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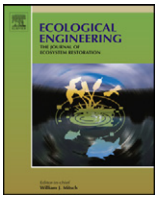

Accounting for space and time in soil carbon dynamics in timbered rangelands

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ABSTRACT

Employing rangelands for climate change mitigation is hindered by conflicting reports on the direction and magnitude of change in soil organic carbon (ΔSOC) following changes in woody cover. Publications on woody thickening and deforestation, which had led to uncertainty in ΔSOC, were re-evaluated, and the dimensional-dependence of their data was determined. To model the fundamentals of SOC flux, linked SOC pools were simulated with first-order kinetics. Influences from forest development timelines and location of mature trees, with a potential for deep-set roots, were considered. We show that controversy or uncertainty has arisen when ΔSOC data were not measured along sufficient lengths of the three Cartesian axes and the time axis, i.e. in 4D. Thickening and deforestation experiments have particularly neglected factors affecting the time and depth axes, and sometimes neglected all four axes. Measurements of thickening must use time-spans beyond the calculable breakeven date – when thickening just recovers the SOC lost through land degradation: then all ecosystems are likely to incur net sequestration. The similarity between half-life of carbon pools, and the half-time required for sequestration, mandates that millennial time-spans must be considered in design of SOC experiments. Spatial and temporal averaging of ΔSOC data that accounted for environmentally dependent decomposition rates, revealed that deforestation to pasture incurred a higher and longer-term net emission than earlier reported. Published reports on thickening or deforestation appear no longer contradictory when one considers that they only presented views from lengths of the 4D axes that were too limited. Adoption of this understanding into carbon accounting will allow more precise estimates of carbon fluxes for emission trading schemes and national reports.

1. Introduction

For many rangelands woody vegetation plays a major ecological role, through vegetation types such as: (a) shrubland, woodland, open-forest, riparian forests in grasslands, or savannah; (b) improved pastures after deforestation; or (c) extant grassland experiencing woody thickening; (e.g. Carnahan, 1977; Lund, 2007; Ellis, 2011). The term ‘timbered’ rather than ‘forested’ is used here with respect to rangelands, to avoid confusion between different countries’ definitions of forests, and to include the woody-thickened state. Soil organic carbon (SOC) is a substantial terrestrial carbon (C) pool, often positively correlated with plant biomass (Su and Zhao, 2003; Harms et al., 2005; Hughes et al., 2006; Wheeler et al., 2007). The correlation means that SOC in many rangelands can be influenced by: overgrazing and land rehabilitation; deforestation and regrowth; woody thickening; fire; and climate change (Batjes and Sombroek, 1997; Reeder, 2002; Smith and Johnson, 2004; Luo et al., 2007). Consequently, rangeland SOC can act as a C sink in support of greenhouse gas (GHG) mitigation projects (McKeon et al., 1992; Glenn et al., 1993; Walker and Steffen, 1993). However, the difficulty in measuring and forecasting rangeland SOC may have resulted in conflicting reports on the direction and magnitude of change in SOC (ΔSOC)

Abbreviations: DOC, dissolved organic carbon; GHG, greenhouse gas; SOC, soil organic carbon; ΔSOC, change in SOC; 4D, four dimensions (3 Cartesian plus time).

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that accompanies land management. This is especially true where there's only tenuous evidence for causation between observed effects and anthropogenic activity. The magnitude and direction of ΔSOC, can differ between decadal and centennial time-scales for rangeland grazing (for example), being more-definitive in the longer term (Piñeiro et al., 2006). Similarly, shallow measurement of SOC ($\leq$0.2 m) can both greatly underestimate the SOC pool and lead to incorrect conclusions on the direction of ΔSOC following management effects (Harrison et al., 2011). Uncertainty, which is higher for ΔSOC, stifles climate change mitigation projects in the rangelands (Harper et al., 2007; Brown et al., 2010) and it has tacitly prevented inclusion of some rangeland SOC fluxes in national GHG accounts, thereby detracting from accounting accuracy. Conceptualisation in four dimensions (4D, the three Cartesian axes plus time) has provided scientific insight and management options, in ecology and C dynamics (e.g. Ward, 1989; Dean et al., 2004; Dean and Roxburgh, 2006; Turnbull et al., 2008; Colyan and Ginzburg, 2010). Woody thickening in rangelands, has significant 4D diversity in SOC concentrations (Boutton et al., 1998). We hypothesize that conceptualising rangeland C dynamics in 4D can provide a coherent solution to dissonance over ΔSOC for significant rangeland processes. Two examples are selected for re-evaluation using this hypothesis, from reports where conclusions had important consequences for climate change mitigation.

The sampling span (extent, length) used in rangeland experiments is crucial. For example, a correlation between biomass and SOC has sometimes appeared ambivalent but was confirmed as positive when experiments were longer-term and when SOC was sampled at depths more related to root extent under woody vegetation (Groenenberg et al., 1998; García-Olivia and Masera, 2004; Liao et al., 2006a,b). Longer-duration experiments on change in biomass or ΔSOC are generally more definitive than shorter ones (Lugo and Scatena, 1996; Diochon et al., 2009). Conversely, short-duration (decadal) experiments may yield low-magnitude and conflicting results for ΔSOC (Lugo et al., 1986; Guo and Gifford, 2002; Liu et al., 2004; Marin-Spiotta et al., 2009). Although SOC is generally correlated with vegetation cover there can be short-term fluctuations in SOC when the vegetation cover changes, which can occlude the influence of interest. For example, such as from the priming effect (Fontaine et al., 2007), and early oscillations in SOC following deforestation, followed by long-term emission and an asymptote (García-Olivia et al., 1994; García-Olivia and Masera, 2004). SOC can take approximately two millennia to stabilize, such as for rangeland thickening (Hibbard et al., 2003) and for the decrease in SOC when forests were replaced by prairie due to fire during the Holocene (Baker et al., 1996).

Accounting for dimensions is also important during data processing. For example, when averaging samples, their equivalence with respect to the effect being studied is assumed, but that effect may change nonlinearly in a particular dimension. Therefore Jensen's inequality (Jensen, 1906; Welsh et al., 1988; Chesson, 1998; Ruel and Ayres, 1999) becomes relevant. It implies for a non-linear function that the average of the means is not necessarily equal to the means of the averages. For example, site location (environment), is a function of x–y position but SOC decomposition rates may vary between environments. SOC emission following deforestation is higher from higher SOC sites (Holmes et al., 2006) but proportionally higher from poorer soils (i.e. lower SOC sites) (Harms et al., 2005). Averaging over such complexity would blur effects and thereby limit accuracy of results. Here we consider the influences over 4D of deep-set SOC, and deep-rooted, long-lived plants and their decomposition products. The focus here is on the time and depth (z) axes as these have been the most neglected, but data from all four axes are integrated into our re-analyses.

Firstly, we provide an introduction to SOC distribution in rangelands and demonstrate the relative benefits of one-, two- and three-pool SOC models, then use one of those to emulate results from the CENTURY model (a three-SOC-pool system with feedbacks (Parton et al., 1987)). We did not run CENTURY directly because: (a) of the amount of site-specific data required (e.g. for climate, plant growth and decomposition), (b) the number of sites examined, and (c) we wanted to display the keystones of the dynamics transparently, using the simplest, applicable mathematics.

In the first example we address the influence of the time axis (t-axis) and z-axis (depth) in data sampling, processing and interpretation. Rangelands in the southwest USA were overgrazed in the 19th century, inducing degradation, with erosion, net C efflux, and reduction in ecosystem function, followed by recovery and thickening (Lund, 2007; Wheeler et al., 2007; Wilcox et al., 2008). Sequestration associated with such thickening in a Texan grassland was found to approach an asymptote with a nearly fourfold increase in SOC after ~2500 years (Hibbard et al., 2003). Conversely, in Jackson et al. (2002) where rainfall was above ~460 mm year^{-1}, thickening of mesquite (*Prosopis* spp.) was found to induce net SOC emission. This latter study was unique in that it tested for roots nearly as far down as a phreatophyte's lowest root (in this instance to 10 m), and proportional change in SOC with thickening, was determined to 3 m depth. Principally, its conclusions were that woody thickening incurs a net emission in wetter sites and, more generally that 'assessments relying on C stored from woody plant invasions to balance emissions may therefore be incorrect'. The findings, published in 'Nature', caused apprehension over whether or not the USA national C sink had been overestimated (Goodale and Davidson, 2002). While scepticism was voiced, there were no compelling explanations (Archer et al., 2004; Wheeler et al., 2007; Liao et al., 2008) and controversy remains.

In the second example we scrutinise data interpretation on the t-axis and the x–y plane. Approximately 22 Mha of rangeland in Australia has been deforested for intensified, commercial grazing (Dean et al., submitted for publication). Curtailing the accompanying change in biomass was instrumental in Australia's adoption of the Kyoto Protocol, though the accompanying ΔSOC has not yet been sufficiently reconciled (Henry et al., 2002). Rates for the State of Queensland (QLD), Australia, have been the highest nationally for several decades, e.g. ~0.343 M ha year^{-1} in 2006, 59% of which was remnant native vegetation (DNRW, 2008). We analyse and reinterpret data from a comprehensive study of deforestation in QLD where ΔSOC following deforestation ranged from −5.4% to 1 m depth (Harms and Dalal, 2003; Harms et al., 2005), to −31% for 0.05 m depth (Dalal et al., 2005). The former measurement contributed to high uncertainty for grazing businesses in a study considering GHG benefits of land rehabilitation (Bray and Golden, 2008).

Lastly we discuss how identifying the components of events and their C fluxes can facilitate concord between existing reports on ΔSOC for rangelands.

2. Background to the 4D distribution of SOC in timbered rangelands

The likely distribution of C in 4D, when the SOC is supplied by woody vegetation, forms a foundation for our interpretation of ΔSOC. To portray key features, the biomass distribution of a semiarid thickening species (Fig. 1) was idealised from the literature (Heitschmidt et al., 1988; Gile et al., 1995, 1997; Dean et al., 2009). The time-dependent changes illustrated are inherent in the natural growth and decomposition of woody vegetation, of which self-thinning is a key component (discussed in the Appendix). From