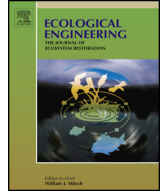




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Research paper

## 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.

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### 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<sub>2</sub>) 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.

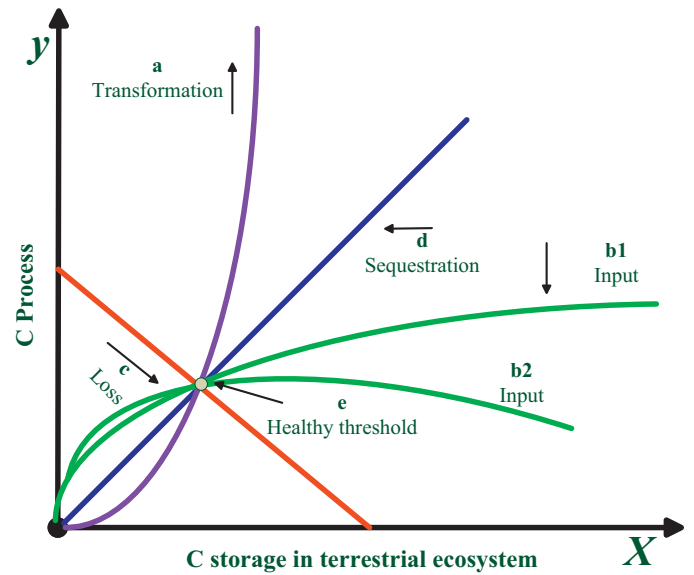
Gao et al. (2011) indicated that ecological thresholds exist for ecosystem degradation and recovery processes, and that a breach of these thresholds will lead to irreversible losses in soil productivity by long-term effects of self-adjustment that relate to vegetation recovery and soil degradation. As 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



**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<sub>2</sub> 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.

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.

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

the same time lead to an increase or decrease in the converse direction. This makes evident the health threshold balance point for terrestrial ecosystem C storage, owing to its innate facility for self-adjustment in order to maintain both a C mass balance and a continued state of healthy cycling.

## 2.2. Data analysis

The relationship between water erosion and C loss and C sequestration engineering and SOC changes were analyzed using generalized linear models ( $y = ax + b$ ); atmospheric CO<sub>2</sub> emissions through physiological and biogeochemical processes associated with plant and soil biota were analyzed using exponential models ( $y = ab^x$ ); increases in soil productivity through C inputs were analyzed using logarithmic models ( $y = a \log_b^x + c$ ); and increases in soil productivity through N inputs were analyzed by polynomial models ( $y = ax^2 + bx + c$ ). All above statistical analyses were carried out using software release 8.0. The soil C storage dynamical change concept diagram (Fig. 1) was generated using Microsoft Office Visio 2007.

## 3. Results

In order to demonstrate that coupling relationships between C, N, and water regulates the C health threshold, a meta-analysis was carried out on the effects of C inputs, C sequestration, N addition, and water erosion on terrestrial ecosystem C storage. In all, 11 sites

were selected for the C, N, and water coupling analysis. As Fig. 2a shows, logarithmic curves can be successfully used to illustrate relationships between C inputs and SOC levels ( $R^2 = 0.60$ ) (indicating soil C saturation statuses) (Table 1). At high C input levels, the effect would be a lesser apparent saturation response of SOC accumulation. This effect was also observed by Stewart et al. (2007) who assumed that this response was attributable to faster decomposition rates due to optimal temperature and moisture conditions. Although no significant relationships were found between N inputs and SOC by the polynomial model (Fig. 2b), it showed that as N inputs increase, the tendency of soil C is to become saturated. Consequently, N inputs have an opposite effect on C accumulation at high levels, thereby extending the C saturation theory. SOC or nutrient cycling has been significantly correlated to water availability and hydrologic transport for hillslopes (Gao et al., 2009, 2010). Fig. 2c illustrates that under control of hydrologic factors, C transport significantly correlated with runoff for cropland ( $R^2 = 0.63$ ). As Fig. 2d shows, increases in vegetation cover or plant density was positively correlated to SOC, calculated by the organic matter conversion coefficient ( $R^2 = 0.81$ ).

Through the research provided above, it was found that a cross point exists when the four curves are overlapped together. This cross point is the dynamic equilibrium point of water, C, and N for C processes that take place in terrestrial ecosystems. C storage values lower or higher than the equilibrium point would promote self-adjustment in order to maintain both a C mass balance and a continued state of healthy cycling. Therefore, the dynamic

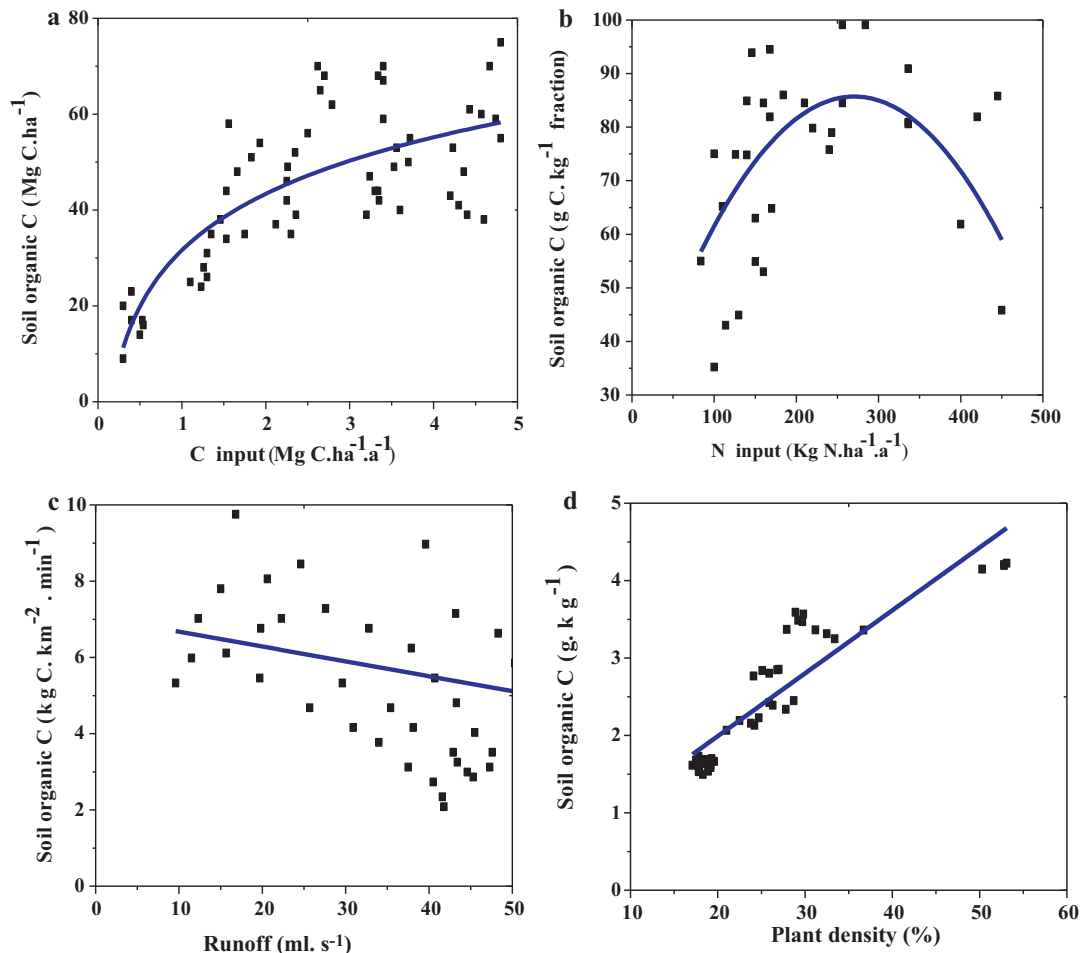


Fig. 2. SOC content. SOC content expressed as a function of C input levels (a); SOC content expressed as a function of N input levels (b); SOC content expressed as a function of runoff levels (c); SOC content expressed as a function of plant density levels (d) for the long-term agroecosystem experiments shown in Table 1.

**Table 1**  
Long-term sites selected for C health threshold analysis.

Site	Treatment (years)	Treatment	Verified C process	Reference
Mandan	12	Fertilizer addition	b1	Halvorson et al. (2002)
Breton	51	Fertilizer addition	b1	Izaurrealde et al. (2001)
Changting	12	Plant addition	d	Gao et al. (2011)
Yanting	10	Plant addition	c	Gao et al. (2008, 2009)
Sanborn	25	Manure addition	b1	Buyanovsky and Wagner (1998)
Swift Current	13	Fertilizer addition	b1	Campbell et al. (1999)
Ellerslie	40	Fertilizer addition	b2	Chung et al. (2009)
Fermilab	40	Plant addition	d	Matamla et al. (2008)
Alt Penedès	12	Plant addition	c	Ramos and Martínez-Casasnovas (2006)
Lexington	50	Fertilizer addition	b2	Chung et al. (2007)
Yanting	20	Fertilizer addition	b2	Wang (2007) and Wang et al. (2010)

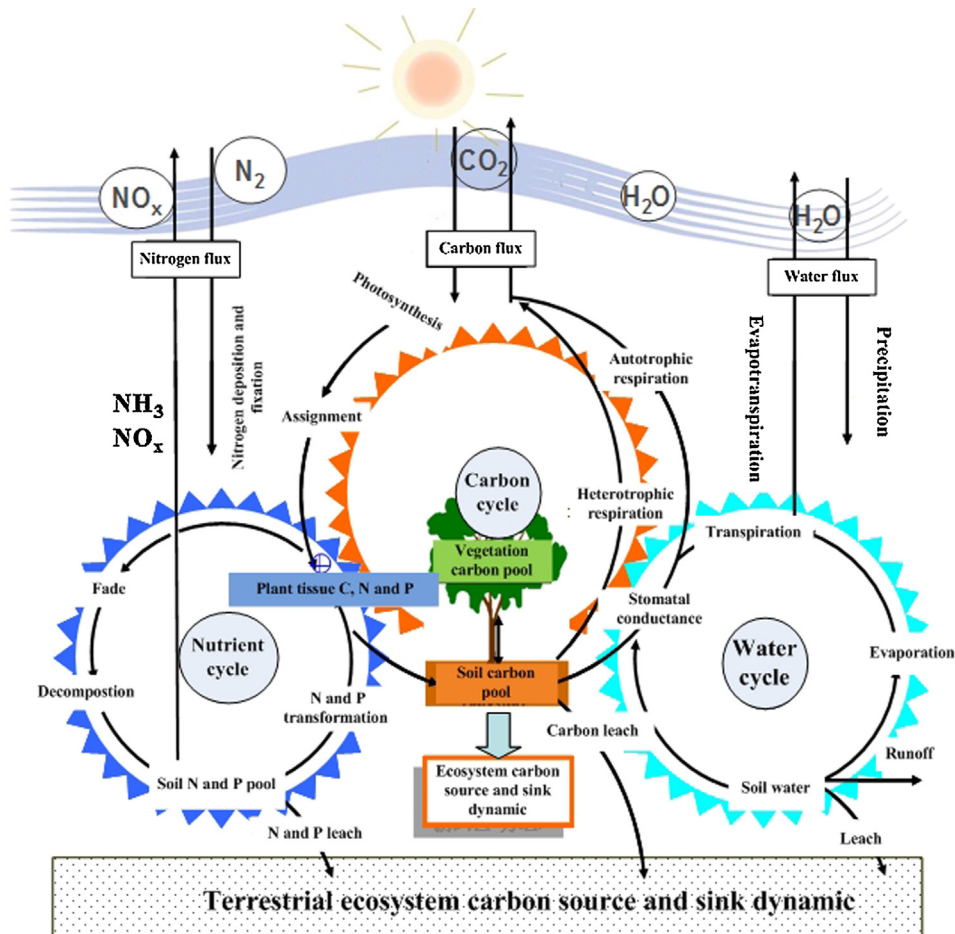
equilibrium point of water, C, and N for C processes can also be referred to as the health threshold for terrestrial ecosystem C storage.

**4. Discussion**

*4.1. Coupling relationships between C, N, and water*

As it relates to terrestrial ecosystems, water in plant cells and soil transpires and evaporates into the atmosphere (evapotranspiration). Precipitation can feed river flow above the surface flow or can leach through the soil, typically generating groundwater flow (Fig. 3). C cycling shows that interactions between energy inputs

and ecosystems will lead to the compound transformation of C for a biosphere. In the atmosphere, the photo-oxidation of C generates carbon monoxide (CO) or CO<sub>2</sub>. In aquatic systems, key processes include respiration and decomposition of organic matter, generating CO<sub>2</sub> and CO in addition to CO<sub>2</sub> sequestration. In the lithosphere, key processes include decomposition of organic matter by bacteria and yeast and CO<sub>2</sub> sequestration by plants and respiration, which produces methane and CO<sub>2</sub>. N cycling shows that most biological N fixation takes place due to symbiotic N fixing plants or free living microorganisms as a result of organic matter decomposition, which may occur both as denitrification to N<sub>2</sub>O and volatilization of NH<sub>3</sub>. Another terrestrial ecosystem N input takes place through means of both wet and dry deposition to soils or water stores. In



**Fig. 3.** Coupled terrestrial ecosystem C, N, and water cycles.

connection to denitrification and ammonia volatilization, N outputs from terrestrial ecosystems include runoff and leaching, which transport reactive N to rivers or ocean bodies.

N is a fundamental nutrient for living organisms. C productivity of plants and soil is strongly dependent upon nutrients, imposing stoichiometric constraints at an individual organism level (Zaehle and Dalmonech, 2011). C and N cycling are inherently and physically linked to water availability and hydrologic transport through transpiration, evaporation, runoff, and leaching (Vitousek and Howarth, 1991). These cycles have a considerable impact on ecosystem productivity and its exchanges with both the atmosphere and water bodies (Manzoni and Porporato, 2011). Despite differences between C, N, and water biogeochemical cycling, fundamental processes and strong coupling relationships are similar (Fig. 3).

#### 4.2. C balance model

In order to better understand the C health threshold, the C mass balance equation was improved according to Falkowski et al. (2000) (Fig. 1). According to the C balance model, effects of C sequestration, N addition, and water erosion on terrestrial ecosystem C storage were estimated. The equations are presented as follows:

$$C_v = (GPP + GPP_n - R_a - R_h - R_b) \times t \times a \quad (1)$$

where  $C_v$  is the vegetational C pool;  $GPP$  is gross primary productivity;  $GPP_n$  is C productivity increased by nutrient inputs such as fertilization, N addition, and N deposition (Janssens et al., 2010);  $R_a$  is plant autotrophic respiration;  $R_h$  is microorganism heterotrophic respiration;  $R_b$  is animal and insect biome respiration;  $t$  is time; and  $a$  is area.

$$C_T = C_v + C_s - E_p - Lg_p(Lg_{w1} + Lg_{w2}) - L_{gl} - L_a \quad (2)$$

where  $C_T$  is the total terrestrial ecosystem C storage capacity;  $C_s$  is the soil C pool;  $E_p$  is the physical carbon emission;  $L_g$  is the geological carbon leakage, including water erosion ( $Lg_{w1}$ ) and leaching ( $Lg_{w2}$ ), which is caused by precipitation and wind erosion ( $Lg_{gl}$ ); and  $L_a$  is anthropogenic carbon leakage. The sum of  $E_p$ ,  $L_g$ , and  $L_a$  is the gross ecosystem C leakage. As seen in Eqs. (1) and (2), an increase or decrease in C sequestration, N addition, and water erosion will change  $C_v$ ,  $GPP_n$ , and  $Lg_p$  parameters, respectively, leading to an increase or decrease in terrestrial ecosystem C storage ( $C_T$ ) capacity, which can have a direct impact on ecosystem health.

#### 4.3. C health threshold

Fig. 2 shows that as carbon fixation increases, the amount of N flux increases that can be captured in organic matter. As water flux increases, N flux increases (inputs and losses) as well as the potential for C fixation. As more N is captured in organic matter, its subsequent turnover also contributes to plant available N, allowing for increased plant productivity. Thus, the tendency of water and nutrient limitation of plant primary productivity and ecosystem carbon storage is toward equilibration (Schimel et al., 1997).

According to the C balance model, this study has concluded that there may be a balance point for dynamical changes to occur in C processes, which maintains healthy terrestrial ecosystem C cycling processes. Based on C, N, and water interactions, different conditions in understanding the C health threshold of ecosystems are discussed. According to Eqs. (1) and (2), if C storage ( $C_v$ ) is increased through forestation (Fig. 4a), plant C productivity ( $GPP$ ) will require an adequate nutrient and water supply. However, if  $C_v$  exceeds nutrient and water supply limits, either plant life will die out or C will be transported outside the boundaries of an ecosystem by means of soil erosion or other pathways. This is due to the balanced

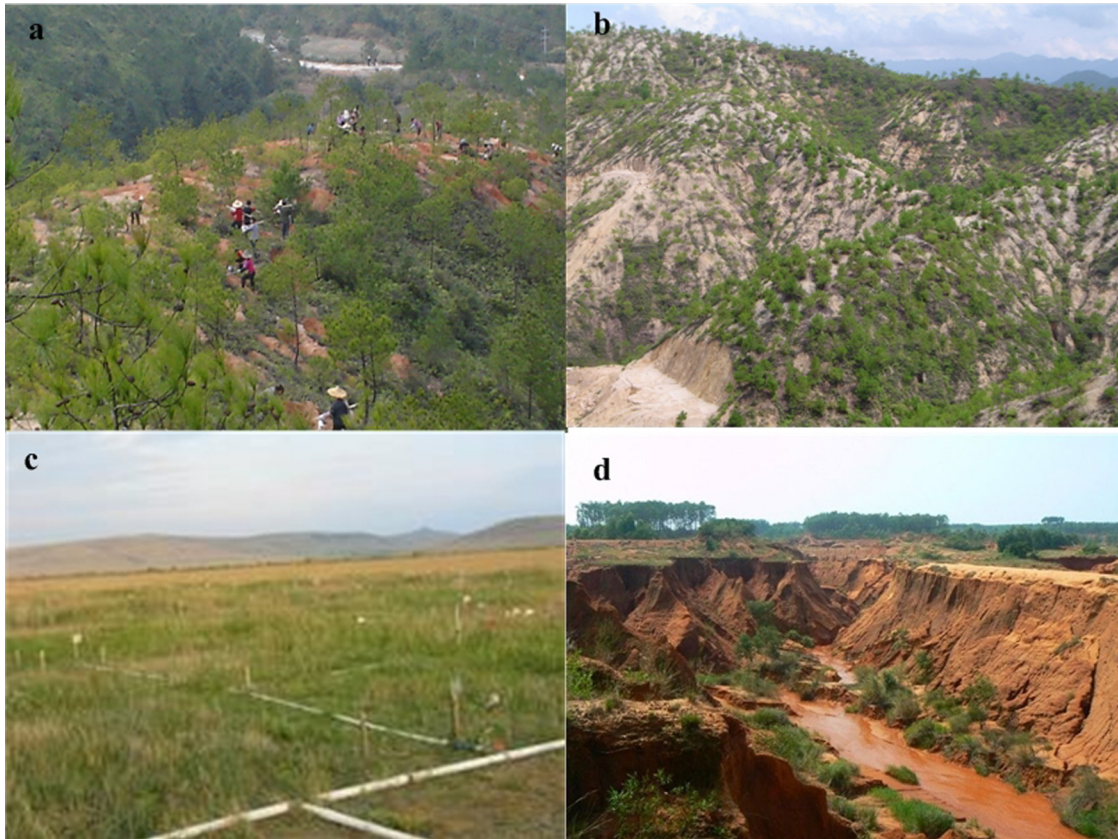
relationships that exist between C, N, and water (Fig. 4b). There must therefore be existing natural balance thresholds for C, nutrients, and water. The second condition is that an increase in N inputs stimulates plant growth ( $GPP_n$ ) and C sequestration ( $C_v$ ). When nutrients supplied by N deposition exceeds the  $GPP$  limit, plant life will either die out in order to increase denitrification through  $N_2O$  and volatilization through  $NH_3$  or the ecosystem will deteriorate into a sub-health state of fitness (Fig. 4c). In addition, N inputs may have an indirect impact on the climate and increase levels of tropospheric ozone, impairing both plant health and growth, which would also have an influence on overall C storage capacity. The last condition is that an increase in precipitants leads to a large amount of nutrient and C loss through soil erosion. When existing soil C can no longer maintain normal C cycling processes, either plant life will die out or the ecosystem will subsist within a sub-health state of fitness. The loss of soil C causes a decline in soil quality, requiring more fertilizers, tillage, and additional inputs to replicate comparable or even lower crop yields. There is also an increased risk of soil erosion, flooding, and the leaching of pollutants from soils into waterways (Fig. 4d). It can therefore be concluded that if ecosystem C storage is not controlled under normal ranges of fluctuation and is not maintained within a healthy threshold, ecological degradation will occur.

#### 4.4. Effects on terrestrial ecosystem C storage

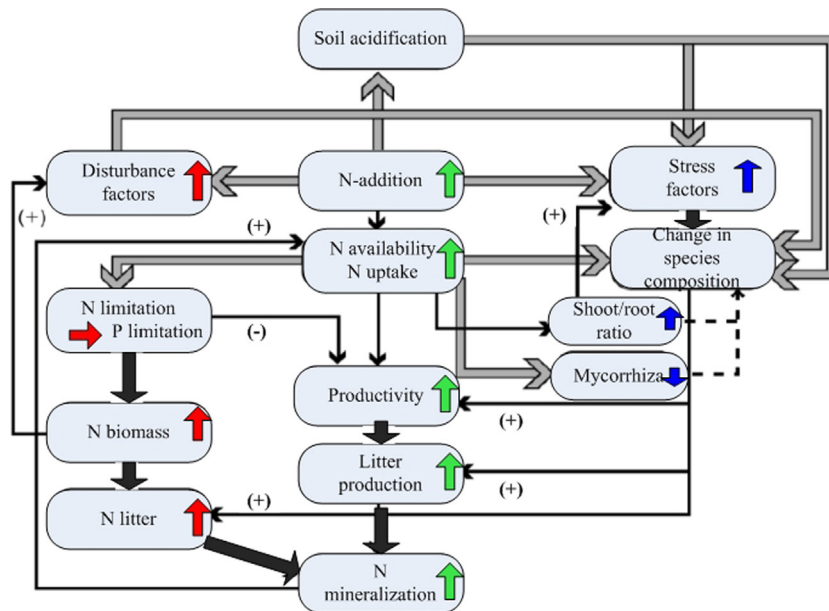
Stewart et al. (2009) found that additional C influenced SOC storage in measurable soil fractions because the amount of C added to soil generally increases SOC as well as soil fertility. However, as C addition levels increase, SOC stocks do not show a move toward equilibrium with C addition at higher input levels (Huggins et al., 1998; Reicosky et al., 2002), indicating that soil C content becomes saturated in connection with C inputs at equilibrium states (Six et al., 2002; Janzen, 2006; Stewart et al., 2007). Kimetu et al. (2009) also demonstrated that a threshold in soil C saturation takes place with decreasing SOC and increasing soil degradation beyond which soil C mineralization increases, which suggests a limit in the stabilization of soil C addition (Six et al., 2002; Stewart et al., 2007). The C health threshold theory also considerably improves the concept of soil C saturation.

Excess N inputs have aroused concerns with regards to their negative impacts on ecosystem health and services (Bobbink et al., 2010), such as loss of biodiversity (Stevens et al., 2004), eutrophication, C and N saturation (Liu et al., 2011), soil acidification (Richter et al., 2005), and rising levels of increased susceptibility to secondary stresses (Witzell and Shevtsova, 2004). Water erosion would lead to soil degradation and as a result would become a threat to food security. There is also a risk of accelerated emissions of  $CO_2$  and other greenhouse gases into the atmosphere as well as the potential impact on C dynamics and climate change (Lal, 2003).

N enters terrestrial ecosystems through biological fixation and reactive N deposition. Accelerated N deposition will increase inorganic N as well as net N mineralization and nitrification rates in soil but reduce soil microbial biomass C (Yu et al., 2007; Liu et al., 2011). In many cases, N addition under conditions of global climate change may increase C sequestration for temperate steppes (Niu et al., 2009). Zaehle and Dalmonech (2011) suggested that increased atmospheric N loading may indirectly influence climate change through its effect on terrestrial C sequestration since N deposition generally stimulates plant growth and C uptake as a consequence in addition to increased levels of tropospheric ozone that impairs plant health and growth. N availability affects energy and water fluxes, the terrestrial albedo effect, plant C production, respiration, and soil organic matter (SOM) decay (Fig. 5). N limitation occurs in ecosystems when C productivity is limited by N availability.



**Fig. 4.** Effects of C sequestration, N input, and water erosion on terrestrial ecosystem health. Image (a) depicts a forestation initiative in southern China; image (b) depicts a decrease in overall vegetation cover and species richness and an increase in soil erosion due to inappropriate forestation measures that took place in Fujian Province; image (c) depicts (by way of a statistical contrast experiment) that excess N deposition and exogenous N inputs considerably impacted plant growth; and image (d) depicts that water erosion through rainfall led to high losses in C, N, and soil at a terrestrial ecosystem in Fujian Province.



**Fig. 5.** N input impacts on terrestrial ecosystem health.

N fixation reduces the extent of N limitation when C availability is increased, and it may synergistically lead to an increase in C storage (Esser et al., 2011). Interactions between N fixation coupled with climate change and CO<sub>2</sub> fertilization may substantially alter future N fixation, which could potentially have a sizeable effect on C sequestration globally (Wang and Houlton, 2009).

Precipitation, one of the most important factors influencing soil erosion, can lead to C and N transport through runoff and leaching. C and N transport at the soil-water interface is largely controlled by C and N inputs and flow rates. Soil mobilizes N and soluble C during intense periods of rainfall. They are subsequently transported into deeper soil layers, which results in increased substrate availability for the decomposer community and improved nutrient conditions for vegetation (Kalbitz et al., 2000). Initial C and N runoff and leaching are more robust in aquatic than in terrestrial transport. With regards to runoff and leaching losses caused by intense periods of rainfall, however, the stoichiometric requirements of decomposers largely controls the balance of C and organic nutrients in decomposing plant residues for both terrestrial (Cleveland and Liptzin, 2007; Manzoni et al., 2008, 2010) and aquatic ecosystems (Elser et al., 2000; Cross et al., 2005). Soil erosion affects C dynamics in terrestrial ecosystems by slaking or the disruption of aggregates; preferential removal of C in runoff (Miao et al., 2010, 2011); site mineralization of SOM; SOC mineralization, displacement, and redistribution that takes place throughout the landscape as well as transportation via river systems; soil re-aggregation through the formation of organo-mineral complexes in depositional or protected sites; and deep burial of C enriched sediments in depositional sites (Lal, 2003).

The terrestrial C pool (comprised of both soil and vegetation components) is the third largest pool within an ecosystem. This pool includes a SOC pool estimated at 1550 Pg and a soil inorganic C pool estimated at 750 Pg (Eswaran et al., 1995; Batjes, 1996), with a combined terrestrial C pool volume of approximately 2300 Pg at a soil layer depth of 1 m. Global land area affected by water erosion is estimated at 1094 million ha, of which 751 million ha has been severely affected (Lal, 2003). Assuming a delivery ratio of 10%, a sediment load of 20 billion Mg, and a SOC content of 2–3%, total SOC displacement by way of erosion would be in the order of 4.0–6.0 Pg C (Lal, 1998), all of which would be transported through water erosion each year with the exception of 1.14 Pg C that would be emitted into the atmosphere each year (Lal, 1998). Although the effects of

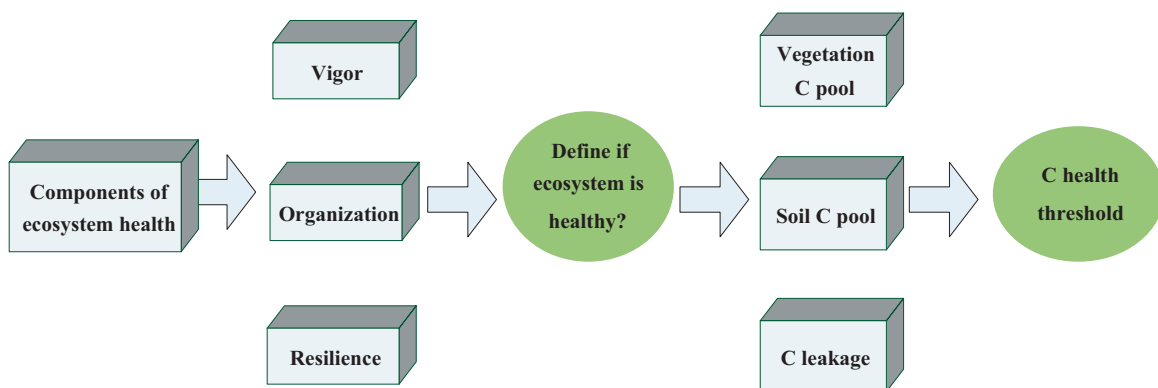
soil erosion on C dynamics and atmospheric emission rates of CO<sub>2</sub> (in addition to rates of other greenhouse gases) are evident and widely known, their impact on ecosystem C storage is still not well understood.

There are many pathways by which to increase C sequestration, such as the containment of C in natural storage vessels in addition to using it to enrich soil. Terrestrial C sequestration is considered an advantageous condition all around. It is mainly carried out by means of forest and soil conservation initiatives that enhance C storage (such as initiatives to restore and establish new forests, wetlands, and grasslands) or those that reduce CO<sub>2</sub> emissions (such as decreasing agricultural tillage and suppressing wildfires). However, in addition to the potential risk of global warming, soil to atmosphere C loss has agronomic and environmental consequences. Implementing measures to increase terrestrial C sequestration requires careful consideration with regards to the priorities and tradeoffs involved. For example, converting farmland to forest or wetland may increase C sequestration, enhance wildlife habitat and water quality, and increase flood storage and recreational potential, but the loss of farmland would simultaneously decrease crop production.

Wang and Cao (2011) reported that C sequestration engineering could generate negative effects on ecosystem health since forestation without understory protection may potentially increase the erosive energy of water, thereby accelerating soil erosion. This takes place because in certain regions the water supply for grasslands and forests has been historically in a state of equilibrium, but C sequestration engineering would reduce soil water reserves, and, as a result, woody vegetation would eventually die out from the resulting water stress conditions, leading to desertification (Cao et al., 2009a,b, 2010, 2011; Cao, 2011). Climatic effects of CO<sub>2</sub> storage in these planned forests may be offset by changes in the albedo effect. Moreover, the conversion of previously designated conservation areas to areas of intensive cultivation, while producing valuable crops, may diminish wildlife habitat, reduce water quality and supply, and increase overall CO<sub>2</sub> emissions.

#### 4.5. Quantifying the C health threshold

Quantifying the C health threshold would help in evaluating the relative health of similar ecosystems and the effects of natural or anthropogenic stress on the health of ecosystems over



**Fig. 6.** Quantifying the terrestrial ecosystem C health threshold. Between vigor, organization, and resilience, vigor is the most straightforward component used to measure health along with GPP and organic metabolism for ecological systems and Gross Domestic Product (GDP) for economic systems. Quantifying organization involves measuring both the diversity and magnitude of system components in addition to the pathway exchanges that exist between them. Related measures of organization include the diversity index, average mutual information (Ulanowicz, 1986), and predictability (Turner et al., 1989). Network analysis is another potential approach to measure organization. Measuring system resilience and predicting ecosystem impacts over time generally requires dynamic simulation models (Costanza et al., 1990). Related measures of resilience include scope for growth (Bayne, 1987), population recovery time (Pimm, 1984), and the disturbance absorption capacity (Holling, 1987). Refer to Costanza and Mageau (1999) for more detail on quantitative assessments of ecosystem health. Refer to Falkowski et al. (2000) for information related to the calculation of the vegetation C pool, soil C pool, and gross ecosystem C leakage.

time. On the other hand, it is inherently more difficult in determining the qualitative and quantitative complexity of ecosystem health owing to the greater modeling and synthesis required. According to the definition of an ecosystem described by Costanza and Mageau (1999), ecosystem health is closely linked to the idea of sustainability, which is understood to be a comprehensive, multiscaled, and dynamic measure of system resilience, organization, and vigor. Three components of ecosystem health can be identified and the quantification of these components can be described, used to judge whether an ecosystem is healthy (Fig. 6). A healthy ecosystem is capable of developing an efficient diversity of components and exchanges in pathways (high organization) while maintaining some redundancy or resilience as insurance against stress and overproduction by which to quickly recover or utilize stress productively (Costanza and Mageau, 1999). After concluding an ecosystem health evaluation, the C health threshold can be obtained by calculating the vegetation C pool, the soil C pool, and the leaching that occurs from gross ecosystem C production. As Fig. 6 shows, defining ecosystem health is a key step in quantifying the C health threshold. If the study ecosystem is diagnosed being sub-health, we can know the C health threshold through evaluating the relative C pool of similar healthy ecosystems.

## 5. Conclusion and perspective

The aim of this study was to advocate the conceptual C health threshold model for terrestrial ecosystems. According to the description of the model, there is a limit to the capacity of terrestrial ecosystems on increases in C storage under conditions of increasing C and N input levels and high C soil contents. This decreased C stabilization efficiency suggests an upper limit or inflection point on terrestrial ecosystems. If C storage exceeds the C health threshold, ecological degradation will either take place or the ecosystem will fall into a sub-health state of fitness. During the Copenhagen Summit held in December 2009, China agreed to reduce CO<sub>2</sub> emission intensity by 40–45% below 2005 levels by the year 2020 (Wu et al., 2012). Moreover, to decrease CO<sub>2</sub> emissions while at the same time combat climate change, China initiated reforestation projects to enhance C storage by 16–30 billion tons C per year, starting in 2006 and ending in 2050. These projects were inaugurated by increasing the country's forested area by 40 million ha (Yin et al., 2010). However, C sequestration engineering, such as reforestation, may have an unforeseen effect on C health cycles. Becoming familiar and proficient in understanding terrestrial ecosystem C health thresholds will therefore help in determining the appropriate ecological restoration measures to take when combating climate change and working to maintain C health cycling processes in the future.

C sequestration, N inputs, and water erosion leads to changes in terrestrial ecosystem C storage capacities, thereby impacting terrestrial ecosystem health. N inputs contribute to the current global C uptake to some extent while N limitation strongly reduces terrestrial ecosystem C sequestration capacity. Water erosion has a strong affect on terrestrial ecosystem C cycling and must therefore be taken into consideration when assessing issues related to global C storage. Adoption of conservation-effective measures may reduce risks associated with C emissions and the sequestration of C within soil reservoirs. Coupling relationships that take place between C, N, and water shape the response of ecosystems to the effects of global climate change. Moreover, expanding coupled C and N biogeochemical and water cycles from regional to global scales would provide a better insight by which to understand the terrestrial ecosystem health threshold related to C storage capacity. Analysis of interannual variability in the carbon cycle and its potential future behavior must also take into account mechanisms that act

through the coupling of water, C, and N cycles. The long-term effective stabilization of terrestrial ecosystem C storage that defines the maximum C sequestration potential with increasing C and N input levels under a particular management scenario is therefore supported by this study. However, future research is needed to firmly establish the validity of the health concept and better quantify the controls on terrestrial ecosystem C kinetics.

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