43	V3	36.5	0.27	0.34	V3	17.2	0.13
9	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
10	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
11	0.26	V2	8.7	0.06	0.2	V2	6.6	0.04
12	0.26	V2	8.7	0.06	0.2	V2	6.6	0.04
13	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
14	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
15	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
16	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
17	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
18	0.3	V3	10.7	0.07	0.26	V2	8.7	0.06
19	0.3	V3	10.7	0.07	0.26	V2	8.7	0.06
20	0.38	V3	25.1	0.19	0.3	V2	9.8	0.08
21	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
22	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
23	0.26	V2	8.7	0.07	0.2	V2	6.6	0.05
24	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
25	0.22	V2	7.3	0.05	0.18	V2	5.9	0.04
26	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
27	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
28	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
29	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
30	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
31	0.22	V2	7.3	0.05	0.18	V2	5.9	0.04
32	0.22	V2	7.3	0.05	0.18	V2	5.9	0.04
33	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
34	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
35	0.38	V3	25.1	0.19	0.3	V2	9.8	0.08
36	0.26	V2	8.7	0.05	0.2	V2	6.6	0.04
37	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
38	0.12	V1	4	0.03	0.1	V1	3.4	0.02
39	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
40	0.26	V2	8.7	0.07	0.2	V2	6.6	0.05
41	0.43	V3	36.5	0.27	0.34	V3	17.2	0.13
42	0.26	V2	8.7	0.06	0.2	V2	6.6	0.04
43	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
44	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
45	0.26	V2	8.7	0.06	0.2	V2	6.6	0.04

Table 4 continued

Conventional practices					Conservational practices			
Site	Vulnerability index (0.00–1.00)	Risk class (V1–V5)	Soil loss rate ($\text{t ha}^{-1} \text{ year}^{-1}$)	Soil depth reduction (cm year^{-1})	Vulnerability index (0.00–1.00)	Risk class (V1–V5)	Soil loss rate ($\text{t ha}^{-1} \text{ year}^{-1}$)	Soil depth reduction (cm year^{-1})
46	0.22	V2	7.3	0.05	0.18	V2	5.9	0.04
47	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
48	0.26	V2	8.7	0.06	0.2	V2	6.6	0.05
49	0.54	V4	59.7	0.43	0.44	V3	38.7	0.28

Fig. 3 The zonation of vulnerability index for sugar beet cultivation in Mashhad plain

soil loss of 11 t ha^{-1} is a widely accepted tolerable soil loss value, but values as low as 2 t ha^{-1} are recommended for sensitive areas where soils are thin and highly erodible (Hudson 1981). The advantages of conservation tilling and straw residue treatment versus the use of conventional tillage practices and grazing straw treatment in terms of less soil loss have been documented by Raclot et al. (2009). Studies have revealed that in dry areas, approximately 50 % of the biomass from herbaceous vegetation roots is added to the soil as OM (USDA 2000). It has also been noted that covers help to retain OM and nutrients in sloping soil (Gay et al. 2004), which limits crusting due to fracturing of the crusts themselves (Aljibury and Christensen

1972). In compare to conventional tillage practices the average values of soil losses by conservation management practices showed a reduction of 33.2 %. Several studies have shown that conservation tillage can significantly reduce erosion (Montgomery 2007). A 6-years study was set up in Belgium to study the effects of conservation tillage on runoff and soil loss under Western European conditions using rainfall simulation. Over 250 rainfall simulation experiments on small plots were carried out on fields with sugar beet, maize and winter wheat. These experiments clearly showed a reduction of inter rill soil loss and runoff on the conservation tillage plots, with a mean reduction of 43 and 23 % with respect to the values

Fig. 4 The zonation of soil loss rate for sugar beet cultivation in Mashhad plain

measured on paired, conventional tillage plots, respectively (Leys et al. 2007). Corresponds to vulnerable areas of the plain, the zonation of soil losses by conventional management practices revealed that the most soil loss values are scattered in southeast and northwest of the plain, where the slopes are more undulated and southward, soil texture is fine and/or silty, the drainage is very slow and the soil organic matter is commonly low (Fig. 4).

Long-term changes in crop productivity

Following soil loss prediction, the rate of change in relative productivity of soils can be calculated on the basis that favorable rooting characteristics are present in the soil profile. As erosion removes the upper soil profile, productivity will decline if the subsoil is limiting for crop growth. The effect of diminishing soil organic matter and nutrient contents on crop productivity is not considered in this analysis. The concept of soil loss tolerance was introduced in order to give a measurement of how much erosion a soil could tolerate before experiencing excessive

damage. In general terms, the soil loss tolerance is defined as the maximum rate of annual soil erosion that will permit a high level of crop productivity to be sustainable. This tolerance value is considered to range from 1 to 10 Mg ha⁻¹ per year depending upon intrinsic soil profile characteristics (Larson 1981). According to the profile characteristics of the dominant soils of the study area the soils were grouped as maximum tolerance (Soil group A), which corresponds to deep alluvial soils with favorable characteristics to a depth exceeding 120 cm. Soil erosion at the rate estimated by the ImpelERO model was simulated for four time horizons: current, 2020, 2050 and 2100. Vulnerability index, soil loss and soil depth reduction rates are facilitated directly by the model application; and the corresponding soil depth reductions are calculated using the depth reduction rate (Table 4; Fig. 5). After calculations of soil erosion, crop productivity was calculated at each time horizon by application of the MicroLEIS–ALBERO sugar beet yield prediction model (De la Rosa 1996) (Fig. 6). The predicted yield (PY) was converted to productivity index (Pi) as follows:

Fig. 5 The zonation of soil depth reduction for sugar beet cultivation in Mashhad plain

Fig. 6 The zonation of erosion risk class for sugar beet cultivation in Mashhad plain

$$P_i = PY / \max PY$$

where $\max (PY)$ was considered to be 43.2 t ha^{-1} . By using this procedure for the four time horizons, the rooting depth moved down the profile as soils eroded, unless some limiting layer occurred in the first 120 cm or until a limiting layer was encountered. Figures 7 and 8 show productivity changes with three simulated time horizons: 2020, 2050 and 2100 for the 49 sites. For the land unit with high vulnerability index an initial productivity index of 0.81 was calculated. While the current erosion rate in this land unit ranged from 59.7 to $38.7 \text{ t ha}^{-1} \text{ year}^{-1}$ by

conventional and conservation practices, the productivity index under these practices dropped to 0.745 to 0.772, revealed a loss of 8 and 4.7 %, for the time horizon 2100 of simulated erosion, respectively. For 5 land units with moderately medium vulnerability index the average productivity index of 0.91 was estimated. As the average current soil loss rate in these land units ranged from 29.66 to $12.76 \text{ t ha}^{-1} \text{ year}^{-1}$ by conventional and conservation practices, the productivity index under these practices dropped to 0.875 to 0.898, exhibited a loss of 3.86 and 1.36 %, for the time horizon 2100 of simulated erosion,

Fig. 7 Productivity changes with the time horizon for the 49 sites under conventional practice in Mashhad plain

Fig. 8 Productivity changes with the time horizon for the 49 sites under conservational practice in Mashhad plain

Table 5 The regression equation between long term productivity reductions versus soil depth reduction

Vulnerability index	Number of sites	Conventional practice		Conservational practice	
		Regression equation	R ²	Regression equation	R ²
High	1	–	–	–	–
Moderate	5	$y = 0.0421x + 0.0595$	0.99	$y = 0.0544x + 0.026$	0.98
Low	37	$y = 0.0222x + 0.0389$	0.52	$y = 0.0192x + 0.0415$	0.5
Very low	6	$y = 0.0204x + 0.0361$	0.51	$y = 0.0667x + 0.02$	0.99

respectively. For 37 land units with low vulnerability index the mean productivity index of 0.92 were calculated. While the average current soil loss rate in these land units ranged from 8.81 to 6.71 t ha⁻¹ year⁻¹ by conventional and conservation practices, the productivity index under these practices dropped to 0.91 to 0.916, showed a loss of 0.99 and 0.4 %, for the time horizon 2100 of simulated erosion, respectively. For the rest 6 land units with very low vulnerability index the mean productivity index of 0.94 were determined. As the average current soil loss rate in above land units ranged from 6.75 to 5.48 t ha⁻¹ year⁻¹ by conventional and conservation practices, the productivity index under these practices dropped to 0.935 to 0.937, showed a loss of 0.52 and 0.25 %, for the time horizon 2100 of simulated erosion, respectively. The regression equation between long term productivity reductions in percentage versus soil depth reduction in centimeter by conventional and conservation management practices indicated a high correlation between these parameters (Table 5).

Our results revealed that although productivity is sustained for a short time, but it will drop with continued erosion in long term period. Comparing two management practices, no special differences were observed on productivity index at medium, low and very low soil vulnerability indexes over long term time horizon. Only by conservation management practice the productivity was less declined compared to conventional practice over long time period (Figs. 7, 8).

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