Terrestrial carbon (C) offsets – sequestration of organic C in soils or biomass brought about by intentional changes in land management – offer the possibility of reducing the concentration of atmospheric carbon dioxide (CO$_2$), offsetting emissions from other sectors. However, their inclusion in US climate and international C policy is controversial.

Forest growth and agricultural soil organic C (SOC) sequestration currently offset about 13% of US fossil-fuel emissions (US EPA 2008) and, given policies to promote adoption of land-management practices that sequester C, that percentage could increase in the future (Pacala et al. 2007). In agricultural lands, terrestrial SOC offsets can be realized relatively quickly, through existing technology (Figure 1); in many cases, such options could cost less than the expense associated with direct emission reductions, providing flexibility in meeting emission targets or restrictions (Smith et al. 2007). However, the Kyoto Protocol’s Clean Development Mechanism has demonstrated that in the absence of well-formulated regulations on allowable offsets, billions of US dollars can be spent obtaining offsets with doubtful claims of actual greenhouse-gas reductions (Wara 2007). The debate about the legitimacy of terrestrial offsets versus their utility pits public interest groups, who demand genuine emission reductions, against the sectors likely to face emission caps, who desire a variety of options for achieving emission reduction targets at the lowest possible cost.

Policies that encourage greenhouse-gas emitters to mitigate emissions through terrestrial carbon (C) offsets – C sequestration in soils or biomass – will promote practices that reduce erosion and build soil fertility, while fostering adaptation to climate change, agricultural development, and rehabilitation of degraded soils. However, none of these benefits will be possible until changes in C stocks can be documented accurately and cost-effectively. This is particularly challenging when dealing with changes in soil organic C (SOC) stocks. Precise methods for measuring C in soil samples are well established, but spatial variability in the factors that determine SOC stocks makes it difficult to document change. Widespread interest in the benefits of SOC sequestration has brought this issue to the fore in the development of US and international climate policy. Here, we review the challenges to documenting changes in SOC stocks, how policy decisions influence offset documentation requirements, and the benefits and drawbacks of different sampling strategies and extrapolation methods.

In a nutshell:

- Dependable methods for measuring terrestrial carbon offsets are critically important for developing a legitimate terrestrial carbon offset market
- Existing methods for quantifying soil organic carbon (SOC) concentration in samples are well established and have a high analytical precision
- Quantifying changes in SOC stocks relies on a set of measurements that are extrapolated in various ways to represent a larger geographic area
- The main challenge in documenting plot-level changes in SOC stocks is in designing an efficient, cost-effective sampling system
- The most dependable SOC stock estimation systems will be those that are accurate, flexible, and inexpensive, and that can most easily integrate new data and knowledge

for developing a broad – and legitimate – terrestrial offset market. Verification methods that accurately attribute net emission reduction or sequestration to a parcel of land or a practice have not yet been agreed upon. Methods of establishing baselines and their associated uncertainty and that account for additionality, leakage, and permanence (WebPanel 1) are necessary, but remain unresolved. Here, we review the requirements for quantifying agricultural SOC offsets, the challenges to verifying those C offsets, and both the benefits and the limitations of various approaches.

Different approaches to measurement and monitoring

Field sampling of changes in C stocks

Methods for analyzing the SOC concentration of a given sample are well-established and easily carried out, with high precision and negligible analytical error (Nelson and Sommers 1996). However, SOC stocks vary as a function of soil texture, landscape position, drainage, plant productivity, and soil density, all of which vary spatially and contribute to the spatial variation in SOC stocks, making it difficult to quantify changes in SOC stocks over time (Table 1; Cambardella et al. 1994; Robertson et al. 1997; Van Den Bygaart 2006). Two samples taken from different areas in the same field are likely to have different SOC concentrations; accounting for this spatial variability is essential, otherwise a considerable degree of uncertainty is introduced into SOC stock estimates (Figures 2 and 3). Furthermore, all of the processes that lead to C sequestration in agricultural soils – reduced tillage, enhanced residue inputs, fallow reduction, cover crops, etc – do so non-uniformly across fields and landscapes. In quantifying agricultural SOC offsets, the challenge is further compounded by the fact that SOC changes will be small relative to changes in the large C stocks typically found in most soils (i.e a low signal-to-noise ratio). Sampling error can therefore be large and “the cumulative effects of managing small net sinks to mitigate fossil-fuel emissions will have to be understood, analyzed, monitored, and evaluated in the context of larger, highly variable, and uncertain sources and sinks in the natural cycle” (Birdsey et al. 2007).

The main difficulty in documenting plot-level changes in SOC stocks is not with measuring the SOC, but rather in designing an efficient, cost-effective sampling and SOC stock estimation system. All field sampling methods for verifying changes in SOC stocks rely on a set of measurements that are extrapolated to represent a given geographic area. Classical and geospatial sampling are based on approaches commonly used in agronomic and ecological experiments and analyses that employ well-established, highly accurate analytical methods (WebPanel 1) are necessary, but remain unresolved. Here, we review the requirements for quantifying agricultural SOC offsets, the challenges to verifying those C offsets, and both the benefits and the limitations of various approaches.

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Practical and laboratory analyses. In the future, such approaches may provide a potentially low-cost method for comprehensive sampling, but much additional research is needed before these approaches are ready for wide-scale implementation.

**Practice-based estimates of SOC sequestration**

One common approach for assessing changes in SOC stocks is to use information synthesized from previously published studies on how changes in management practices affect SOC stocks. Markets (such as the Chicago Climate Exchange, www.chicagoclimatex.com) and direct offset trades in the US (such as the Pacific Northwest Direct Seed Association's Carbon Offset Project) currently rely on such practice-based approaches. Offsets can be verified by monitoring agronomic practices (e.g., monitoring no-tillage by surveying residue coverage on the soil surface). Such verification is already established for other conservation programs and can be relatively inexpensive. Syntheses of existing field experiments (e.g., Ogle et al. 2005) provide empirical estimates of the average SOC change for a particular practice within a broad region. However, because published studies of land-management impacts on SOC stocks are so uncommon and site-specific, the utilization of those studies to estimate sequestration rates in a given region—such as for a specific farm or group of farms—will lead to substantial uncertainty. This uncertainty is difficult to quantify through statistical methods with limited data. Moreover, the sequestration rates are typically based on relative changes in SOC stocks, which could differ from the actual rates if other environmental drivers (e.g., climate change) are also contributing to changes in SOC stocks. If uncertainty is high, permitted SOC offsets may be substantially discounted relative to estimated C sequestered, in order to limit the risk that the offsets do not represent realistic reductions in CO2 emissions to the atmosphere (e.g., VCS 2008). Another limitation of a broad practice-based approach is that it is economically inefficient (Antle et al. 2003). Because of heterogeneity in the response of soils to specific management practices (resulting from differences in soils, climate conditions, land-use history, etc.), broadly based payments by practice will overcompensate poor performance and undercompensate good performance (thereby reducing the incentive to participate). Thus, even if the practice-based credit was an accurate estimate for average performance within the region, the actual benefits achieved would be overestimated, and this inefficiency would increase as a function of the degree of spatial heterogeneity in soil response (Antle et al. 2003). An estimation system that can account for more of the local variability in soil responses to a particular manage-
Combining measurement with mechanistic modeling

Researchers can quantify terrestrial SOC offsets using a mechanistic ecosystem model. Such an approach is widely used for reporting national SOC inventories under the UN Framework Convention on Climate Change. For example, the Century model (Parton et al. 1987) is used to estimate SOC stocks in the US and Canadian national inventories. This approach has also been used to document voluntary SOC offsets through the US Energy Information Administration’s 1605(b) program (eg Paustian et al. 2009). Coupled with published information on management impacts, systems such as this are capable of estimating uncertainty associated with SOC sequestration estimates (Ogle et al. 2010). Quantification systems based on mechanistic models are inherently flexible, because they are able to represent a wide range of distinctive climate and soil management conditions. They can also be designed to be run with a small set of driving data, making them easy to use, and updated as new information becomes available (Jones et al. 2004).

A dynamic database, one that is regularly populated with the most recent terrestrial SOC offset data, could integrate field measurements with state-of-the-art knowledge about ecosystem function and enable up-to-date calculations of model uncertainty estimates through statistical methods similar to those described by Ogle et al. (2007). Such a system would benefit from a mechanistic modeling framework that captures process-based understanding of C dynamics, and an underlying suite of independent observations to verify model results. Combining measurement of SOC with models would have several distinct benefits not possible through modeling or measurement alone. Carbon exchange accounting rules that discount or withhold credits in reserve to account for uncertainty – some carbon exchange rules, like those developed by the Voluntary Carbon Standard (www.v-c-s.org), require that a portion of the estimated SOC sequestration be held in reserve to ensure against non-compliance or reversals (eg through fire) – could use uncertainty derived from the model analysis associated with a particular offset activity to determine reserve requirements. Combining measurement and modeling would have the flexibility of a model-based approach – being able to account for all types of terrestrial offsets, unlike relying entirely on direct measurements, which is likely to have gaps. A combined modeling–measurement approach would be robust, because it could be continually updated with new sample data and could be used to direct sampling toward those areas where uncertainty is largest relative to offset activity. Combining modeling and measurement could also potentially encourage more innovation by agricultural producers, because new measurements could be incorporated from the latest management options. This would allow all producers to receive credit from the latest
innovations based on modeled data without necessarily requiring new measurements on each farm. Finally, a combined system could exploit published information on how other factors (such as global change, widespread land-use changes, etc.) affect SOC stocks both on- and offsite, to account for shifting baselines, additionality, and leakage.

Conclusions

The variety of approaches proposed to quantify agricultural offsets is a testament to the inherent difficulties in estimating changes in SOC stocks over time — including spatial variation, slow overall turnover times, small changes relative to SOC stocks, and the intangibility of SOC for scientists, policy makers, and/or natural resource managers who are unfamiliar with soil science or related fields. These challenges contribute to objections to mitigation policies that include agricultural offsets for C sequestration in soils. In the future, these challenges may limit the role of agricultural offsets in reducing greenhouse-gas emissions, despite the fact that SOC stocks have been accurately measured for decades (Nelson and Sommers 1996) and that the cost of such measurements may represent only a small fraction of project expenses (Mooney et al. 2004). Developing a set of terrestrial SOC offset standards from this suite of approaches is crucial for widespread acceptance and implementation of reliable, accurate, and credible agricultural C offsets that can mitigate greenhouse-gas emissions and reduce the influence of anthropogenic activities on climate.

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