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Original Research

Modeling Impacts of Land Uses on Carbon and Nitrogen Contents, Carbon Dioxide and Water Effluxes of Mediterranean Soils

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Abstract

Local alterations of land uses by policy, planning, and management decisions have global implications for coupled biogeochemical cycles. Quantification and prediction of impacts of land-use changes on carbon (C), nitrogen (N), and water (H_2O) cycles are of great significance, in particular to the Mediterranean ecosystems that are already vulnerable to climate change. The present study was aimed at empirically modeling the four response variables of soil carbon (SC), nitrogen (SN) contents, carbon dioxide (CO_2), and H_2O effluxes as a function of the 10 predictors of land use type (forest, grassland, cropland, and their degraded states), soil organic matter, soil moisture, silt, clay and sand fractions, pH, electrical conductivity, soil microorganisms, and soil temperature. Our results showed that soil respiration rate was highest for cropland and lowest for forest ($p = 0.002$). Land use type was found to be the primary control and significantly related linearly to SC, SN, and soil CO_2 efflux and non-linearly to all the responses. Goodness-of-fit and predictive power of the best-fit multiple non-linear regression (MNLR) models varied between 80.8% for soil CO_2 efflux and 99.9% for SC, and between 67.4% for soil CO_2 efflux and 99.1% for SN, respectively.

Keywords: data-driven modeling, Mediterranean basin, soil respiration, watershed management

Introduction

Better understanding of drivers and patterns of spatiotemporal changes in soil organic carbon and nitrogen (SOC-N) pools, soil respiration, and soil evaporation is of vital importance to the stabilization and regulation of the global atmospheric carbon dioxide (CO_2) concentration [1], to locally sustainable management of net ecosystem and biome productions [2], and to the explanation for the discrepancy also known as residual terrestrial uptake of ca. 2 Gt C/year in budget estimates of the global C cycle

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[3]. The first- and second-largest terrestrial C effluxes to the atmosphere belong to fossil fuel burning, and cement production and to soil respiration – CO_2 efflux from soil heterotrophic (microbial) and autotrophic (root) biota-, respectively [3, 4]. Mean annual global soil respiration was estimated at 91 Pg C/year (1 Pg = 10^{15} g) over the period of 1965 to 2012 (with a 95% confidence interval of 87-95 Pg C) based on a spatiotemporally varying global soil database and a semi-empirical model by Hashimoto et al. [5], and at 97.01 Pg C/year (9.05±0.53 Mg C/ha/year) based on a meta-analysis of 563 datasets by Zhong et al. [6].

Land-use and -cover changes (LULCC) and management practices are the two main driving forces behind changes in SOC-N pools, and soil CO_2 and water (H_2O) effluxes. According to the IPCC [4], LULCC led to annual CO_2 efflux rates of 1.4±0.8 Pg C between 1980 and 1989, 1.6±0.8 Pg C between 1990 and 1999, and 0.9±0.8 Pg C between 2002 and 2011. The net C flux from LULCC accounted for 12.5% of total anthropogenic C emissions from 1990 to 2010 [7-8]. From a broader perspective, the net C fluxes attributable to sink- or source-enhancing decisions on terrestrial LULCC and management such as deforestation versus reforestation; losses versus conservation of farmland, wildlife habitat, wetlands, and peatlands; and degradation versus rehabilitation of forest, cropland, and grassland would be essential to international emissions trading under the post-2012 regime of the Kyoto Protocol signed in 1997 [9]. Stoichiometrically coupled SOC-N contents are closely linked to variations in the basic properties of ecosystem function and structure such as productivity, nutrient cycling, energy flow, and biodiversity, thus serving to act as an ecosystem-scale indicator that can signal deviations from sustainable management in the face of anthropogenic disturbance regimes [10]. The maintenance and sustainable management of an adequate level of SOC-N stocks constitute the basis for securing net ecosystem and biome productivity and are closely coupled to water cycle and biodiversity [10-11]. Land use and management govern the main soil properties (C and N content, soil moisture, pH, microbial activity, and structure), thus affecting CO_2 and H_2O effluxes from cropland as much as intact forest when appropriate land use policies and ecosystem management practices are adopted on a watershed scale [12-14]. Different land uses, topography, climate, and soil properties should be accounted for in the quantification of SC-N stocks of and CO_2 and H_2O effluxes from LULCC and associated uncertainties.

With a rise in public awareness of its linkage to human wealth and ecosystem health, the process of public policy and management of soil and water resources continues to play an increasingly central role in national development strategies [10]. In particular, this process is more challenging and urgent in hotspots of the developing world such as the Mediterranean countries with historical anthropogenic disturbance regime, complex terrain, high vulnerability of ecosystem structure and function to climate change, and lack of holistic approaches by the related state institutions [2, 15]. Therefore, the main objective of this study was to model impacts of different land uses on SC-N contents, and soil CO_2 and H_2O effluxes.

Materials and Methods

Study Area

The Darıdere watershed of 2,498 ha, one of the sub-watersheds of Isparta in the Mediterranean region of Turkey, was selected as the study region (Fig. 1). The study region has an average altitude of 1,569 m above sea level with a peak of 2,271 m and an average slope of 58% with the steepest slope covering 65% of the area [16]. The watershed includes a strategic Darıdere dam that provides drinking water for Isparta province. The long-term mean annual precipitation was 587.8 mm in 1931-90 and 511.5 mm in 1975-2005 [16], which points to a water deficit between May and October and to a surplus between January and March [17]. Four geological formations exist: Upper Cretaceous (Maastrichtian) limestone, Pliocene andesite, Eocene flysch, and quaternary alluvion (47%, 27%, 24%, and 2% of the total watershed area, respectively) [16]. All the land uses considered in the present study have soils formed on the Eocene flysch that has characteristics of brown forest soils with a very shallow soil depth that are very sensitive to erosion [16]. The six dominant land use mosaics of the study region are 1) forest, 2) degraded forest, 3) fallow cropland, 4) cultivated cropland,

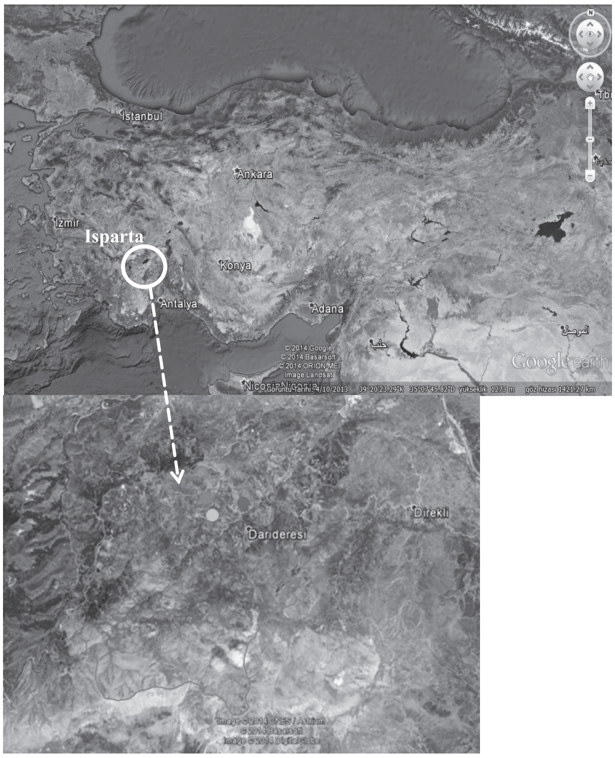

Fig. 1. Location of Darıdere watershed (Isparta, Turkey) and its sampling sites.

5) grassland, and 6) degraded grassland. Depending on the altitude, the dominant vegetation cover consists of *Cedrus libani*, *Quercus coccifera, Jauniperus excels*, *Crataegus* Tourn. Ex. L., *Pinus nigra*, and herbaceous plants [16].

Soil Sampling and Analyses

Triplicate soil samples from a depth of 30 cm were taken in July 2014 from the six land uses of the watershed with similar characteristics at the same elevation (1,300 to 1,500 m) and aspect (northwest) at an interval of 5 to 15 m (Fig. 1). Soil moisture (SMC), soil texture, total SC-N contents, C/N ratio, pH, electrical conductivity (EC), SOM, and colony count of soil microorganisms (CSM) were measured. Soil samples were sieved (2 mm mesh), air-dried, and stored at room temperature until analyses. Soil texture was measured by the Bouyoucos hydrometer method. pH (1:2 suspensions) and SMC (%) were measured using the methods of soil analysis. Soil moisture content was determined gravimetrically in the laboratory using 50-g soil subsamples that were oven-dried for at least 24 h at 105ºC. Soil electrical conductivity was measured using a Delta-T Wet 2 sensor (Delta-T Devices Ltd., UK). Elemental analyses of total SC-N (mg) were performed using the Dumas combustion method (Elementar vario MACRO CUBE CN, Germany). SOM content (%) was measured using the Walkley-Black method [18], while CSM (CFU/g) was determined using the soil dilution plate method [19]. *In situ* CO_2 and H_2O effluxes from soil respiration and evaporation, respectively, were measured using a CFX-2 soil CO_2 flux system (PP Systems, Hitchin, UK) that consists of an integral CO_2 analyzer, H_2O sensor, a soil respiration chamber, and a soil temperature probe [20]. The measurement accuracy of CO_2 and H_2O concentrations is 1%. Three recordings on days 1, 15, and 30 of July that represent typical mid-summer conditions for CO_2 and H_2O effluxes (expressed in g CO_2 or H_2O m^{-2} h^{-1}, respectively) were randomly taken for five hours from each of the six land uses. A CO_2 chamber (with a diameter of 21 cm and height of 11 cm) was inserted into a soil depth of 1.5 cm in a randomly selected location.

Statistical Analyses

The data analyses were performed using Minitab 17.0. The presence of Gaussian distribution, autocorrelation, multicollinearity, and homoscedasticity was checked using the Anderson-Darling (AD) test, Durbin-Watson statistic (DW), variance inflation factor (VIF), and the plot of residuals versus fits, respectively. Pearson's correlation matrix was performed to detect the significance, direction, and strength of linear associations. Tukey multiple comparison tests following one-way analysis of variance (ANOVA) were used to find significant mean differences among the land uses in terms of the measured soil properties.

Results and Discussion

Multiple Comparisons of Land Uses in terms of Soil C-N Contents and Soil CO_2 and H_2O Effluxes

Erol et al. [16] reported that soils of the watershed are very shallow as they are sensitive to erosion, and the erosion rate of the grassland soils was higher than those of the cropland and forest soils. The six land uses did not significantly differ in their soil moisture content, clay fraction, soil H_2O efflux, and soil microorganism count ($p > 0.05$), but in the remaining variables (Table 1). pH of the forest soil (5.9±0.3) was lowest ($p < 0.001$), and EC of the degraded forest soil (87±2.3 µS/cm) was the highest relative to that of the remaining soils ($p = 0.002$). Soil temperatures of the (degraded) forests and (degraded) grasslands were significantly higher than those of the (fallow) croplands ($p < 0.001$). The mean values of soil texture showed that soils of the land uses in the study region ranged from sandy loam to loam. Sand fraction of the forest soil was the highest (75.7%) and significantly different from that of the (fallow) croplands ($p = 0.005$). Silt fraction of the cropland soil was the highest (47.2%) and significantly different from that of the forest soil ($p = 0.01$). SOM content of the (degraded forests) was higher than that of the remaining land uses ($p < 0.001$). The forest had the highest contents of SC and SN (4.8±1.9 and 0.47±0.1 mg, respectively) relative to those of the remaining land uses except for the degraded forest (p = and < 0.001, respectively). The forest had higher soil C/N ratio (10.0±0.9) than the (degraded) grasslands and the cropland ($p = 0.002$). The maximum mean soil CO_2 efflux of 0.58±0.1 $g/m^2/h$ belonged to the cropland and was significantly higher than that of the forest ($p = 0.002$). The significantly lower soil CO_2 efflux, and the significantly higher SC-N contents and C/N ratio found in this study for the forest than for the cropland and grassland were consistent with the findings by Srivastava et al. [21].

Linear Relationships of Soil C-N Contents and Soil CO_2 and H_2O Effluxes to Land Uses and Soil Properties

With forest, degraded forest, grassland, degraded grassland, cropland, and fallow cropland, respectively, SC and SN contents decreased (r = -0.71 and -0.74, respectively; $p \leq 0.001$), while soil CO_2 efflux increased linearly ($r = 0.65$; $0.001 < p \leq 0.01$) (Table 2). The land uses in the same order were negatively correlated with EC ($r = -0.72$; $p \leq 0.001$), sand fraction and C/N ratio ($r = -0.65$; $0.001 < p \leq 0.01$), and SOM ($r = -0.64$; $0.001 < p \leq 0.01$), and positively correlated with soil pH ($r = 0.76$; $p \leq 0.001$) and silt fraction ($r = 0.66$; $0.001 < p \leq 0.01$). The content of SC was correlated positively with sand fraction and soil moisture content

Table 1. A multiple comparison of mean soil properties for a depth of 30 cm among six land uses based on Tukey test (n = 3).

Land use types	SMC (%)		Sand (%)		Clay (%)		Silt (%)		S-CO$_2$ (g/m^2/h)		S-H$_2$O (g/m^2/h)		T$_{soil}$ (ºC)		SC (mg)		SN (mg)		C/N		pH		EC (µS/cm)		SOM (%)		CSM (CFU/g)	
	Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD		Mean ± SD	
Forest	2.6	0.5	75.7^a	15	5.5	2	18.7^b	15	0.07^b	0.005	13.2	4	19.2^a	0.8	4.8^a	1.9	0.47^a	0.1	10.0^a	0.9	5.9^b	0.3	66a^b	13	10.8^{ab}	2.9	453	217
Degraded forest	2.4	0.1	54.4^{ab}	2	9.8	1	35.7^{ab}	1	0.44^a	0.1	10.5	2	18.7^a	1.8	3.1^{ab}	1.0	0.32^{ab}	0.06	9.4^{ab}	1.3	6.4^a	0.1	87^a	23	13.1^a	1.3	399	93
Grassland	1.7	0.7	57.3^{ab}	5	9.2	1	33.4^{ab}	4	0.32^{ab}	0.04	10.6	3	20.9^a	0.9	1.1^b	0.03	0.17^{bc}	0.005	6.7^{bc}	0.1	6.7^a	0.1	60^{ab}	3	6.9b^c	0.3	367	76
Degraded grassland	1.8	0.3	59.3^{ab}	1	9.5	0.8	31.3^{ab}	1	0.29^{ab}	0.05	16.6	9	20.0^a	1.0	1.0^b	0.1	0.15^c	0.01	7.1^{bc}	0.6	6.7^a	0.06	55^b	1	6.3^c	0.8	373	143
Cropland	2.1	0.1	42.7^b	1	10.0	0.4	47.2^a	1	0.58^a	0.1	6.1	1	15.2^b	0.5	1.1^b	0.03	0.18^{bc}	0.005	6.3^c	0.3	6.7^a	0.04	40^b	3	6.9b^c	0.4	480	72
Fallow cropland	2.1	0.05	50.6^b	9	7.7	3	41.6^a	8	0.50^a	0.1	7.5	2	15.6^b	0.6	1.3^b	0.4	0.17b^c	0.03	7.5^{abc}	1.5	6.7^a	0.06	39^b	5	7.3b^c	0.6	605	223
p value	> 0.05		0.005		> 0.05		0.01		0.002		> 0.05		< 0.001		0.001		< 0.001		0.002		< 0.001		0.002		< 0.001		> 0.05	

(r = 0.71 and 0.69, respectively; $p \leq 0.001$) and negatively with silt fraction (r = -0.70; $p \leq 0.001$) and soil CO$_2$ efflux (r = -0.51; $0.01 < p < 0.05$). The content of SN was correlated positively with SC, sand fraction, and soil moisture content (r = 0.99, 0.70 and 0.69, respectively; $p \leq 0.001$) and negatively with silt fraction (r = -0.69; $0.001 < p \leq 0.01$) and soil CO$_2$ efflux (r = -0.51; $0.01 < p < 0.05$). A significant negative correlation existed between SC-SN contents and soil pH (r = -0.79 and -0.81, respectively; $p \leq 0.001$), and we found significant positive correlations between SC-SN contents and SOM (r = 0.62 and 0.64, respectively; $0.001 < p \leq 0.01$) and between SC-SN contents and EC (r = 0.51 and 0.50, respectively; $0.01 < p < 0.05$). We found soil CO$_2$ efflux to be correlated negatively with sand fraction (r = -0.74, $p \leq 0.001$) and positively with silt fraction (r = 0.70, $p \leq 0.001$) and clay fraction (r = 0.57, $0.01 < p < 0.05$). There existed a negative correlation between soil H$_2$O efflux and silt fraction and a positive correlation between soil CO$_2$ efflux and soil pH (r = -0.48 and 0.58, respectively; $0.01 < p < 0.05$) (Table 2).

Based on 90 different soils characterized by forest, grassland, and cropland from 12 countries, Moyano et al. [22] found significant soil respiration correlations to be negative for sand and positive for clay and silt along a wide range of soil moisture content, which was consistent with our findings. Coarse texture (high clay content, low water holding capacity, high infiltration potential, and high porosity) versus fine texture (high sand content, high water holding capacity, low infiltration potential, and low porosity) in interaction with the degree of plant cover control magnitude and variability of soil water storage, water holding capacity, and water movement directly, and evapotranspiration and runoff indirectly [23]. In our case, this interaction led to a significant negative correlation between silt and soil H$_2$O efflux and an insignificant positive correlation between sand and soil H$_2$O efflux (r = 0.46, $p \geq 0.05$). An unexpected negative correlation between soil respiration and soil temperature obtained in the present study (r = -0.55, $0.001 < p \leq 0.01$) points to the presence of confounding variables such as land use types to modify the response of soil respiration to soil temperature. Similarly, in the quantification of spatiotemporal variations in soil respiration in a 3-year-old Eucalyptus plantation in coastal Congo, Epron et al. [24] attributed the same surprising negative correlation found between soil respiration and soil temperature to the mulch effect of forest litter accumulation. Similarly, Lai et al. [25] observed a negative effect of soil temperature on soil respiration under Mediterranean conditions and associated this with the progressive senescence of the crop. As with our study (r = 0.58, n = 18, $0.001 < p \leq 0.01$), significantly positive correlations were also reported between soil respiration and soil pH (r = 0.32, n = 21, $p < 0.05$) for the forest soils [26], for grassland, fallow cropland, and forest soils (r = 0.48, n = 5, $p < 0.01$) [27], and for forest and grassland soils (r = 0.28, n = 12, $p > 0.05$) [28].

Table 2. Pearson's correlation matrix among land use types (LUT) and soil properties for a depth of 30 cm (n = 18).

Variables	LUT													
Soil moisture content	-0.32	SMC												
(SMC, %)	ns													
Sand (%)	-0.65	0.38	Sand											
	**	ns												
Clay (%)	0.25	-0.25	-0.55	Clay										
	ns	ns	*											
Silt (%)	0.66	-0.37	-0.98	0.4	Silt									
	**	ns	***	0.09										
Soil CO_2 efflux	0.65	-0.19	-0.74	0.57	0.7	S-CO_2								
(S-CO_2, g/m^2/h)	**	ns	***	*	***									
Soil H_2O efflux	-0.33	0.28	0.46	-0.08	-0.48	-0.38	S-H_2O							
(S-H2O, g/m^2/h)	ns	ns	ns	ns	*	ns								
Soil temperature	-0.62	-0.19	0.51	0.04	-0.57	-0.55	0.43	T_{soil}						
(T_{soil}, °C)	**	ns	*	ns	**	**	ns							
SC (mg)	-0.71	0.69	0.71	-0.41	-0.7	-0.51	0.18	0.15	SC					
	***	***	***	ns	***	*	ns	ns						
SN (mg)	-0.74	0.69	0.7	-0.42	-0.69	-0.51	0.16	0.14	0.99	SN				
	***	***	***	ns	**	*	ns	ns	***					
C/N	-0.65	0.61	0.53	-0.34	-0.51	-0.42	0.17	0.13	0.9	0.88	C/N			
	**	**	*	ns	*	ns	ns	ns	***	***				
pH	0.76	-0.43	-0.57	0.36	0.56	0.58	-0.19	-0.19	-0.79	-0.81	-0.74	pH		
	***	ns	*	ns	*	*	ns	ns	***	***	***			
Electrical conductivity	-0.72	0.25	0.34	0.01	-0.38	-0.37	0.29	0.47	0.51	0.5	0.59	-0.56	EC	
(EC, µS/cm)	***	ns	ns	ns	ns	ns	ns	*	*	*	**	**		
Soil organic matter	-0.64	0.53	0.21	-0.07	-0.22	-0.21	0.16	0.11	0.62	0.64	0.71	-0.71	0.79	SOM
(SOM, %)	**	*	ns	ns	ns	ns	ns	ns	**	**	***	***	***	
Soil microorganism count	0.33	0.38	0.14	-0.32	-0.09	0.02	0.08	-0.44	0.06	0.06	-0.11	0.05	-0.24	0.001
(CSM, CFU/g)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[*]Correlation is not significant (ns) when $p \geq 0.05$ and significant when *$0.01 < p < 0.05$; ** $0.001 < p \leq 0.01$; and ***$p \leq 0.001$. LUT codes of 1 to 6 refer to forest, degraded forest, grassland, degraded grassland, cropland, and fallow cropland, respectively.

Non-Linear Relationships of Soil C-N Contents and Soil CO_2 and H_2O Effluxes to Land Uses and Soil Properties

There were no issues of Gaussian distribution, autocorrelation, and homoscedasticity according to the AD test, DW statistic, and the plot of residuals versus fits, respectively, to proceed with the building of MNLR models. The issue of multicollinearity existed according to VIF values > 10 for all the best-fit MNLR models (except for soil CO_2 efflux). Among the four best-fit MNLR models of soil CO_2 and H_2O effluxes, and SC and SN contents, the goodness-of-fit values ranged from SC (r^2_{adj} = 99.9%) to soil CO_2 efflux (r^2_{adj} = 80.8%), while the predictive power

Table 3. The best-fit multiple non-linear regression model of soil CO_2 efflux (g/m^2/h) based on stepwise selection of the following 10 predictors: categorical predictor of land use type (LUT), continuous predictors of count of soil microorganisms (CSM), soil organic matter, soil moisture, sand, silt, clay, pH, EC, and soil temperature (r^2_{adj} = 80.8%; r^2_{pred} = 67.4%; SE = 0.08; DW = 2.5; n = 18; p-to-enter and -remove < 0.05).

Model terms	Coefficient	SE	T value	*p* value	VIF
Intercept	0.941	0.127	7.42	< 0.001	
LUT (cropland as the baseline)					
Forest	-0.806	0.119	-6.75	< 0.001	5
Fallow cropland	-0.099	0.069	-1.43	0.18	2
Degraded forest	-0.3279	0.091	-3.57	0.004	3
Degraded grassland	-0.527	0.103	-5.11	< 0.001	4
Grassland	-0.4751	0.099	-4.76	0.001	3
Silt^2 (%)*CSM (CFU/g)	-0.0000001	0.0000001	-3.08	0.01	4

SE: Standard error, VIF: Variance inflation factor

values varied between SN (r^2_{pred} = 99.1%) and soil CO_2 efflux (r^2_{pred} = 67.4%). The categorical (indicator) variable of the land use type with the six levels was forced into the MNLR models, excluding the cropland as the baseline. Our findings showed that the land use type was the primary driver of rates of change in mean soil CO_2 and H_2O effluxes and mean SC content, while the interaction terms of sand^2 by land use type, and T_{soil} by pH^3 were the primary controls over mean SN content. Mean soil CO_2 efflux rate decreased by 0.80, 0.52, 0.47, 0.32, and 0.09 g/m^2/h with forest, degraded grassland, grassland, degraded forest, and fallow cropland, respectively, relative to cropland (Table 3). The mean soil H_2O efflux rate declined by 45.3, 27.4, 12.1, 8.2, and 7.7 g/m^2/h with degraded grassland, fallow cropland, grassland, degraded forest, and forest, respectively, relative to cropland (Table 4). Mean SC

Table 4. The best-fit multiple non-linear regression model of soil H_2O efflux (g/m^2/h) based on stepwise selection of the following 10 predictors: categorical predictor of land use type (LUT), continuous predictors of count of soil microorganisms (CSM), soil organic matter, soil moisture, sand, silt, clay, pH, EC, and soil temperature (r^2_{adj} = 98.1%; r^2_{pred} = 83.8%; SE = 0.74; DW = 3.1; n = 18; p-to-enter and -remove < 0.05).

Model terms	Coefficient	SE	T value	*p* value	VIF
Intercept	12.86	3.29	3.91	0.011	
LUT (cropland as the baseline)					
Forest	-7.74	3.94	-1.96	0.107	70
Fallow cropland	-27.41	5.1	-5.37	0.003	118
Degraded forest	-8.2	3.76	-2.18	0.081	64
Degraded grassland	-45.37	4.24	-10.69	< 0.001	81
Grassland	-12.14	3.53	-3.44	0.018	56
SMC (%)*EC (μS/cm)	-0.1384	0.038	-3.63	0.015	171
SOM (%)*CSM (CFU/g)	0.001562	0.0002	6.99	0.001	4.76
SMC (%)**EC (μS/cm)*LUT					
Forest	0.1398	0.039	3.53	0.017	238
Fallow cropland	0.3168	0.058	5.44	0.003	114
Degraded forest	0.1274	0.038	3.29	0.022	342
Degraded grassland	0.5801	0.045	12.69	< 0.001	103
Grassland	0.1973	0.039	4.96	0.004	84

SE: Standard error, VIF: Variance inflation factor.

Table 5. The best-fit multiple non-linear regression model of soil C content (mg) based on stepwise selection of the following 10 predictors: categorical predictor of land use type (LUT), continuous predictors of count of soil microorganisms (CSM), soil organic matter, soil moisture, sand, silt, clay, pH, EC, and soil temperature (r^2_{adj} = 99.9%; r^2_{pred} = 91.9%; SE = 0.01; DW = 3.0; n = 18; p-to-enter and -remove < 0.05).

Model terms	Coefficient	SE	T value	*p* value	VIF
Intercept	-0.819	0.1	-7.93	0.001	
LUT (cropland as the baseline)					
Forest	3.936	0.11	35.49	< 0.001	79
Fallow cropland	-4.134	0.13	-30.38	< 0.001	119
Degraded forest	23.221	0.36	64.41	< 0.001	837
Degraded grassland	3.728	0.26	-14.01	< 0.001	456
Grassland	-2.817	0.19	-14.6	< 0.001	239
Sand (%)*pH	0.0049	0.0003	15.0	< 0.001	23
Silt (%)*CSM (CFU/g)	-0.000009	0.000001	-6.87	0.002	4
pH*EC (µS/cm)	0.0028	0.00008	31.72	< 0.001	4
Silt (%)*LUT					
Forest	-0.0839	0.002	-34.77	< 0.001	20
Fallow cropland	0.0983	0.002	33.82	< 0.001	97
Degraded forest	-0.629	0.009	-63.99	< 0.001	795
Degraded grassland	0.0861	0.008	10.54	< 0.001	424
Grassland	0.0554	0.004	11.44	< 0.001	171

SE: Standard error, VIF: Variance inflation factor.

Table 6. The best-fit multiple non-linear regression model of soil N content (mg) based on stepwise selection of the following 10 predictors: categorical predictor of land use type (LUT), continuous predictors of count of soil microorganisms (CSM), soil organic matter, soil moisture, sand, silt, clay, pH, EC, and soil temperature (T_{soil})) (r^2_{adj} = 99.8%; r^2_{pred} = 99.1%; SE = 0.005; DW = 2.1; n = 18; p-to-enter and -remove < 0.05).

Model terms	Coefficient	SE	T value	*p* value	VIF
Intercept	0.259	0.02	10.97	< 0.001	
$Sand^2$ (%)*LUT (cropland as the baseline)					
Forest	0.00005	0.000001	66.08	< 0.001	1
Fallow cropland	-0.00002	0.000003	-7.95	< 0.001	4
Degraded forest	0.00017	0.00001	10.67	< 0.001	183
Degraded grassland	-0.00002	0.000009	-2.42	0.052	79
Grassland	0.000002	0.000004	0.39	0.708	12
T_{soil} (°C)*pH^3	-0.00001	0.000005	-3.11	0.021	10
Sand (%)*$Silt^2$ (%)*LUT					
Forest	-0.000001	0.0000001	-4.94	0.003	2
Fallow cropland	0.000001	0.0000001	6.55	0.001	4
Degraded forest	-0.000005	0.000001	-7.56	< 0.001	191
Degraded grassland	0.000001	0.000001	2.13	0.077	77
Grassland	0.0000001	0.0000001	0.52	0.625	12

SE: Standard error, VIF: Variance inflation factor.

content increased by 23.2, 3.9 and 3.7 mg with degraded forest, forest, and degraded grassland, and decreased by 4.1 and 2.8 mg with fallow cropland, and grassland, respectively, relative to cropland (Table 5). According to the two-way interaction term of sand^2 by land use type, mean SN content increased by 0.0001, 0.00005, and 0.000002 mg with degraded forest, forest, and grassland, and decreased by 0.00002 mg with degraded grassland and fallow cropland, respectively, when compared to cropland (Table 6). The rate of decrease in SN content was estimated at 0.00001 mg in response to a one-unit increase in T_{soil} by pH^3 interaction term.

Consistent with our findings, a meta-analysis by Guo and Gifford [29] indicated that SC stocks increased with conversion from cropland to plantation by 18% and to secondary forest by 53%. Similar to the decrease in SC content found in the present study, very low SOC accumulation rates of $\leq$ 3.1 g C/m^2/year even without the consideration of additional agents of SOC losses – including erosion – were reported over a 50-year period with the conversion of cropland to grassland [30]. This suggests that a very long duration may be required for a pronounced increase in SC to occur with conversion from cropland to grassland under semi-arid conditions of shallow soil depth, low biological productivity, and high erosion.

Conclusions

Rates of local changes in SC-N pools and soil CO_2 and H_2O effluxes in response to land-use change are of global concern due to their pivotal role in the quantification of enhanced sinks and reduced sources of GHG emissions through mitigation actions. The relatively high predictive power of the best-fit MNLR models obtained in this study can be extrapolated to watersheds with the help of remotely sensed data, spatiotemporally dynamic interpolation techniques, and mechanistic biogeochemical models. Besides land-use changes, the potential of ecosystem-specific best management practices remains to be explored for rates of SC-N sequestration and CO_2 and H_2O effluxes using data-driven models.

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