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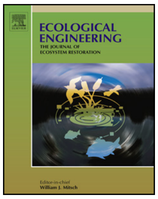

Research paper

Equilibration of the terrestrial water, nitrogen, and carbon cycles: Advocating a health threshold for carbon storage

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ABSTRACT

The world has long neglected the negative impacts that carbon (C) sequestration has on ecosystem health. Accordingly, the aims of this study were to advocate a conceptual C health threshold model devised for terrestrial ecosystems while proposing a method by which to qualify the C health threshold of ecosystems. Since coupling relationships between C, nitrogen (N), and water can shape the response of ecosystems to conditions of global climate change, this study concentrated on C sequestration, N input, and water erosion impacts on ecosystem health. If C storage exceeds the terrestrial ecosystem C health threshold, ecological degradation will either take place or ecosystems will fall into a sub-health state in accordance with the C health threshold model. Additionally, C sequestration engineering approaches, excess N inputs, and water erosion destroy the balance of C cycling processes and may consequently have an effect on the C health threshold. Therefore, analysis related to the interannual variability of C cycles and their potential future behavior must take into account mechanisms driven through the coupling of water, C, and N cycles. Defining ecosystem health will help familiarize and eventually lead to proficiency in understanding C health threshold awareness. This will aid in determining the appropriate ecological restoration measures to take when dealing with climate change impacts, leading to the preservation of biogeochemical C cycling native to terrestrial ecosystems.

1. Introduction

Global warming is currently the hottest research topic within the expansive environmental and ecology disciplines. Owing to this, governments and researchers have paid considerable attention to C sequestration with respect to decreasing atmospheric carbon dioxide (CO_2) emissions. The consequential effect of this focus has been to neglect in ascertaining whether C sequestration through forestation gives rise to negative effects on ecosystem health (Wang and Cao, 2011). Cao (2008) and Cao et al. (2007, 2009a) indicated that long-term ecosystem restoration engineering initiatives through afforestation have in fact increased environmental degradation in arid and semiarid regions, resulting in deterioration prompted by effects such as wind erosion. Costanza and Mageau (1999) defined a healthy ecosystem as self-sustainable, capable of maintaining its structure and function in the face of external stresses. It does so through homeostasis, the absence of disease, diversity or complexity, stability or resilience, vigor or scope, and a balance between system components. Conversely, a diseased or sub-health ecosystem is an unsustainable system undergoing irreversible degradation, incapable of achieving its maximum life span. Therefore, to be healthy, ecosystems must maintain a metabolic activity level as well as an internally diverse structure and organization. It must also be resilient to outside environmental stresses that take place over time and space (Costanza and Mageau, 1999).

Both Gulde et al. (2008) and Chung et al. (2010) reported that higher C inputs did not further increase soil organic carbon (SOC) stocks in long-term experiments. This can be attributable to the concept of whole soil or terrestrial ecosystem C saturation (Stewart et al., 2007; Heitkamp et al., 2012). C saturation theory implies that the stabilization efficiency of C inputs or sequestration depends on the C saturation deficit and that a continuous C input and sequestration influx is less effective in enhancing C stocks at higher levels. Recent advances in soil C saturation concepts have increased our understanding of soil C storage and mineralization from C, nitrogen (N), and water coupling theories (Castellano et al., 2012; Gao et al., 2012a). This understanding is due to the fact that ecosystem C and N concentration ratios are well correlated to strong biological links and consistent stoichiometry (Cleveland and Liptzin, 2007; Maria

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et al., 2012). C saturation concepts can also be applied to N stabilization and mineralization. Alvarez (2005) showed that N addition would increase C stocks by means of a global meta-analysis. N addition may be accompanied by a higher mineralization of residue C or SOC (Khan et al., 2007). This higher mineralization may counterbalance higher C inputs, which can result in ecosystem SOC storage changes (Heitkamp et al., 2009). Furthermore, enhanced mineralization through N addition preferentially impacts ecosystem processes, including primary productivity and nitrate leaching (Castellano et al., 2012).

According to the C mass balance of ecosystems (Falkowski et al., 2000), if excess C is absorbed through C sequestration, there would be a decrease in excess C that would have been redirected to other cycling processes. This could lead to disorder and self-adjustment of C cycling processes because each process requires sufficient C support to function. C and nutrient cycling processes are inherently linked to water availability and hydrologic transport through overland flow and subsurface runoff (Manzoni and Porporato, 2011; Gao et al., 2012b,c). Moreover, these cycling processes have an impact on ecosystem productivity and exchanges between the atmosphere and water bodies. Ecosystem health issues related to C, N, and water biogeochemical cycling processes were assessed because they are connected to a range of ecosystem services such as climate regulation, food production, soil formation, hydrological regulation, etc. (Watanabe and Ortega, 2011). The close coupled relationship between N flux and evapotranspiration implies that either climate change or changes in N inputs will have large and long-lived effects on both productivity and N loss through hydrological processes and emissions. As a result, a comprehensive analysis on the role of ecosystems in C cycling must consider mechanisms that arise from interactions between hydrological, C, and nutrient cycles. Gao et al. (2012a) determined that if C storage exceeds nutrient and water supply limits, an ecosystem will fall into a sub-health state of fitness and C runoff will result through soil erosion or through other such pathways due to the innate coupled balanced relationships that occur between C, N, and water.

Gao et al. (2011) indicated that ecological thresholds exist for ecosystem degradation and recovery processes, and that a breach of these thresholds will lead to irreversible losses in soil productivity by long-term effects of self-adjustment that relate to vegetation recovery and soil degradation. As a result, there must also be a C storage health threshold for terrestrial ecosystems by which ecosystem degradation and irreversible losses in soil productivity will take place after the threshold is exceeded. Becoming familiar and developing proficiency in understanding C health thresholds while maintaining ecosystem C balances are important when dealing with climate change as well as in determining appropriate future climate policies.

Since coupling relationships between C, N, and water can shape ecosystem response to global climate change, C sequestration, N addition, and water erosion impacts on ecosystem health were the primary focus of this study. The aim of this study was therefore to advocate a conceptual C health threshold model devised for terrestrial ecosystems. It advocates development of the ecosystem health concept and puts forward a method on how to qualify the C health threshold.

2. Methods

2.1. C health theory

According to the coupling relationships that occur between C, N, and water as well as the C mass balance theory, soil C cycling is divided into four processes: transformation (a), input (b1 and b2), loss (c), and sequestration (d) (Fig. 1). Exponential curves are widely used by researchers to indicate growth phrases (Briggs et al., 1920). As a result, exponential curves can also be used to indicate relationships related to heterotrophic and autotrophic respiration in addition to soil biota and soil C storage capacity as it relates to terrestrial ecosystem C transformation processes. On account of soil C saturation, continuous C inputs and sequestration is less effective in enhancing C stocks at higher levels (b1) (Buyanovsky and Wagner, 1998; Campbell et al., 1999; Izaurralde et al., 2001; Halvorson et al., 2002). When exogenous nutrients enter the soil by way of an increase in N deposition, fertilization, and straw decomposition, the promotion of plant growth and soil biota are stimulated. However, N addition may be accompanied by a higher mineralization of residue C, and this higher mineralization effect may counterbalance higher C inputs (b2) (Chung et al., 2007, 2009). These excessive supplies of nutrients enhance soil productivity to an unattainable, limitless standard because an unchecked increase in soil productivity will gradually diminish soil quality. Accordingly, a polynomial curve was used to indicate dynamic changes in soil C under C and exogenous nutrient inputs.

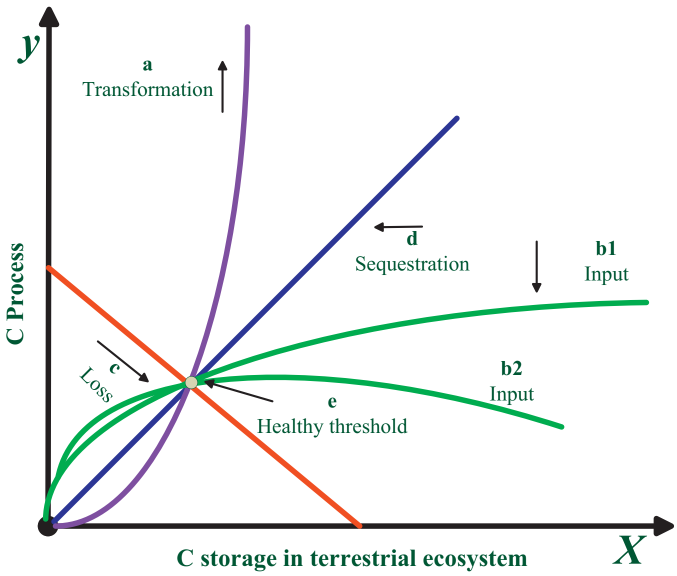

Fig. 1. Conceptual diagram of dynamical change in terrestrial ecosystem soil C storage capacity. Exponential curve (a) denotes that soil C transformation is in a state of natural cycling, primarily comprised of atmospheric CO_2 emitted through physiological and biogeochemical processes associated with plant and soil biota (expressed by the $y = ab^x$ model). Logarithmic and polynomial curves denote that C inputs (b1) and exogenous nutrients (b2) increase soil productivity (C), primarily comprised of fertilization, N inputs, and straw decomposition (expressed by the $y = a\ \log_b^x + c$ and $y = ax^2 + bx + c$ models, respectively). Linear curve (c) denotes that soil erosion processes decrease soil C storage capacity, primarily comprised of wind and water erosion (expressed by the $y = -ax + b$ model). Linear curve (d) denotes that C sequestration engineering increases the soil C pool (expressed by the $y = ax + b$ model). There is a cross point for the differing soil C dynamical change processes. This cross point is described as the terrestrial ecosystem C health threshold.

Soil, wind, and water erosion are the most widespread forms of soil degradation. Given that the effects of soil erosion on soil C storage and atmospheric C emissions are widely known, negative linear equations were used to indicate relationships between soil erosion and soil C storage capacity (Gao et al., 2008, 2009). Moreover, given that forestation and other C sequestration engineering approaches would significantly increase C storage capacities, positive linear equations were used to indicate relationships between C sequestration engineering and soil C storage capacity (Matamla et al., 2008; Gao et al., 2011). According to the C mass balance theory, an increase or decrease in soil C (whichever way) will at