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FEATURE

Impact of soil erosion on soil organic carbon stocks

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Soil erosion by wind and water and subsequent sediment transport and depositional processes may lead to soil organic carbon (SOC) loss especially from a sloping agricultural land unit. The erosion processes change land unit SOC stock by transporting SOC-rich sediment off an agricultural land unit, oxidizing SOC stocks, and releasing carbon dioxide (CO_2) into the atmosphere, as well as causing loss of SOC through surface runoff. Thus, erosion, transport, and depositional processes redistribute landscape SOC, enhance oxidation, and create a SOC source and a sink. However, redistributed SOC to bottomland soils is not sequestered SOC if it originates outside the borders of the measured land unit. In order to establish an active sink for soil carbon (C) sequestration, plants on a land unit must take CO_2 from the atmosphere and store it in the humus or SOC fraction within the agricultural land unit. Therefore, the objective of this review and analysis paper is to understand and highlight the effects of soil erosion, transport, and deposition of SOC stock.

Natural or so-called geological erosion, an important terrestrial process, has shaped the surface of the earth and formed some of the most fertile (alluvial and loess) soils since the beginning of time. However, acceleration of this process by anthropogenic activities (e.g., deforestation, biomass removal/burning, plowing, drainage, and change in land use by conversion of natural ecosystems to managed agroecosystems) has adversely affected the SOC stock, impacted water resources, and negatively impacted the net primary productivity of the land as a source for SOC stocks and the environment (Lal et al. 1998).

Before determining the impacts of wind and water erosion, and their related processes of transport and deposition on SOC stocks, we need to establish clear standard for SOC stock recharge. This mechanism is referred to as SOC sequestration (Olson 2013; Olson et al. 2014a, 2014b; Sundermeier et al. 2005; Lal et al. 1998; Mann 1986). The definition of soil C sequestration requires that an agricultural land unit with borders must be identified for monitoring soil C sequestration, storage, retention, and loss. There are three basic types of land units (study plots) often used by researchers for actually measuring SOC stock change and sequestration: (1) eroding, (2) depositional, and (3) mixed landscape (combined eroding and depositional). The SOC of these three types of land units is impacted differently by the mechanisms of wind and water erosion, transport, and deposition. The underlying effects of soil erosion process are biological, physical, and chemical changes of the SOC stocks. Soil erosion processes and mechanisms negatively affect the SOC sequestration amounts and rate, and jeopardize soil productivity (Lal 2003) and increase greenhouse gas (GHG) emissions (MEA 2005).

Land units, especially sloping and eroding, under row cropping systems with intensive tillage, can lose considerable amount of sequestered SOC stock and sediment through water and wind erosion. Troeh et al. (2004) state, "The sorting action of either water or wind removes a high proportion of the clay and humus from the soil and leaves the less productive coarse sand, gravel, and stones behind. Most of the fertile soil is associated with the clay and humus." Change in land use is a major factor affecting the SOC stock, especially in sloping soils prone to erosion, as the land use is changed from native prairie or forest to conventional and erosive row crop agricultural systems (Olson et al. 2012, 2013a, 2013b). Franzluebbers and Follett (2005) reported that the SOC stock of timberland and prairie soils declined with cultivation in North America. The rate of decline was 25% + 33% for southwestern, 36% + 29% for southeastern, 34% + 24% for northwestern, and 22% + 10% for the northeastern United States. Lal (1999) reported SOC stock loss by cultivation of 30% in the north-central United States. This compares with a summary of historical studies in the Great Plains by Cihacek and Ulmer (1995). Depending on the length of time, cultivation resulted in SOC losses of 7% to 51% with longer periods of cultivation showing more SOC loss than shorter terms of cultivation (see table 1). They also summarized the effects of tillage or residue management where the latter showed positive increases in SOC while various intensities of tillage reduced SOC by 1% to 51% (see table 2) (Cihacek and Ulmer 1995). However these "classical" studies do not often clearly define what their baseline SOC stock was at the start of the studies to permit verification of results.

These losses in SOC can be attributed to several processes that include the acceleration of SOC loss by mineralization of SOC stock and water and wind erosion where sloping soils are devoid of crop residue cover. The role of erosion process in changing soil C stocks is by a preferential transport of the light organic component and alteration of the soil physical and biological properties, which are drivers for soil C sequestration.

Results from field experiments (Salemme and Olson 2014; Olson et al. 2014c, 2013a, 2011; Kumar et al. 2012; Gennadiyev et al. 2010) have shown, after approximately 150 years of agricultural use and accelerated soil erosion, that the agricultural lands have significantly less SOC stocks of the same soil than when previously under a native forest or prairie. Table 1 summarizes the percent change in native SOC stocks after 90 to 150 years of agricultural use. Some researchers (Salemme and Olson 2014; Olson et al. 2014c, 2013a, 2011; Kumar et al. 2012; Gennadiyev et al. 2010) reported that the conversion of prairie to agricultural land

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for 90 to 140 years resulted in a loss of between 20% and 51% of the SOC stock, and conversion of forest to agricultural land for 100 to 150 years resulted in a SOC stock loss of 10% to 52%. Thus, it is essential to understand the effects of soil erosion in the context of agricultural use, especially in intensive agriculture production systems, where erosion process becomes a driver in establishing C sources and loss as CO_2 rather than a significant contributor to soil C retention within a land unit (Lance et al. 1986).

Olson et al. (2013b) and Young et al. (2014) showed that nearly level (<1%) upland agricultural plots were also subject to erosion, transport, and deposition of SOC-rich sediments. It has often assumed that plots with nearly level (<1%) slope gradients have been significantly affected by erosion. Tillage can accelerate the loss of soil C stocks in conventional agriculture systems. Intensive tillage plays significant role in accelerating soil C loss through oxidation of organic matter, destruction of soil aggregates, and reduction in water infiltration rate leading to significant water erosion and surface runoff of C-rich sediments. Olson et al. (2013b) used a fly ash method and determined the SOC concentration of Muscatune and Sable soils for a nearly level (<1%) agricultural plot area located near Monmouth, Illinois. The crop sequence was corn (*Zea mays*) and soybean (*Glycine max*) for the previous 27 years, and plot area had been cultivated for the last 130 years. There was no tile drainage system in the plot area. The 0 to 50 cm (0 to 20 in) layer of Sable soil had a 19% higher fly ash content and 4% more SOC than the Muscatune soil. The erosion rate, using the fly ash method, was 4.35 Mg ha^{-1} y^{-1} (1.98 tn ac^{-1} yr^{-1}), which was more than the calculated RUSLE2 erosion rate of 3.3 Mg ha^{-1} y^{-1} (1.50 tn ac^{-1} yr^{-1}). Approximately, 6 cm (2 in) of the 21 cm (8 in) difference between Sable and Muscatune A horizons was a result of the erosion of the Muscatune soils and the deposition on the Sable soils. The remaining difference (15 cm [6 in]) was a result of higher water table and saturated or anaerobic soil conditions for much of the time, which protected the SOC from decomposition.

Table 1

The effects of soil erosion through land use change on soil organic carbon (SOC) stocks.

Location	Land use	Years of cultivation	Soil organic carbon (% change from native vegetation baseline)	References
Brookings, South Dakota	Prairie	—	Baseline	Olson et al. 2014c
	Cropland	90	–20%	
Harlan, Iowa	Prairie	—	Baseline	Salemme and Olson 2014
	Cropland	140	–51%	
Knoxville, Illinois	Forest	—	Baseline	Olson et al. 2013a
	Cropland	150	–52%	
Albany, Illinois	Forest	—	Baseline	Olson et al. 2011
	Cropland	150	–48%	
Dixon Springs, Illinois	Forest	—	Baseline	Olson 2007
	Cropland	140	–10%	
Hanover, Illinois	Forest	—	Baseline	Gennadiyev et al. 2010
	Cropland	140	–35%	
Hoytville, Ohio	Forest	—	Baseline	Kumar et al. 2012
	Cropland	100	–52%	
Wooster, Ohio	Forest	—	Baseline	Kumar et al. 2012
	Cropland	130	–35%	

WIND AND WATER EROSIONAL PROCESSES IMPACT ON SOIL ORGANIC CARBON STOCK

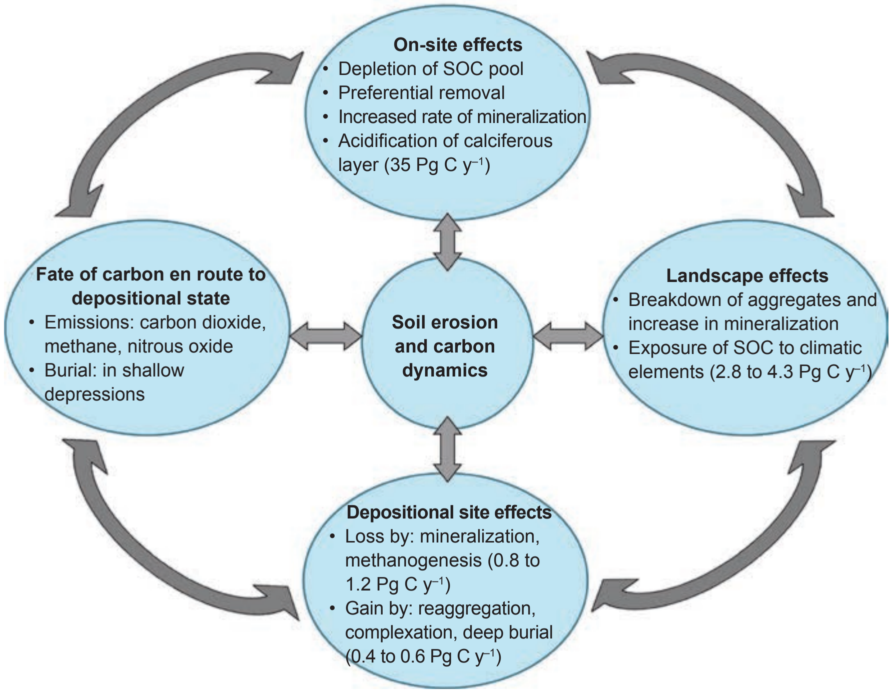
Soil erosion is a four-step process: (1) breakdown of structural aggregates, (2) transport of C and sediment in water runoff or wind, (3) redistribution of C and sediment over the landscape, and (4) deposition and burial of C and sediment in depressions under inundated anaerobic conditions (figure 1) (Lal 2003).

Basic principles governing the fluvial processes are similar for wind erosion whereby aggregates are disrupted exposing the hitherto encapsulated C to microbial attack and mineralization. The lighter fraction is carried much farther than a heavier fraction by both wind and water processes. The enrichment ratio (ER) of SOC for wind-driven sediments (e.g., ratio of C in the sediments carried by wind to the C in the original soil [Chepil 1945]) can be greater than 5. Similarly, the ER for SOC in water-carried sediments from runoff plots with short slope length (~25 m [82 ft]) may range from 3 to 5 (Lal 1976a, 1976b, 1976c). The high ER for soil C (organic and inorganic) for wind-blown deposit is due to fine size (<2 μm [79 μin]) for both organic and inorganic particles. Once air-borne, the light C fraction can be carried long distances. However, Cihacek et al. (1992) worked with sand grain–sized wind erosion sediments on high clay soils (Vertisols) and soils with higher SOC stock. Soil particles smaller than sand moved if wind has enough energy. In contrast, heavy particles (sand and fine gravels) move in close proximity to the ground surface (Stoke's law) by a process called "saltation" by which one particle strikes another setting up a chain reaction (Troeh et al. 2004).

Deposition of soil particles by saltation or surface creep also results in wind erosion sediments often being deposited on the leeward side of landscapes and on specific landscape features (e.g., depositional areas or drainage features) that reduce wind velocity (Bagnold 1941). Areas of permanent vegetation near wind eroding soils can capture substantial quantities of SOC-containing sediments (Cihacek and Ulmer 1997; Cihacek and Meyer 2002). Direct deposition of fresh or aged plant materials occurs where the materials move along with soil sediments in wind erosion events, sliding across the soil surface until a leeward face of a drift is reached. At this point, the plant materials drop out of the wind stream and are buried within the sediment deposit, enriching the SOC as the plant materials decompose at a later time.

Figure 1

Fate of soil organic carbon (SOC) transport by erosional processes. Modified and adapted from Lal (2003).



Soil erosion is caused by energy from water, wind, gravity, and chemical reactions. However, water erosion receives most attention because its after-effects are more noticeable and it is linked to other negative outcomes, such as water quality and loss of productivity that resonate with the general populations of the United States through its link with food insecurity. Transport of SOC and nutrients by windblown soil particles is of potential relevance to water quality (Cihacek et al. 1992) Wind eroded sediments have been analyzed for SOC and major nutrients by other investigators but primarily in relation to the effects of wind erosion on soil quality and productivity (Larney et al. 1998; Leys 1994; Stoorvogel et al. 1997; Van Pelt and Zobek 2009).

Detachment of soil particles and breakdown of aggregates by the kinetic energy of raindrops and/or the velocity of flowing water and blowing wind is a process exactly the opposite of formation of aggregates according to the hierarchy theory (Tisdall and Oades 1982). The SOC encapsulated within the stable aggregates is protected against microbial processes and has a long mean residence time. Breakdown of structural aggregates exposes the SOC hitherto encapsulated and protected against microbial processes (Jacinthe and Lal 2009; Lal 2003; Polyakov and Lal 2004, 2005). Breakdown of aggregates and redistribution of SOC over the landscape with different soil temperature and moisture regimes can accelerate its decomposition and emission of GHGs into the atmosphere as CO_2 under aerobic conditions and methane (CH_4) and nitrous oxide (N_2O) under anaerobic environments (Lal 2009).

SOIL MANAGEMENT PRACTICES AND SOIL ORGANIC CARBON CHANGE

Conversion of native or natural ecosystem soil to conventional agriculture use can result in 30% loss of the original SOC stock (it is no longer remaining within the land unit) (Lal et al. 1998; Lal 1999). The other 70% of the SOC is subjected to wind or water erosion and transported as SOC-rich sediment. It may be retained and redeposited on foot-slope or depositional land unit soils in the upland. If transported SOC is deposited on an adjacent depositional land unit, it can increase the SOC stock of that unit (Olson et al. 2014a, 2014b). This process is a redistribution of already sequestered and stored SOC. The total SOC stock of the depositional unit is a combination of sequestered SOC by unit plants and deposition of previously stored SOC transported from adjacent eroding units. The erosion-caused change in SOC stocks creates an unbalanced C sink and source that leads to significant C stock loss as indicated above through different pathways (mineralization, leaching, surface runoff, etc.). These outcomes are accelerated by modern agriculture management practices coupled with erosion as a driver. It has been documented that sloping lands under shifting land use between cultivation and fallow act as a conveyor that stores atmospheric CO_2 in soils during the regeneration of natural fallows (CO_2 stored by volunteered weeds and other plants and in some cases no tillage when fallow) and ultimately transfers it by water erosion process from the steepest areas of hill slopes to bottomland soils, where it is accumulated (Chaplot et al. 2009). Change in soil C distribution within a land unit cannot be interpreted as soil C sequestration because of the absence of the plant's role in the capture and storage of atmospheric CO_2 (Olson et al. 2014a, 2014b).

LAND UNIT TYPE CONSIDERATIONS WHEN MEASURING SOIL ORGANIC CARBON STOCK

The three basic types of agricultural land units often used for measuring SOC sequestration and monitoring SOC stock change include (1) eroding, (2) depositional, and (3) mixed landscape (combined eroding and depositional).

Eroding Agricultural Land Unit. On an eroded agricultural land unit, some sequestered SOC stock can be transported to the adjacent depositional land unit, carried into water bodies, or released as CO_2 to the atmosphere. These losses can result in a lower reported SOC stock or sequestration rate in the eroded agricultural land unit than depositional land unit. Some researchers (Kreznor et al. 1992; Olson et al. 2011, 2013b) measured the SOC on stable uncultivated sod or forested summits, slightly eroded cultivated interfluves, severely eroded side-slopes, and depositional basins (134 Mg C ha^{-1} [60.9 tn C ac^{-1}]). The depositional agricultural land unit had more SOC present in the 0.5 to 1 m (1.6 to 3.3 ft; soil profile) layer as a result of soil erosion, transport, and deposition of SOC stock that was sequestered on another landscape position and protected by anaerobic conditions, but it was not sequestered SOC by plants growing within the borders of the depositional land unit. The SOC lost from the eroded side-slope land units (table 2) through different pathways made the accurate determination of the SOC sequestration of the depositional land unit more difficult. Similar results were reported by Salemme and Olson (2014) and Olson et al. (2013a). Sediment erosion, transport, and deposition of already stored SOC can result in an overestimation of SOC sequestration in depositional agricultural land units and can underestimate it for adjacent eroding land units (Olson 2010, 2013). Researchers need to consider monitoring the eroding agricultural source land units in addition to the depositional land units. An additional concern is the movement by wind and water of plant materials/residues that can be buried in sediments from eroding land units to depositional land units.

The SOC status within an agricultural landscape unit has a different dynamic once it is retained within its boundaries. Therefore, the SOC losses from the eroded part of the land unit can be added to the depositional land unit SOC stock and considered as sequestered SOC within landscape unit boundaries. However, if some of this redistributed SOC-rich sediment leaves the landscape unit, it would result in a loss of the transported SOC (across land unit borders) to the water and adjacent landscape by surface runoff or wind erosion or to the atmosphere as CO_2 during the oxidation process, which no longer can be counted as sequestered SOC. Several researchers (Gennadiyev et al. 2010; Golosov et al. 2011; Olson et al. 2011, 2012, 2013a, 2013b) measured the SOC in agricultural landscape units with both eroding and depositional sites. The amount of SOC-rich sediment lost during the erosion process to a depositional unit can be quantified (Kreznor et al. 1989, 1990, 1992; Jones and Olson 1990) using the presence of fly ash. The fly ash spheres are a product of coal burning, dating back to the 1910s (in some cases the 1860s) and can be used as indicator for determining SOC deposition over time. The other component of SOC deposition is through geological deposition, which can be separated from accelerated erosion, transport, and deposition SOC since geological sediments do not contain fly ash spheres.

Often the eroded agricultural land unit used by most researchers is large scale (1 to 2 ha [2.5 to 5 ac] in size), and SOC stocks are only measured in plot areas and do not include buffer or filter strips between the plot areas and a waterway. Consequently, any SOC-rich sediment deposited and retained on the lower part of the slope and outside of the defined agricultural land unit is not measured. Even if the SOC stock of pretreatment measurements were made, it would not be easy to determine the individual SOC treatment source when plots are randomized and transported SOC-rich sediment from all treatments are collected in the filter or buffer strip. This often leads to unreliable determination of actual soil C change due to the dynamic nature of sediment and associated C movement between land units.

Depositional Agricultural Land Unit. If transported SOC is deposited on an adjacent depositional land unit, it can increase the SOC stock of that unit (Olson et al.

Table 2

The effects of soil erosion through land use change on soil organic carbon (SOC) stocks.

Site location	Soil series	Land use prairie and/or forest vs. agricultural land	Landscape position	Soil organic carbon stocks (Mg C ha^{-1} layer^{-1})	Reference
Bureau County, Illinois	Tama	Uncultivated sod	Summit	90.0	Kreznor et al. 1992
	Tama	Slightly eroded	Interfluve	75.0	
	Tama	Severely eroded	Sideslope	17.0	
	Radford	Depositional	Toeslope	134.0	
Knoxville County, Illinois	Rozetta	Uncultivated forest	Summit	67.3	Olson et al. 2011
	Rozetta	Slightly eroded	Interfluve	37.3	
	Hickory	Severely eroded	Sideslope	53.5	
	Lawson	Depositional	Toeslope	69.7	
Albany County, Illinois	Lamont	Uncultivated forest	Summit	45.5	Olson et al. 2013a
	Lamont	Slightly eroded	Interfluve	31.4	
	Seaton	Severely eroded	Sideslope	23.1	
	Mt. Carroll	Depositional	Toeslope	39.0	
Shelby County, Iowa	Marshall	Uncultivated prairie	Summit	214	Salemme and Olson 2014
	Marshall	Slightly eroded	Interfluve	109	
	Exira	Severely eroded	Sideslope	46	
	Judson-Ackmore-Colo	Depositional	Toeslope	257	

2014a). This process is a redistribution of already sequestered and stored SOC. The total SOC stock of the depositional unit is a combination of sequestered SOC by plants growing on the unit and deposition of previously stored SOC transported from adjacent eroding units. The change in SOC stocks because of erosion processes creates an unbalanced C sink and source that leads to significant C stock loss as indicated above through different pathways (mineralization, leaching, surface runoff, etc.). These outcomes are accelerated by modern agricultural management practices coupled with erosion as a driver.

Depositional agricultural land units most often receive previously sequestered SOC from adjacent or at distance eroded agricultural land units (Young et al. 2014). Sometimes researchers have not separated the measurements of SOC stocks of an eroded land unit from the SOC stocks transported and deposited on the depositional unit (David et al. 2011). This can result in an inaccurate overestimation of SOC sequestration in depositional land units (Kreznor et al. 1989, 1990, 1992).

Several approaches can be used to determine the amount of SOC-rich sediment deposited on a depositional agricultural land unit. Kreznor et al. (1989, 1990, 1992) and Jones and Olson (1990) used the presence and quantity of fly ash and SOC to determine erosion and depositional rates. Using a fly ash time marker, Jones and Olson (1990) and Kreznor et al. (1990) measured the sediment and SOC retained in a 2.49 ha (6 ac) basin with one outlet. The 10.54 ha (26 ac) watershed was conventionally (moldboard plow) cultivated for 134 years. The 2.49 ha basin with one outlet retained 16,480 Mg (18,166 tn) of sediment (basin deposition rate of 49.4 Mg ha^{-1} y^{-1} [22.45 tn ac^{-1} yr^{-1}]) with an average SOC concentration of 22 g kg^{-1} (2.2%). The 10.54 ha watershed soil erosion rate, based on total retained basin sediment, would be 12.8 Mg ha^{-1} y^{-1} (5.8 tn ac^{-1} yr^{-1}). The total SOC retained in the 2.49 ha basin was 362 Mg C (399 tn C) or a basin C deposition rate of 1.08 Mg C ha^{-1} y^{-1} (0.49 tn C ac^{-1} yr^{-1}).

Another approach used to estimate gross erosion sediments retained in basin and delivered to the stream was the sediment delivery method in Iowa and Illinois (Stewart et al. 1975; Spomer and Piest 1982; Water Resource Planning Staff 1984). Approximately 45% of the SOC-rich sediment was retained in the basin and the other 55% delivered to the high gradient stream using the mean of all these sediment delivery estimates for the 10.54 ha (26 ac) watershed (Kreznor et al. 1990). The tolerable (T) soil loss for the Tama soil, the most common soil in watershed, is 11 Mg ha^{-1} y^{-1} (5 tn ac^{-1} yr^{-1}). The total sediment retained in the 2.49 ha (6 ac) basin (45%) and delivered to the stream (55%) would total 37,455 Mg (41,286 tn; soil erosion rate of 26.5 Mg ha^{-1} y^{-1} [12.05 tn ac^{-1} yr^{-1}]), which is 2.4 times T for the entire 10.54 ha watershed. Since the watershed had 5% to 10% slopes; was primarily in a corn–soybean rotation; and did not have conservation practices such as contour farming, terraces, cover crops, and no-tillage used during the last 134 years, this soil erosion rate is very realistic. The watershed did, however, have a grassed waterway, which helped trap sediments in the basin. The 10.54 ha watershed would have a SOC stock loss of 824 Mg C (908 tn C; the rate of loss of C watershed would be 0.58 Mg C ha^{-1} y^{-1} [0.26 tn ac^{-1} yr^{-1}]).

Mixed Landscape Agricultural Land Unit. If an agricultural unit is a mixed landscape, it is possible to consider both the eroding unit losses and the depositional unit gains when determining the SOC sequestration of the larger agricultural landscape unit. The SOC sequestration cannot be claimed when the depositional gain from C-rich sediment being deposited on a land unit is determined without measuring and deducting the SOC stock loss from the adjacent eroding unit (Lal et al. 1998; Lal 2003; Kreznor et al. 1990).

To accurately determine SOC change of the agricultural landscape (combined eroding and depositional land units) within landscape units under various agriculture management practices that induce erosion, a mass balance approach must be used within large scale unit (1 to 10 ha [2.5 to 24.7 ac] in size), where the measured plot areas are included through the entire landscape and extend from the summit to the waterways (either closed outlet or one outlet). Therefore, SOC stocks that were lost from the agricultural landscape unit can be determined by sampling across the entire landscape unit and by way of a difference that was transported to the stream, atmosphere, or leached below the root zone. This leads to a more accurate account of the SOC stocks change in the landscape land unit and understanding of the distribution of SOC-rich sediment from the eroding to the depositional site within the landscape unit.

CONCLUSIONS

Soil erosion and agricultural land unit management affect SOC stock of sloping agricultural land units along with the attendant changes in SOC sequestration, storage, retention, and loss. It is imperative to recognize that water and wind erosion processes of transport and deposition of SOC enriched-sediments within a landscape unit contribute to redistribution of SOC stock, in particular within the upland agricultural land unit boundaries, water bodies beyond those land units, or into the atmosphere. Redistribution of SOC because of soil erosion process neither constitutes nor is equivalent to SOC sequestration, which involves the dynamic interactions between soil, plant, and atmospheric CO_2 within the designated unit. The absence of such dynamics leads to the conclusion that soil erosion is a destructive process altering and changing soil C stocks (organic and inorganic) causing the loss of significant amount of relatively stable SOC that has been retained in the soil system for millennia, and adversely affecting net primary productivity and use efficiency of inputs.

The selection of agricultural land unit and its position for study and determining SOC stock can affect the results and their interpretations. An eroding land unit will underreport the SOC stock, a depositional agricultural land unit will overestimate the SOC stock, while an agricultural mixed landscape (combined eroding and depositional) land unit can have a different and an uncertain SOC distribution outcome because of losses by decomposition, leaching, and runoff.

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