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The effect of climate and cultivation on soil organic C and N

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Abstract. Here, we investigate the response of soil organic carbon (SOC) and soil organic nitrogen (SON) to cultivation within two different climatic regimes by comparing large soil data sets from India and the Great Plains. Multiple regression models for both regions show that SOC and SON, as well as C/N ratios, increase with decreasing temperatures and increasing precipitation, trends also noted in soil data organized by Holdridge life zones. The calculated difference between natural and cultivated soils in India revealed that the greatest absolute SOC and SON losses occurred in regions of low temperatures and high precipitation, while the C/N ratio decreased during cultivation only with decreasing temperature. In India, the fractional loss of SOC relative to undisturbed soils increases with decreasing temperature whereas, in the Great Plains, it increases with increasing precipitation. Also, the fractional loss of SOC increased in India with increasing amounts of original C, whereas no relationship between fractional loss and original C was noted for the Great Plains. The differential response of each region to cultivation is hypothesized to be due to differences in both climate and management practices (crop cycles, fertilization). These findings suggest that estimates of soil C loss due to cultivation should be based on an array of factors, and that it is unlikely that a constant relative C loss occurs in any region.

Introduction

Until sometime in the mid 20th century, the major anthropogenic input of CO_2 to the atmosphere was caused by land use (Houghton et al. 1999). This source, which consists of the combined effects of biomass burning/clearing and SOC oxidation continues to be a large global flux of CO_2 (1–2 Pg C yr^{-1}) (Houghton 1996) that is surpassed only by fossil fuel burning. Agronomic research, beginning in the early 20th century, recognized that cultivation reduces the SOC and SON storage of soils (Alway 1909; Jenny 1933, 1941; Hide and Metzger 1939; Haas et al. 1957). This early research has been supplemented by a growing list of papers which compile and analyze data on paired plot comparisons of native vs. cultivated sites (Mann 1986; Post and Mann 1990; Davidson and Ackerman 1993) as well as time series observations of C storage following land conversion to agriculture (Schlesinger 1986). Despite these studies, questions concerning the rate and magnitude (both absolute and relative) of C loss following cultivation remain (Davidson and Ackerman 1993). In particular, little is known of the role that climate plays in the response of soils to cultivation (Burke et al. 1989).

In this paper, we evaluate two large data sets of natural and cultivated SOC and SON within two climatically distinct regions: India and the Great Plains, USA. India encompasses climates where present deforestation/clearing activity is now the greatest (semi-arid to humid tropics and sub-tropics) and the Great Plains encompasses climate zones where agricultural expansion in the $19^{th}/20^{th}$ century is now being partially returned to range or forest (temperate grasslands). Assessing patterns that occur across large regions and comparing these patterns across continents allows us to evaluate generalities, and potentially make predictions for future conditions (Paruelo et al. 1998). Our objective was to compare data for India and the Great Plains, focusing on (1) the effect of climate on native SOC and SON, (2) the effect of cultivation on the absolute and relative losses of SOC and SON, and (3) differences between the two regions and how they compare to general global trends.

Data set background

A. India

A survey of SOC and SON in cultivated and native soils of India by Jenny and Raychaudhuri (1960) has not previously been used in recent evaluations of the effect of cultivation on soil organic matter storage. A likely reason is the relative obscurity of the publication. Here we report the methods of the data collection and report on how we sorted and analyzed the data. In the Jenny and Raychaudhuri study, soils were sampled throughout India between the latitudes of 8 and 32 degrees N. The mean annual temperatures (MAT) ranged from 10 to 30 °C while the mean precipitation (MAP) ranged from near 0 to over 5 meters (Figure 1). The soils span a breadth of tropical and subtropical climates.

These data have several positive characteristics. First, the authors chose sites to minimize the effect of confounding factors (topography, etc.) in order to highlight the effects of MAT and MAP on SOC and SON storage. Second, the data are comparable in depth to analyses of the Great Plains by Burke et al. (1989). Finally, the sheer number of sites (> 500) makes this comparison valuable. However, the India data are not perfect for present-day C storage analyses: (1) soils were sampled only from the upper 20 cm and (2) bulk density was not measured. The data set is available electronically upon request.

Soil samples were collected in India between December, 1954 and April, 1955. Sites were chosen with an emphasis on nearly-level, well-drained surfaces and, where possible, native vegetation. Each soil was sampled to a depth of 20 cm. Laboratory analyses were conducted in Berkeley, California. Meteorological data were obtained from a network of official government meteorological stations, many initiated in 1881, and were complemented by information from several local Indian

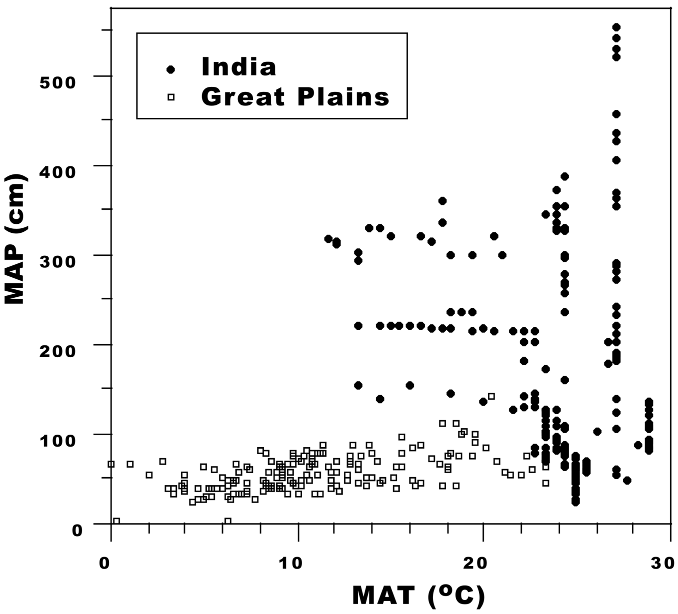

Figure 1. The climatic ranges for India and The Great Plains data sets.

sources. The MAT and MAP for a given sampling location was estimated by interpolating between nearby stations or by developing climate vs. elevation relationships from meteorological stations in mountainous regions (Jenny and Raychaudhuri 1960).

Soil analyses were reported on an oven dry soil basis (110 °C for 24 h). Moisture retention at 1/3 bar suction was determined using a pressure-plate apparatus. Total N was determined using the Kjeldahl technique (Bremner 1965), which measures organic N and NH_4^+. Inorganic C was measured manometrically following acidification with HCl (Williams 1948). Organic C values were determined by loss on ignition (Allison et al. 1965), after correcting for inorganic C.

Data reduction

The original data contained C and N analyses for over 520 soil samples, and required some refinement to perform statistical analyses. Data were manually transferred from analog text to a digital spreadsheet and separated into two fields: cultivated and natural soils. Many of these samples are same-site replicates. In order to avoid overrepresentation errors in the regression analyses, the replicate values were averaged to obtain a single value for each cultivated and/or natural soil of that location. The number of replicate values for a location varied from 2 to 12. The data were then grouped into 8 geographic zones as suggested in the text (Assam Hills and Valleys, Deccan Plateau, Hill and Ridge Soils, Himalaya Ranges, Indo-Gangetic Alluvium, South East Coast, Tist-Brahmaputra Plains, West Coast).

Within each zone or region, individual soil units were separated by locality (city or place name) and by climate (where the temperature and rainfall range differed by less than 1.1 °C (MAT) or cm of precipitation (MAP)). Following this grouping, the India soil data were represented by 175 individual cases (Table 1).

Clay content is an important control on SOC and SON storage (e.g., Torn et al. (1997)). Jenny and Raychaudhuri (1960) were not able to maintain a constant clay % among all sites. Instead, they conducted a post-sampling analysis to determine whether clay content had a major role on the observed geographical trends in SOC and SON. Briefly, Jenny and Raychaudhuri (1960) derived a model in which clay and SOM were the two contributors to soil moisture retention. From this, a value was empirically determined to represent a generalized SOM/moisture retention factor. By subtracting the SOM contribution to the moisture retention of a sample, we obtained the fraction of the moisture retention apparently due to clay for each sample. The SOM/moisture factor was subsequently plotted against SOC and SON for the entire data set and no statistically significant relationship was seen ($P > 0.05$), which indicates that climate (and not clay content) was the primary control on patterns of SOC and SON in this study.

Using MAT and MAP as the independent variables, and the measured soil properties as the dependent variables, multiple regression analyses were performed to determine the patterns of soil C and N for the different data sets. We chose MAP and MAT as the climatic proxies because of their availability and their common use as climatic variables in soil ″climosequences″ (Amundson and Jenny 1997). The results of the analyses produced ″best fit″ regression models using a logarithmic relationship of soil properties to climate (Table 1). We used the t-ratio as an appropriate method for standardizing the relative contribution of each variable to the model. The multiple regression equations were subsequently utilized to construct 3-dimensional surface trend models.

B. Great plains

The Great Plains soils examined here lie between approximately 30° and 50° N and 85° and 105° W. The climate of the Great Plains ranges from sub-humid to arid, with warm to very cool MATs (Laurenroth and Burke 1995). The climate varies from 0 to 25 °C MAT and from near 0 to a little over 100 cm MAP. There is no overlap between the climate ranges of India and the Great Plains (Figure 1).

These data previously were used in a study of cultivation effects on soil organic matter in the Great Plains (Burke et al. 1989). Here we re-examine the data for comparisons to the India soils and to address some additional questions regarding soil response to cultivation. The data consist of chemical and physical properties of about 500 natural and 300 cultivated soils from USDA-NRCS databases.

Data reducing was difficult to do (we lacked the background site information that was available for the India data), and therefore the data were used in their entirety. *Apriori*, we expected MAT and MAP to explain much of the SOC and SON distribution based on the analyses of Burke et al. (1989). Multiple regression models, and 3d figures, were developed employing the procedures described above for

Table 1. Multiple regression model parameters for the India, Great Plains to 20 cm, Great Plains to 100 cm, and global data sets. Temperature is in degrees C and precipitation in mm. India C and N data in %, Great Plain in kg m^{-2} (to depth indicated), and Holdridge data in kg m^{-2} to 100 cm.

Land Use	Variable	Site (depth)											
		India (20 cm)			Great Plains (20 cm)			Great Plains (100 cm)			Holdridge		
		Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio
Natural SOC	Intercept	16.84	(2.69)	6.26	−2.63	(0.78)	−3.37	−3.41	(2.25)	−1.51*	−4.93	(5.338)	−0.92*
	Log P	1.94	(0.51)	3.84	8.04	(0.59)	13.70	14.44	(1.68)	8.61	12.43	(2.067)	6.01
	Log T	−13.88	(1.62)	−8.58	−6.93	(0.57)	−12.20	−10.47	(1.58)	−6.61	−16.68	(2.874)	−5.81
		[r^2 = 0.61]	[n .= 70]		[r^2 = 0.28]	[n .= 557]		[r^2 = 0.14]	[n .= 482]		[r^2 = 0.67]	[n .= 27]	
Natural SON	Intercept	1.13	(0.18)	6.26	0.04	(0.105)	0.38*	−0.027	(0.27)	−0.11*	−0.39	(0.575)	0.67*
	Log P	0.14	(0.034)	4.04	0.57	(0.075)	7.61	1.08	(0.19)	6.33	0.78	(0.211)	3.68
	Log T	−0.93	(0.11)	−8.54	−0.63	(0.065)	−9.76	−0.95	(0.16)	−6.27	−0.88	(0.265)	−3.34
		[r^2 = 0.62]	[n .= 70]		[r^2 = 0.25]	[n .= 314]		[r^2 = 0.14]	[n .= 308]		[r^2 = 0.46]	[n .= 25]	
Natural C/N	Intercept	15.16	(4.25)	3.56	6.462	(−1.406)	4.6	15.171	(2.950)	5.14	6.52	(5.715)	1.14*
	Log P	3.07	(0.80)	3.84	3.796	(−1.005)	3.78	0.026	(2.124)	0.01*	5.47	(2.094)	2.61
	Log T	−6.91	(2.56)	−2.70	−1.412	(−0.864)	−1.63*	−2.064	1.870)	−1.10*	−5.43	(2.634)	−2.06
		[r^2 = 0.30]	[n .= 70]		[r^2 = 0.0.05]	[n .= 309]		[r^2 = 0.006]	[n .= 300]		[r^2 = 0.28]	[n .= 25]	

Table 1. Multiple regression model parameters for the India, Great Plains to 20 cm, Great Plains to 100 cm, and global data sets. Temperature is in degrees C and precipitation in mm. India C and N data in %, Great Plain in kg m^{-2} (to depth indicated), and Holdridge data in kg m^{-2} to 100 cm.

Land Use	Variable	India (20 cm)			Great Plains (20 cm)			Great Plains (100 cm)			Holdridge		
		Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio	Parameter	STD Error	t-ratio
Culti-vated SOC	Intercept	6.62	(1.75)	3.79	0.988	(1.16)	0.85*	0.077	(3.70)	0.20*			
	Log P	1.52	(0.28)	5.34	5.76	(0.77)	7.48	12.35	(2.46)	5.03			
	Log T	−6.32	(1.06)	−5.98	−7.09	(0.52)	−13.64	−10.92	(1.66)	−6.58			
		[r^2 = 0.48]	[n .= 105]		[r^2 = 0.33]	[n .= 380]		[r^2 = 0.11]	[n .= 380]				
Culti-vated SON	Intercept	0.72	(0.10)	7.29	0.0915	(0.13)	0.68*	−0.137	(0.34)	−0.40*			
	Log P	0.11	(0.016)	6.87	0.437	(0.094)	4.62	1.08	(0.24)	4.56			
	Log T	−0.62	(0.060)	−10.30	−0.518	(0.059)	−8.71	−0.866	(0.15)	−5.79			
		[r^2 = 0.67]	[n .= 106]		[r^2 = 0.23]	[n .= 258]		[r^2 = 0.12]	[n .= 260]				
Culti-vated C/N	Intercept	6.58	(3.87)	1.70*	12.699	(7.744)	1.64*	21.692	(9.668)	2.24			
	Log P	3.02	(0.63)	4.77	5.253	(5.406)	0.97*	−4.727	(6.762)	−0.70*			
	Log T	−1.33	(2.34)	−0.57*	−9.24	(3.384)	−2.73	0.115	(4.243)	0.03*			
		[r^2 = 0.23]	[n .= 104]		[r^2 = 0.03]	[n .= 255]		[r^2 = 0.003]	[n .= 257]				

* indicates that a parameter t-test was not significant to P = 0.05

the Indian soils. These models differ from those of Burke et al. (1989) in that they are simple, first order multiple regression models using only climate as the independent variables. Burke et al. (1989) examined the higher order dependence of C on climate and the effect of texture. Neither silt nor clay content by itself was a significant predictor of soil organic matter (Burke et al. 1989), but (precipitation × silt) and (precipitation × clay) proved significant, though the regression coefficients of these combinations were about two orders of magnitude smaller than the climatic parameters alone. Therefore in order to compare to the India data, while admittedly a simplification of all factors affecting soil C and N, we examine only the effect of climate on the Great Plains data.

C. Global (Holdridge life zones)

A global data set provides a reference to which the regional trends can be compared. We used the mean SOC and SON content of Holdridge Life Zones (Post et al. 1982, 1985), the median MAT and MAP for each life zone as listed on the Holdridge ″triangle″ (life zones are defined by defined ranges in MAT, MAP, and potential evapotranspiration) (Holdridge 1947), and analyzed these data via multiple regression analyses as described above. Out of 29 life zones identified by the Holdridge triangle, we eliminated 2 zones (subtropical desert bush and subtropical wet forest) because only 1 data point existed within those zones.

Results

C and N content of native soils vs. climate: 0–20 cm depth

Natural (uncultivated) SOC and SON for both India and the Plains were positively correlated with MAP and negatively with MAT (Table 1), a relationship observed in previous analyses (Jenny 1930; McDaniel and Munn 1985; Burke et al. 1989). The effect of MAT (vs. MAP) on SOC and SON was far greater for India than for the Great Plains, because the Plains are drier and decomposition processes are strongly linked to precipitation (Epstein et al. 2002). Both climatic coefficients of the Plains SOC and SON were very similar to those of the Holdridge data (Post et al. 1982, 1985) (Table 1), while the temperature dependence in India resembled the Holdridge data set. In India, the only regional data set for which a statistically significant C/N model could be developed, the C/N ratio increased with increasing MAP and decreasing MAT. This was similar to global trends of C/N (Post et al. 1985).

The strength of the climatic relationships, as reflected by the r^2 values, was relatively poor for the Plains data but was similar to the climate relationships for raw data used to develop Holdridge averages. The high r^2 of mean values for individual life zones (mean values were used in our Holdridge model) obscures the large variance of raw data within the Life Zones (see Post et al. (1982, 1985) for variance values). A preliminary analysis using all raw soil data (used in the Post et al. analyses) that had corresponding climate data (~ 1000 soils) had a low correlation to climate (r^2 = 0.19 for SOC and 0.068 for SON). For India, strong relationships with climate were shown for natural SOC and SON (r^2 = 0.61 and 0.62 respectively) while the C/N was weaker (r^2 = 0.30) (Table 1). The strong correlation for India is likely due to the combined effects of sampling strategy and data reduction. In the end, both the India and Great Plains data sets correlate better with climate than the raw global data we used. This is not surprising in that the Holdridge soil data contain numerous parent materials, topographies, ages, etc. (Post et al. 1982), all of which affect C storage. While the correlation is in many cases low, all models reported were statistically significant ($P < 0.05$).

Effect of cultivation on SOC and SON Contents in 0–20 cm depths

Because the cultivated and non-cultivated soils were not deliberately paired, we used multiple regression analyses to examine the effects of climate on cultivated soil properties, and their differences relative to native soils. Table 1 reports the regression models of C, N, and C/N for the cultivated soils in India and the Great Plains. In general, SOC and SON in cultivated soils are also inversely related to MAT and positively related to MAP, although the model coefficients are different than for the native soils. In India, cultivated soil had a lower temperature dependence than native soils. In the Plains, the SOC dependence on MAP was reduced slightly.

The natural C/N ratio increased in India with decreasing MAT and increasing MAP, with maximum values around 15. Cultivated C/N, however, varied with precipitation only and had a narrower range of values extending from around 13 at high MAP to around 9 at low MAP. The C/N models for the Great Plains were not statistically significant (using only climate variables) and are not reported. The microbial processing of soil organic matter progressively reduces the C/N ratio of incoming, labile, plant material (25/1 or more) to that approaching microbial cellular material (5/1 to 10/1) (Paul and Clark 1996). For India, it is likely that the difference in C/N between these two land use categories is a result of the enhanced microbial activity induced by cultivation and has lead to a preferential reduction of high C/N, and presumably labile, SOC pools in the cooler regions.

Because there were no paired soils in native and cultivated systems, our approach was to assume that uncultivated and cultivated soil conditions are related by origin but differ only as a result of land use practices. To calculate loss, we combined the two models mathematically, which ignores actual data values and therefore loses statistical information. It is important to know whether or not the model differences between cultivated and uncultivated conditions have some statistical significance. We therefore derived model interaction statistics between the two data sets. This was achieved by using a ″dummy″ variable to represent the cultivated condition in a model that incorporates data from both conditions. The result is a set of interaction variables where the cultivation effect is added to a model for uncultivated conditions, allowing us to determine the significance of the cultivation factor to the model statistics. This generated a set of statistics that describes the contribution to the model from the cultivation variables (interaction variables) using both t-ratios and P-values (Table 2).

In India, the greatest absolute losses of SOC and SON apparently occur in climatic regions where naturally high concentrations of SOC and SON are found (low temperature) whereas the Great Plains display the greatest losses of SOC from soils in higher rainfall regimes (Figures 2 and 3). In general, greater absolute SOC losses tend to occur in regions of increasingly cool and/or moist climates depending on the region. Soils in the Great Plains appear to lose greater SON with both increasing MAT and MAP, though the interaction variable was significant only at the $P < 0.200$ level, which may arguably be relevant for the coarse scale of this analysis. The C/N ratios of cultivated Indian soils appear to decrease most dramatically at low MAT's, but this model is also significance only at the $P < 0.200$ level ($P = 0.111$).

Discussion

Relative C and N losses with cultivation and climate

A better understanding of the relative losses of soil C and N during cultivation is important for two reasons. First, if fractional C loss is geographically variable, then it will be useful to more accurately predict soil C response to on-going and future land-use changes. Second, a geographical understanding of the fractional C loss is useful in projecting the C sequestration potential of cultivated soils following land abandonment (assuming climate remains constant). Presently, there is some disagreement on the factors controlling relative SOC losses during cultivation. Mann (1986) and Post and Mann (1990) suggest that the fractional loss of C correlates to original C content whereas Davidson and Ackerman (1993) question this idea after analyzing consistently sampled, paired plot (cultivated vs. non-cultivated) comparisons (18 different studies). Davidson and Ackerman (1993) found that (1) about 20 to 40% of the initial soil C inventory is lost by cultivation, (2) the rate of loss declines quickly during the first 20 years, but that (3) the fractional loss was not correlated to the original amount present.

Here, we explore how the fractional loss of soil C behaves with climate by utilizing the regression models for both regions because paired data were not available. In this exercise, the fraction of C that remains following cultivation is:

$$SOC_{remaining}(\%) = [(SOC_{uncultivated}) - (SOC_{cultivated})]/(SOC_{uncultivated}) \times 100$$

where SOC = regression model for SOC (or SON) for cultivated and non-cultivated data sets. In this analysis, we were forced to slightly restrict the climate range to avoid distortions in regions of the figures (i.e., models) where the denominator approaches 0.

Table 2. Interaction statistics between cultivated and non-cultivated soil properties using a dummy variable approach for regression model parameters of India, Great Plains to 20 cm, and Great Plains to 100 cm.

Soil Variable	Statistical Parameter	Site (depth)					
		India (to 20 cm) t-ratio	P-Value	Great Plains (to 20 cm) t-ratio	P-Value	Great Plains (to 100 cm) t-ratio	P-Value
SOC	Intercept	7.43	0.0001	−3.58	0.0004	−1.52	0.1277
	Log P	4.56	0.0001	14.57	0.0001	8.67	0.0001
	Log T	−10.18	0.0001	−12.97	0.0001	−6.65	0.0001
	Log P/Cult	−0.77	0.44	−2.23	0.0257	−0.59	0.5547
	LogT/Cult	4.1	0.0001	−0.22	0.8284	−0.18	0.8593
	Cult	−3.35	0.001	2.44	0.0150	0.67	0.5010
SON	Intercept	7.95	0.0001	0.18	0.8545	0	0.9975
	Log P	5.13	0.0001	8.6	0.0001	6.46	0.0001
	Log T	−10.84	0.0001	−10.85	0.0001	−6.42	0.0001
	Log P/Cult	−0.84	0.405	−1.19	0.2340	0.06	0.9516
	LogT/Cult	2.67	0.0084	1.33	0.1837	0.28	0.7826
	Cult	−2.15	0.033	0.41	0.6818	−0.3	0.7658
C/N	Intercept	3.54	0.0005				
	Log P	3.82	0.0002				
	Log T	−2.68	0.008				
	Log P/Cult	−0.04	0.965				
	LogT/Cult	1.6	0.111				
	Cult	−1.49	0.138				

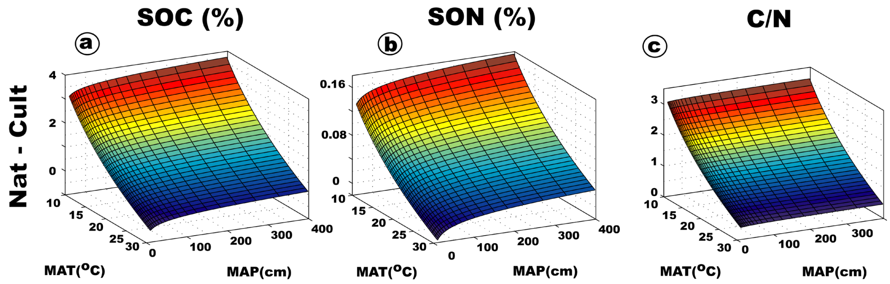

Figure 2. Multiple regression-based comparison showing absolute cultivation-induced changes in SOC, SON, and C/N as a function of climate in India

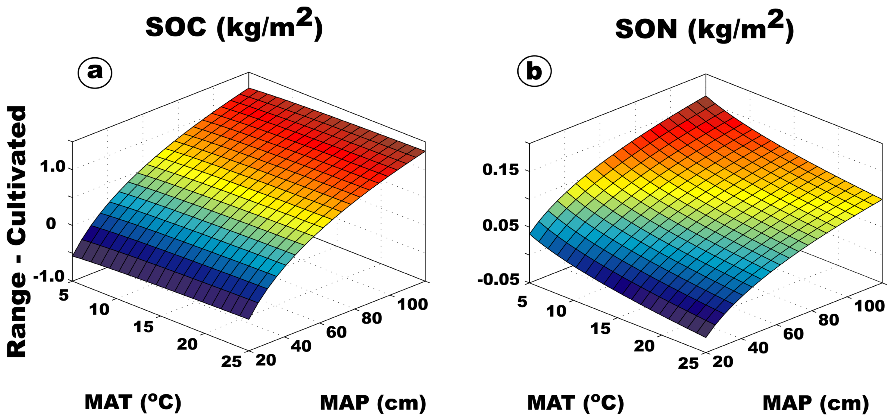

Figure 3. Multiple regression-based comparison showing cultivation-induced changes in SOC and SON as a function of climate for the Great Plains.

Our results reveal that the greatest relative C losses in India (about 50%) occur in areas with a low MAT, and the relative loss decreases to about 10% with increasing MAT's (Figure 4a). For India, greater relative C losses coincide with increasing quantities of original SOC (compare to model in Table 1). The trend in relative losses for India (which correspond to high initial SOC contents) are possibly explainable by the fact that the uncultivated soils with the highest SOC have the highest C/N ratios, indicating the presence of significant proportions of ″labile″ organic matter. In contrast, the Plains models suggest the greatest relative SOC losses occur at high MAP and MAT, with gains apparently occurring under very arid conditions (Figures 4b & 4c). Additionally, in the Plains, the trends of relative SOC loss seem to be unrelated to original SOC content (compare to model in Table 1).

The model for relative SOC loss in the Great Plains shows different climate trends than for India. The basis for this observation may be, in part, explainable by the history of land cultivation practices. The increasing relative losses with increasing MAT may be related to the fact that dryland agriculture in the west central to southwest Great Plains relies on winter wheat with a fallow rotation the following

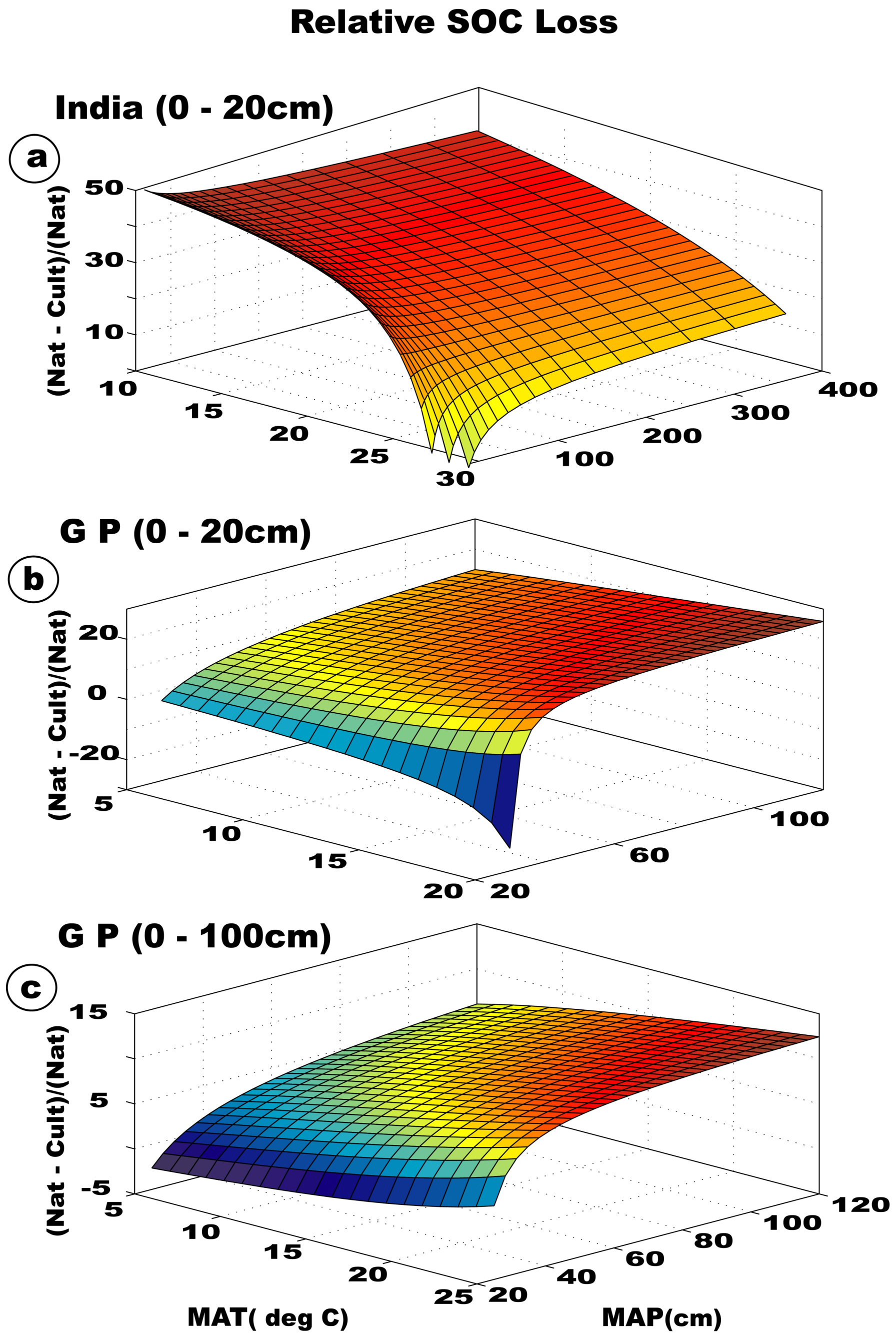

Figure 4. The relative loss in SOC from: (a) the upper 20 cm of India soils; (b) the upper 20 cm of soil in the Great Plains; (c) the upper 100 cm of soil in the Great Plains.

year. During the fallow year, fields are kept bare with no plant C inputs, a situation that would promote relatively larger losses of SOC and SON than agriculture that promotes annual C inputs. Second, the low relative SOC losses at low MAT's ($\sim$7–10 °C) (e.g., parts of Colorado, Nebraska, South Dakota, Minnesota, North Dakota), may coincide with the decline in intensive agriculture (e.g corn and soybean production), and the length of time that agriculture has been practiced, due to temperature limitations. Alternative land-uses (such as small grain production, etc.), and occurrences of land abandonment during periods of climatic stress, particularly in dry regions (Burke et al. 1991), may have resulted in a relative preservation of SOC at this end of the Great Plains temperature/precipitation spectrum. Third, the Great Plains (and American agriculture in general), has benefited from large additions of industrially fixed N, which not only stimulates crop production, but promotes the retention of SOC (which maintains a relatively constant range of C/N ratios) (e.g., Paustian et al. (1997)). An unknown differential geographical application of N fertilizer would likely add complexity to SOC response to cultivation. In contrast, the India data were collected in the early 1950's, a period before the widespread use of N-based fertilizers in this area, and thus possibly provides a less complicated and more direct representation of the organic matter changes caused by cultivation *per se*.

Significance to C sequestration potential of soils

The two data sets examined here have provided added insights into geographical patterns of absolute and relative SOC loss due to cultivation. Alternatively, the combined C and N data provide some guidance to the potential of these cultivated lands to sequester SOC if converted back to native range or related vegetation. The availability of N, which stimulates both NPP and stabilization of SOM, is a key to SOC sequestration. Two measures that may be considered to control C sequestration potential are: (1) the total amount of SOC lost via cultivation (a measure of ″total sequestration potential″); and (2) the change in the total SON, or the C/N ratio (a related index), with cultivation (e.g., N availability is the ″rate control on C sequestration″). This concept applies only to regions not limited by P. The difference between the uncultivated and cultivated total N and/or C/N ratios, which reflects N loss or conservation during agriculture, is likely the key to how quickly soils may recapture SOC upon conversion to range or native flora. Knops and Tillman (2000) examined abandoned fields in Minnesota and found that rates of SON accumulation, driven by atmospheric N deposition and biological N fixation, controlled rates of C sequestration. If a soil loses little N during cultivation (and the C/N ratio decreases) there should be, as a first approximation, a smaller inherent nutrient limitation for the site to recapture some or much of its native steady state SOC pool.

In India, the total SOC loss, and decline in C/N ratios, increases with decreasing temperature, indicating that the cooler soil regions of India not only have a large potential for C storage, but a lesser N limitation than warmer climates. Unfortunately, we were not able to arrive at any models of C/N for the Great Plains with any acceptable level of confidence.

This hypothesis that soil C gain is partially controlled by N availability, and that this is regionally variable, is consistent with a growing literature on SOC and SON storage in the years following land abandonment in the US Conservation Reserve Program. Paustian et al. (1997) in a review of existing data, suggested that the rate of C sequestration upon abandonment/conversion increases with increasing precipitation. Gebhart et al. (1994) report that soils in the semi-arid regions of Texas, Kansas, and Nebraska gained an average of 1.1 tons C ha^{-1} yr^{-1} while Ihori et al. (1995) and Robles and Burke (1998) have found that in the aridic to semi-arid short grass steppe of Colorado and Wyoming, total SOC sequestration following land conversion is almost unobservable over decadal timescales. Clearly, precipitation enhances NPP and C inputs. However, the relatively low rates of atmospheric N deposition in the arid western Great Plains (NADP 1998) are also a slow means of restoring SON, and thus SOC. In contrast, present rates of N deposition increase with precipitation in the central to eastern portion of the Plains (NADP 1998), supporting an observation from Paustian et al. (1997) that C sequestration rates increase with MAP. In summary, it seems that nutrients, as well as climate, likely have a role in the C response of lands to agricultural abandonment (Post and Kwon 2000).

Conclusions

Natural soil C and N patterns are controlled by climate and an array of secondary factors which include parent material, soil age, topography, and the potential biota. Regional analyses of native soils in India and the Great Plains conform to overall climate controls. Here we have also shown that soil C and N response to cultivation appears to be climatically controlled, but that there are some differences with regard to these patterns between our two regions. For the Great Plains, as well as other large agricultural regions, a myriad of agricultural practices may partially distort underlying climatic controls (if they do indeed exist) on cultivated soil C and N losses. The results suggest that no one value (for relative C loss following cultivation) adequately describes the loss of SOC everywhere, and that accurate estimates of C loss will vary with climate and other factors. If the apparent climatic controls on relative C loss are ultimately shown to be widely applicable for tropical regions, then a more accurate assessment of land use change on atmosphere CO_2 budgets will ultimately be possible.

The relative losses of C and N during cultivation is a contributing factor when considering a soil's organic matter response to a reversal of land management back to natural flora. The apparent differential loss of N relative to C across the Great Plains would appear, at least initially, to correlate to the wide range of observed C sequestration rates reported for abandoned lands in this region (Paustian et al. 1997).

As the global population grows, soils will increasingly be affected by a variety of human activities and changing environmental conditions. The integrated impact of these changes will have increasingly large effects on the global cycles of C and N. More local and regional studies are needed to quantitatively project the response of ecosystems to these perturbations. The data reported here, though coarse in nature, suggest that the responses may be variable, but possibly predictable, in relation to fundamental pedological concepts (Jenny 1941).

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