Analytical Methods for Carbon Balance in Grassland Agroecosystems (Postprint)

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Abstract

According to the structure of grassland agro-ecosystems, its carbon balance constitutes the sum of the carbon balances of the four production layers, as well as the sum of the carbon balances of the three interfaces, whereas the carbon balance of a particular production layer or interface represents the sum of its carbon fixation, input, emission, and output. The carbon balance analysis method based on the four production layers of grassland agro-ecosystems quantifies carbon sink and source processes in critical production stages, thereby facilitating improved carbon sink management in grassland agriculture; the carbon balance analysis method based on the three interfaces reveals the mechanisms of carbon source and sink formation, along with their spatial and quantitative relationships, thus enabling the regulation of grassland production components to enhance carbon sequestration and reduce emissions; however, these two methods do not readily distinguish carbon sources and sinks, making it difficult to ascertain utilization efficiency. The input/output method for carbon balance analysis in grassland agro-ecosystems quantitatively identifies carbon sources and sinks, as well as carbon efficiency, with straightforward calculations, yet remains overly generalized and unsuitable for carbon sink management at the ranch scale. Employing three methods to analyze the carbon balance of two ranches—the Gansu Sika Deer Ranch in the Qilian Mountains, China, and a dairy ranch in Tasmania, Australia—the results demonstrate that the primary carbon sources in grazing-managed grassland systems are greenhouse gases generated from leisure tourism and product processing and distribution stages, while the principal carbon sink is carbon stored in grasslands and soils, and that effective grassland management can increase carbon sequestration and reduce emissions.

Full Text

Carbon Balance Analysis Methods of Grassland Agro-Ecosystems

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Abstract

Based on the structure of grassland agro-ecosystems, their carbon balance represents either the sum of carbon balances across four production levels or the sum across three interfaces. The carbon balance of a specific production level or interface equals the sum of carbon that is fixed, emitted, and output through various processes within that level or interface. The four-production-level carbon balance analysis method quantifies carbon sink and source processes in key production stages, facilitating improved carbon sequestration management in grassland agriculture. The three-interface carbon balance analysis method reveals the mechanisms, spatial relationships, and quantitative linkages of carbon sources and sinks, enabling regulation of system components for enhanced carbon sequestration and emission reduction. However, these two methods cannot clearly distinguish carbon origins and destinations or quantify utilization efficiency. The input-output method for grassland agro-ecosystem carbon balance analysis quantitatively tracks carbon pathways, sources, and destinations, as well as carbon efficiency, though it remains relatively general and less applicable to farm-scale carbon sequestration management. Using case studies from a deer ranch in China's Qilian Mountains and a dairy farm in Tasmania, Australia, three methods were applied to analyze carbon balances. Results showed that tourism, product processing, and marketing accounted for major greenhouse gas emissions from the grazing management systems. The primary carbon sinks were carbon stored in forage and soil. Effective grassland management can enhance carbon sequestration and reduce emissions.

Keywords: grassland agro-ecosystems; production level; interface; carbon balance; grazing; greenhouse gases

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Grassland represents the largest terrestrial ecosystem globally, with organic carbon storage in natural grasslands worldwide accounting for 37.1%–52.3% of terrestrial carbon reserves [1-2]. Within certain timescales, grassland soil organic carbon pools show no significant change [5-6], maintaining a neutral carbon sink status [7]. However, the tourism products, cultural products, and livestock products exported from grasslands are increasing annually [8-9]. If these carbon losses are included in calculations, grassland carbon pools become significantly affected by management [10-11], and whether they function as carbon sources or sinks depends on grazing management practices [12-13]. Generally, greenhouse gas (GHG) emissions from grazing systems are lower than those from equivalent-scale confined feeding systems [14]. Grazing systems can maintain carbon sequestration capacity for decades (e.g., cultivated grasslands in the UK and New Zealand) or even millennia (e.g., natural grasslands), and grassland-livestock coupling can enhance this capacity [15].

Grassland carbon sequestration management is based on carbon measurement techniques, which include direct and indirect methods [17]. Direct methods commonly use static chamber techniques, dynamic chamber methods, and micrometeorological approaches, while indirect methods calculate fluxes by measuring changes in soil CO_2 concentrations [17]. For soil respiration in large-scale or cross-regional studies, indirect methods are more practical. Previous research has focused primarily on soil and livestock components, often examining individual components rather than the ecosystem as a whole [16]. Studies on carbon cycling in grassland vegetation, forage-livestock interactions, and carbon balance during product processing and distribution remain limited, particularly regarding how production management affects carbon dynamics and the underlying mechanisms. Discrepancies in grassland system carbon sequestration research results [25-28] primarily stem from inconsistent estimation methods and statistical data variations [25-26], with the fundamental cause being the lack of assessment methods based on grassland system structure and key ecological processes.

This study aims to develop accurate carbon balance analysis methods for grassland agriculture from the perspectives of system structure, key ecological processes, and the system as a whole. The carbon balance of grassland agro-ecosystems (CBGAE), measured in carbon content or equivalent carbon units, refers to the net carbon change over a specific time period.

1. Carbon Flow in Four Production Levels of Grassland Agro-Ecosystems

Carbon in grassland systems flows through four production levels: pre-plant, plant, animal, and post-biological production levels [Figure 1: see original paper]. Solid lines indicate carbon flow within or out of production levels, while dashed lines show carbon input from external sources to production levels.

1.1 Carbon Balance of the Pre-Plant Production Level

The pre-plant production level focuses on landscape services such as soil and water conservation, and tourism/hunting [29]. Carbon sink processes include biological nitrogen fixation and carbon-nitrogen accumulation, while tourism and recreational products represent carbon source processes, including energy consumption for management and grassland trampling. Although research on emissions from this level is limited, carbon emissions from grassland tourism have received increasing attention [30].

The carbon balance of the pre-plant production level (CBPPP) is calculated as:

$$CBPPP = \text{input} - \text{output}$$

Input includes carbon from biological nitrogen fixation, fertilization, and reseeding. Output comprises carbon emissions from tourism, hunting, and management activities. When CBPPP > 0, the level acts as a carbon sink; CBPPP = 0 indicates carbon neutrality at an ecological threshold with degradation risk; CBPPP < 0 indicates a carbon source and degradation stage [10]. Improving economic benefits per unit of carbon emission represents the primary approach for enhancing carbon sequestration and reducing emissions at this level.

1.2 Carbon Balance of the Plant Production Level

The plant production level encompasses traditional forage production in natural and cultivated grasslands, representing the main carbon pool of the system (including plant and soil carbon pools). Carbon sink processes primarily involve photosynthesis and carbon-nitrogen assimilation through biological nitrogen fixation. Carbon sources include soil respiration, management-related energy consumption, and forage output.

The carbon balance of the plant production level (CBPP) is:

$$CBPP = \text{input} - \text{output}$$

Input includes carbon from photosynthesis, nitrogen deposition, and fertilization/reseeding. Output consists mainly of soil carbon emissions and forage removal. When CBPP > 0, natural grasslands face degradation risk, while cultivated grasslands require water and energy inputs to maintain operation, which is considered normal. CBPP < 0 indicates degradation [13,31]. Enhancing forage yield and quality while reducing soil carbon emissions and management inputs are key pathways for increasing carbon sequestration and reducing emissions, particularly in natural grasslands.

1.3 Carbon Balance of the Animal Production Level

The animal production level involves traditional herbivore livestock production and represents a major carbon source. Plant carbon from the plant production level is emitted to the environment through enteric fermentation, excreta volatilization, and decomposition. Management-related emissions from labor and disease control constitute another major carbon source. Carbon input occurs through purchased forage, while only a small fraction of forage carbon is fixed in livestock products. Carbon in meat and blood is quickly emitted, with emissions calculable based on slaughter rates. Carbon in bones and hooves is more easily preserved long-term.

The carbon balance of the animal production level (CBAP) is:

$$CBAP = \text{input} - \text{output}$$

Input is primarily forage. Improving forage conversion efficiency and promoting excreta recycling are main approaches for enhancing carbon sequestration and reducing emissions at this level. CBAP < 0 indicates the level functions as a carbon source.

1.4 Carbon Balance of the Post-Biological Production Level

The post-biological production level involves forage and livestock product processing, storage, transportation, and overall system management, significantly enhancing social and economic benefits. Carbon sources include product processing and infrastructure/equipment manufacturing. Some grassland and livestock products can be preserved long-term.

The carbon balance of the post-biological production level (CBPBP) is:

$$CBPBP = \text{input} - \text{output}$$

If the system prioritizes economic benefits, emissions from production level operations far exceed carbon fixed in products, but economic benefits per unit carbon emission can be improved through this level. If food production is prioritized with economic benefits as secondary, management at this level contributes to overall system carbon sequestration and emission reduction, though processing and transportation emissions should be controlled.

1.5 System Carbon Balance and Case Analysis

The carbon balance of grassland agro-ecosystems equals the sum of the four production levels:

$$CBGAE = CBPPP + CBPP + CBAP + CBPBP$$

When CBGAE > 0, the system is a carbon sink; otherwise, it is a carbon source. Carbon benefit ratio is calculated as carbon fixation per unit economic benefit—higher ratios indicate lower environmental debt and stronger ecological-economic sustainability. CBGAE can be calculated for individual farms, enterprises, production regions, ecological zones, or administrative regions.

Using a deer ranch in the Qilian Mountains (mid-section) and a dairy farm in northwest Tasmania as examples [15,31-39], both systems have relatively complete production chains and represent the global trend of enhanced agricultural system multifunctionality [15].

Table 1 shows the carbon balance analysis across four production levels for both ranches. The Qilian Mountain deer ranch (DRQ) grazes on alpine shrub-meadow, has developed alpine pasture tourism, and processes deer antler and blood products [33]. The Tasmanian dairy farm (DRT) grazes on perennial ryegrass pasture year-round, with agricultural tourism and cheese processing [38].

For the Qilian Mountain ranch, CBGAE > 0, with the plant production level accounting for 97.2% of carbon sequestration and animal/post-biological levels contributing 0.04%. Low deer digestibility results in more carbon emissions to the environment. Post-biological level emissions mainly come from tourism. For the Tasmanian ranch, CBGAE > 0, with higher emissions from the plant production level due to fertilization. Dairy cows always graze at optimal forage stages, resulting in high digestibility. In both ranches, the post-biological level accounts for less than 2.7% of carbon sources (due to rotational grazing).

2. Three-Interface Carbon Balance Analysis of Grassland Agro-Ecosystems

The three interfaces of grassland systems are active zones and pathways for carbon fixation and emission [Figure 2: see original paper]. The herbage-site interface (Interface A) involves carbon exchange between grass plants and the abiotic environment. The grassland-livestock interface (Interface B) involves interactions between grassland and livestock. The social-economic management interface (Interface C) involves complete grassland agro-ecosystem evolution.

Table 2 shows the carbon balance across three interfaces for both ranches. In both systems, CBGAE > 0, with carbon emissions concentrated in the pre-plant production level or social-economic management interface, while carbon sinks are primarily in the plant production level or herbage-site interface. Carbon management should focus on reducing emissions from pre-plant and post-biological levels while enhancing sinks in plant and animal levels or at interfaces.

3. Input-Output Method for Grassland Agro-Ecosystem Carbon Balance Analysis

The carbon balance of any production level or interface can be determined through four components: carbon input (fertilizer, manure), carbon emission (CO , CH), carbon fixation (stored in the system), and carbon output (products). The system carbon balance is:

$$CBGAE = \text{carbon input} - \text{carbon emission} - \text{carbon fixation} - \text{carbon output}$$

When CBGAE > 0, the system is a carbon sink. The sum of initial carbon stock and CBGAE equals current carbon stock. **Table 3** provides an example of input-output analysis for the animal production level in both ranches, showing both as carbon sources, consistent with production-level and interface-level analyses.

4. Discussion

4.1 Comparison of Three Carbon Balance Calculation Methods

The three methods each have distinct advantages. The production-level method focuses on energy and material flow patterns, facilitating production management improvements and corresponding to specific production stages with clear carbon balance mechanisms. However, it requires extensive survey data and involves numerous calculation items. The interface method emphasizes key ecological processes from an ecosystem perspective but lacks connection to specific production stages and mechanisms. The input-output method simply and succinctly reflects carbon movement pathways but is less applicable to farm-scale management. Current carbon balance analyses also employ life cycle analysis and meta-analysis. The former, similar to production-level and interface methods, tracks carbon flows from origin but neglects interactions among components. The latter statistically analyzes existing literature data to reflect broad spatiotemporal carbon dynamics but cannot clarify specific mechanisms.

Table 4 compares these methods for grassland carbon sink analysis.

4.2 Atmospheric Carbon-Nitrogen Deposition

Current methods struggle to distinguish between carbon from photosynthesis versus natural deposition processes like carbon dust fall versus artificial inputs like manure application. This limitation hinders management efficiency improvements. Though not considered in the case studies, carbon-nitrogen deposition significantly affects ecosystem carbon balance in humid regions. Short-term nitrogen deposition enhances plant productivity and increases soil microbial decomposition [51], directly affecting plant and soil carbon pools [51], while long-term deposition reduces soil microbial biomass [52].

4.3 Grassland Carbon-Nitrogen Leaching

Soluble carbon and nitrogen leach into groundwater systems [53-54], influenced primarily by precipitation, irrigation, and land use [38,53,55-57]. Natural grasslands in arid regions experience weak leaching [58], retaining substantial inorganic carbon exceeding soil organic carbon [2]. Increased irrigation enhances inorganic carbon leaching [58]. Grazing intensifies leaching by reducing vegetation cover, accelerating litter decomposition, decreasing precipitation interception [55], and promoting aboveground allocation of decomposition products [59]. Soil air partial pressure and solution pH also control inorganic carbon concentration and flux [38], affecting system carbon balance [60].

4.4 Livestock Excreta

In intensive grassland systems, GHG emissions from livestock excreta cannot be ignored. IPCC emission inventories include manure as a key indicator [35]. Grazing livestock excreta mostly returns to grassland, with small portions stored in barns [10]. This carbon, after fermentation and application to cropland, affects soil microbial respiration and carbon storage. Quantifying how much excreta carbon returns to soil versus becoming soil carbon remains uncertain [50].

4.5 Carbon Footprint of Post-Biological Production Level

International carbon footprint accounting primarily serves the energy sector [61], with no universal standard for grassland systems. The post-biological level' s carbon footprint remains a research gap. Life cycle assessment (LCA) can identify components and quantify energy consumption/emission data [62]. Given China' s vast natural grasslands and expanding cultivated grasslands, product processing is key to grassland development but conflicts with carbon sequestration goals. Developing the post-biological level to improve economic efficiency per unit carbon emission offers a pathway to balance ecology and production. Implementing Clean Development Mechanism (CDM) principles could benefit healthy development of grassland agro-ecosystem post-biological production [63-64].

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Note: Figure translations are in progress. See original paper for figures.