# Response to Comments on "Managing Soil Carbon"

We agree with Renwick *et al*. (*1*) and Van Oost *et al*. (*2*) that the magnitude of organic carbon lost from cultivated soils by erosion and mineralization processes is uncertain. The uncertainty is especially large with respect to the fate of carbon transported, redistributed over the landscape, and deposited in depressional sites; resolving that uncertainty will require additional site-specific data from properly designed experiments. Little uncertainty exists, however, about the benefits of no-till agriculture: It slows water and wind erosion and stops tillage erosion, preserving land fertility and productivity and sequestering carbon.

Renwick *et al*. highlight the importance of understanding the pathways of carbon displaced by erosion and of quantifying the magnitude of erosion-induced emission of $CO_2$, $CH_4$, and $N_2O$ into the atmosphere. In response, we point out that soil erosion exacerbates carbon emission from ecosystem in five ways.

1) Soil erosion increases soil degradation and reduces biomass production on-site. Crop yields in eroded soil can be drastically reduced, even with high fertilizer input (*3*, *4*), which itself increases emission of $CO_2$ and $N_2O$. Yield reduction is especially severe in tropical soils of low inherent fertility (*5*, *6*). Erosion reduces production through adverse effects on soil structure, aeration, effective rooting depth, available water-holding capacity, and nutrient reserves; the reduced production, in turn, further reduces the soil carbon pool. Erosion decreases net primary productivity (NPP) on eroded sites, increases oxidation of soil organic matter, and reduces net ecosystem productivity (NEP). The gains in the soil carbon pool in depressional sites rarely compensate for losses on eroded sites in view of reduced NEP and increased mineralization.

2) Erosion causes the breakdown of macroaggregates into microaggregates and, possibly, complete soil dispersion, exposing hitherto encapsulated organic matter to microbial processes. The outer layer of macroaggregates has more soil organic matter than the inner core (*7*); that outer organic matter is progressively peeled off and transported with the sediments, because aggregation and soil structure control decomposition of organic matter in soil (*8*). Changes in soil moisture and temperature also increase the rate of decomposition of the remaining organic matter at the eroded site. Eroded soils have different radiative and thermal properties, leading to increased soil temperature (*9*), an important factor controlling $CO_2$ emission from soil (*10*).

3) Sediments are often enriched in soil organic carbon (SOC), because SOC has low density and is concentrated in the vicinity of the soil surface. The enrichment ratio of carbon in the sediments can be 5 to 32 times (*11*, *12*) as high as that for the field soil. Most of C transported with sediment is the labile fraction, which is easily mineralizable (*13*); the mineralizable fraction in translocated organic matter may range from 29% to as high as 70% (*14–16*). Thus, assuming that the mineralizable fraction in eroded and redeposited material is close to zero (*17*) can lead to erroneous conclusions. In most cases, sediment deposited may lead to higher emissions ($CO_2$, $CH_4$, and $N_2O$) from depositional sites. Overall, soil erosion is a net source of $CO_2$ and other gases, and in many watersheds a 20% oxidation rate is rather conservative (*14–16*). Taking into consideration the enrichment ratio and the delivery ratio of total soil displaced, emission of 1 gigaton (Gt) C/yr is possible.

4) In truncated soil profiles characterized by carbonaceous subsoil horizons, exposed carbonates may react with acidiferous material, such as fertilizers, and release $CO_2$ into the atmosphere.

5) The fate of carbon deposited in burial and depressional sites is governed by complex processes. The deposition may decrease the rate of mineralization by reaggregation of dispersed clay and silt (*18*) and burial of carbon-rich material and calciferous layer. On the other hand, the rate of mineralization may also be increased in depressional sites because of the high proportion of mineralizable fraction (*19*). Depending on soil moisture and temperature regimes, depositional sites may also undergo methanogenesis with release of $CH_4$ and denitrification with release of $N_2O$. The rate of mineralization on erosional phases strongly depends on soil temperature (*19*).

On the whole, as these mechanisms suggest, accelerated erosion reduces the ecosystem carbon pool, accentuates carbon emissions, and must be controlled effectively. Still, despite success in modeling erosion-induced loss of soil carbon, the fate of the displaced carbon remains largely unresolved (*20*), as both Renwick *et al*. and Van Oost *et al*. suggest.

Van Oost *et al*. also comment on tillage translocation—soil movement during tillage, which in turn leads to soil loss from convex slopes and soil gain by concave slopes. A net downslope displacement of soil on the hillslope by tillage, called tillage erosion, has been discussed as a soil degradation process since the 1940s (*21–23*). In general, the soil flux increases with increase in slope gradient and tillage intensity, and strongly depends on the antecedent soil conditions (*24*). Soil degradation and its adverse effects on productivity on convex slopes are as pronounced in tillage erosion as in water erosion, and both forms of erosion accentuate spatial variability in soil quality.

Yet there are some notable differences between tillage-induced and water-induced erosion. For one, soil erosion by water preferentially removes the light fraction, so sediments thus removed are generally enriched in SOC and other elements. Also, the deposition of sediments in the water erosion process follows Stokes' law: The sequence and the rate of fall depends on the particle size. Further, the depositional site for water erosion, being preferentially enriched in soil C, may have different soil properties and different gaseous flux than concave slopes receiving soil translocated by tillage operations. And tillage erosion generally causes soil loss in the shoulder position, whereas water erosion causes soil loss on mid and lower backslope positions (*25*).

Any tillage and related soil disturbance enhances the rate of mineralization of soil organic matter (*26*) and thus leads to emission of $CO_2$ into the atmosphere. The losses of carbon can be especially high if the depositional sites, where the labile fraction is concentrated in the top 10 to 20 cm, is tilled frequently. Tillage decreases the humification rate compared with no-till techniques (*27*) and leads to depletion rather than sequestration of soil carbon. Further, tillage operations involve fossil fuel consumption of as much as 30 to 40 kg C/ha/season (*28*). Rather than providing a sink, tillage accentuates the capacity of soil as a source of $CO_2$ to the atmosphere. If tillage-induced erosion reduces crop productivity and the amount of residue returned to the soil is also thus reduced, it is extremely difficult to stabilize or increase the SOC pool (*29*). As with the data in figure 1 of Van Oost *et al*. (which does not provide the least significant difference, with which to compare means), extensive research from the midwestern United States (*30*) and from Canada (*31*) also show a higher SOC pool in depositional sites. Yet the total SOC pool in the eroded and deposited landscapes is lower than in uneroded landscapes because of losses by mineralization.

Because the global C budget cannot be balanced, the so-called missing sink or unknown residual sink lumps in all the uncertainties. The magnitude of unknown sink could be 2 to 4 Gt C/yr (*32*) or more because of unaccounted-for erosion-induced effects and other sources. Further, accelerated soil erosion is a threat to world food security, water quality, and health of coastal ecosystems (hypoxia). Although there is indeed uncertainty concerning how much carbon no-till agriculture is preventing from being emitted to the atmosphere, there is no doubt of the value of no-till agriculture in preserving cropland for the benefit of people today and in the future. The latter benefit is sufficient reason to promote no-till extensively, even as the uncertainty about carbon emissions rates is being resolved. No-till agriculture and soil carbon sequestration are win-win options, both locally and globally.

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