Ecosystem Service Trade-offs in the Spatial Restructuring of Grain Production on the Loess Plateau: A Case Study of Yulin City, Northern Shaanxi (Postprint)

Authors: Yang Haijuan

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Abstract

The restructuring of grain production space concentrates the principal contradictions in land system change; exploring the trade-off dynamics of ecosystem services during this process helps clarify the conflicts among food security, ecological restoration, and economic development, thereby promoting regional ecological civilization construction and high-quality development. Using ecosystem service assessment models and the root mean square deviation method, we analyzed carbon sequestration, food supply, soil conservation, and water yield services and their trade-off relationships during the restructuring of grain production space in Yulin City, northern Shaanxi, from 2000 to 2018. The results indicate that: (1) From 2000 to 2018, the Grain for Green Program, urban expansion, and deforestation and grassland reclamation were the primary pathways of grain production space restructuring in Yulin City. (2) From 2000 to 2018, grain production space restructuring in Yulin City significantly enhanced carbon sequestration and soil conservation services while generating negative effects on food supply and water yield services. Specifically, the Grain for Green Program promoted significant improvements in carbon sequestration and soil conservation services but negatively impacted food supply; following urban expansion, carbon sequestration, soil conservation, and food supply services all exhibited declining trends; deforestation and grassland reclamation notably enhanced food supply service. (3) Grain production space restructuring led to intensified trade-offs among regional ecosystem services; however, different restructuring pathways exhibited varying influences on ecosystem service trade-offs: the Grain for Green Program and deforestation and grassland reclamation most significantly affected trade-off changes between carbon sequestration and food supply, soil conservation, and between food supply and soil conservation, while urban expansion played a prominent role in trade-offs between water yield

and other services. The primary reason for these divergent trade-off patterns lies in the changes in relative benefits among services resulting from different restructuring pathways.

Full Text

Trade-off Analyses of Ecosystem Services During the Reconstruction of Grain Production Space in the Loess Plateau: A Case Study of Yulin City

YANG Haijuan[1], SUN Laiding[1], ZHOU Meijun[1], LI Fei[1],[2]

[1]College of Urban and Environmental Sciences, Northwest University, Xi' an 710127, Shaanxi, China
[2]Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, Xi' an 710127, Shaanxi, China

Abstract: Grain production space reconstruction (GPSR) concentrates the principal contradictions in land system change. Scientifically exploring the trade-offs of ecosystem services (ESs) during GPSR is conducive to clarifying the conflicts among food security, ecological restoration, and economic development, thereby promoting regional ecological civilization construction and high-quality development. This study employs ecosystem service evaluation models and the root mean square deviation method to analyze carbon sequestration, food supply, soil conservation, and water yield services and their trade-offs during GPSR in Yulin City, northern Shaanxi, from 2000 to 2018. The results indicate that: (1) From 2000 to 2018, the Grain-for-Green Program, urban expansion, and deforestation for cultivation constituted the main pathways of GPSR in Yulin. (2) During this period, GPSR significantly enhanced carbon sequestration and soil conservation services while negatively affecting food supply and water yield services. Specifically, the Grain-for-Green Program markedly promoted carbon sequestration and soil conservation but reduced food supply. Urban expansion led to declines in carbon sequestration, soil conservation, and food supply services. Deforestation for cultivation significantly improved food supply service. (3) GPSR increased trade-offs among regional ecosystem services; however, different reconstruction pathways exhibited varying impacts on service trade-offs. The Grain-for-Green Program and deforestation for cultivation most significantly influenced trade-offs between carbon sequestration and food supply, soil conservation and food supply, and food supply and soil conservation. Urban expansion played a prominent role in trade-offs involving water yield and other services. Overall, changes in relative benefits among services constitute the primary reason for the divergent patterns of trade-offs during GPSR.

Keywords: grain production space reconstruction; ecosystem services trade-offs; Grain-for-Green; deforestation and reclamation; urban expansion

Introduction

Grain production space (cultivated land), urban-rural development space (construction land), and ecological service space (forest/grassland, water bodies, and unused land) represent a functional reconceptualization of land use. Food production and security have always been matters of vital national importance. Since China’ s reform and opening-up, rapid economic development and population growth have induced significant changes in grain production space. Urbanization has continuously advanced through intensive urban expansion and cultivated land loss, with the national average annual rate of construction land occupying cultivated land increasing from approximately 13.3×10^{3} ha during 1980–2000 to 20.0×10^{3} ha during 2000–2010. Concurrently, ecological restoration projects such as the Grain-for-Green Program have converted cultivated land to forest and grassland. Research indicates that since 2000, the area of cultivated land occupied by ecological projects ranks second only to that occupied by construction land. Both urbanization and ecological restoration directly threaten food security through cultivated land loss. To ensure food security, some forest and grassland areas with strong ecological functions have been reclaimed for cultivation. Direct conflicts between urban-rural development space and ecological service space are relatively rare; instead, their interactions occur primarily through indirect conversion mediated by grain production space reconstruction. Thus, under the subjective trade-offs of different stakeholders regarding land system functions, China’ s grain production space has undergone continuous reconstruction in quantity, quality, and pattern through urban expansion, Grain-for-Green, and deforestation for cultivation, during which ecological problems such as water resource shortages and soil erosion have become increasingly prominent, profoundly affecting residents’ livelihoods and well-being.

Ecosystem services refer to the natural conditions and utilities formed and maintained by ecosystems that humans depend on for survival. The mutually constraining relationships among different services are termed ecosystem service trade-offs. Understanding these trade-offs facilitates ecosystem service management decisions and enhances human well-being. Current research primarily focuses on single processes such as forest management, Grain-for-Green, or urban expansion, with limited attention to ecosystem service trade-offs during the comprehensive process of grain production space reconstruction. GPSR focuses on areas where grain production space interacts intensely with urban-rural development space and ecological service space. Investigating ecosystem service trade-offs during GPSR can more directly reflect the impacts of different human activities on ecosystem services and their trade-offs, clarify the effects and mechanisms of GPSR, and provide stronger theoretical support for rational land resource planning. Therefore, this study selects Yulin City as the research area, employing the Global Agro-Ecological Zones (GAEZ) model crop yield module, the InVEST water yield module, the Revised Universal Soil Loss Equation (RUSLE) model, and the root mean square deviation (RMSD) method to evaluate the spatiotemporal patterns of carbon sequestration, food supply, soil conservation, and water yield services during GPSR from 2000 to 2018, and to analyze the dynamic characteristics of ecosystem service trade-offs, providing theoretical support for promoting high-quality development of the ecological environment and human society.

1 Study Area Overview

Yulin City is located in the northernmost part of Shaanxi Province, in the central hinterland of the Loess Plateau (36°57 -39°34 N, 107°28 -115°11 E), covering a total area of 43,578 km^2. Geomorphologically, the Great Wall divides the region into a wind-sand grassland area in the north and a loess hilly-gully area in the south, with elevations ranging from 589–1,895 m. The climate is temperate continental monsoon, with mean annual temperatures of 8.5–11.0°C and mean annual precipitation of 350–550 mm, with over 60% of rainfall concentrated in July–September. Soils are primarily aeolian sandy soil and loess, highly susceptible to erosion. Land use consists mainly of slope cropland, terraced fields, grassland, and forestland. Staple crops include maize and soybean. In 2018, Yulin' s planting industry gross output value reached 38.4862 billion yuan, up from 7.931 billion yuan in 2000. Since 2000, Yulin has been a key implementation area for the Grain-for-Green Program, with project deployment area and intensity exceeding the Loess Plateau average. Grain production space has continuously converted to ecological service space. Simultaneously, with the upgrading of the energy industry, Yulin' s economy has developed rapidly, leading to continuous urban-rural development space expansion. Conversely, to ensure food security, some forest and grassland areas have been reclaimed to supplement cultivated land. During this process, contradictions among grain production, economic development, and ecological environment have become increasingly prominent, profoundly affecting ecosystem service trade-offs.

2 Data and Methods

2.1 Data Sources and Processing

This study utilized the following datasets: (1) Land use/cover data for 2000 and 2018, obtained from 1:100,000-scale land use data for Shaanxi Province released by the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). Land use types include six primary categories (cultivated land, forestland, grassland, water bodies, residential land, and unused land) and 25 secondary categories. (2) Digital Elevation Model (DEM) data from the Geographic National Condition Monitoring Cloud Platform (http://www.dsac.cn) at 30 m resolution. (3) Meteorological data including daily and monthly precipitation, temperature, and radiation for 2000–2018 from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). (4) Soil data including sand, silt, and clay content from the China Soil Dataset based on the Harmonized World

Soil Database (HWSD) at the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn). (5) Normalized Difference Vegetation Index (NDVI) monthly data from MODIS products at 250 m resolution, obtained from the USGS Earth Explorer (https://earthexplorer.usgs.gov/). All spatial data were unified to the Albers projection coordinate system using ArcGIS 10.2 and resampled to the same grid for analysis.

2.2 Ecosystem Service Quantification and Trade-off Methods

To eliminate climate variability impacts on ecosystem services and more effectively evaluate the role of GPSR, this study used average climate data from 2000–2018 to calculate 各项 ecosystem services. Specific calculations are as follows:

2.2.1 Ecosystem Service Quantification **(1) Food Supply.** The GAEZ model was used to assess regional food supply capacity. The model first evaluates crop climate suitability based on precipitation, temperature, and other conditions, then calculates crop production potential using a stepwise limiting method. Rain-fed and irrigation scenarios were simulated. Under rain-fed conditions, only precipitation effects on crop yield were considered; under irrigation conditions, adequate water availability was assumed. The regional actual food production potential was calculated by integrating total production potential under both scenarios with the proportion of cultivated land in the area:

$$\text{yield}_{\text{total}} = \text{yield}_{\text{rain}} + \text{yield}_{\text{irrigated}} \times i$$

$$\text{yield}_{\text{actual}} = \text{yield}_{\text{total}} \times \text{lu}\%$$

where $\text{yield}_{\text{actual}}$ is the pixel-level food production potential ($\text{kg} \cdot \text{hm}^{-2}$), $\text{yield}_{\text{total}}$, $\text{yield}_{\text{rain}}$, and $\text{yield}_{\text{irrigated}}$ are total, rain-fed, and irrigated food production potentials ($\text{kg} \cdot \text{hm}^{-2}$), respectively; i is the irrigation rate (ratio of effectively irrigated area to total cultivated land area), and lu% is the proportion of cultivated land within the pixel. Effective irrigation area data were obtained from Shaanxi Provincial Bureau of Statistics and Yulin City statistical data.

(2) Water Yield. Water yield service was assessed using the InVEST water yield module.

(3) Carbon Sequestration. Net Primary Productivity (NPP) was used to quantitatively evaluate aboveground vegetation carbon sequestration capacity, estimated using an improved CASA model.

(4) Soil Conservation. Soil conservation was calculated using the widely applied RUSLE model.

2.2.2 Ecosystem Service Trade-off Quantification Method The Root Mean Square Deviation (RMSD) method quantifies the average difference between individual ecosystem service standard deviations and the mean ecosystem service standard deviation, describing the dispersion amplitude from the mean. It is a simple yet effective approach for quantifying trade-offs among three or more ecosystem services:

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{ES}_{\mathrm{std},i} - \overline{\mathrm{ES}}_{\mathrm{std}})^2}$$

where $\mathrm{ES}_{\mathrm{std},i}$ is the normalized value of the i-th ecosystem service; $\overline{\mathrm{ES}}_{\mathrm{std}}$ is the mean of normalized ecosystem services; and n is the number of ecosystem services.

The normalization formula is:

$$\mathrm{ES}_{\mathrm{std}} = \frac{\mathrm{ES}_i - \mathrm{ES}_{\mathrm{min}}}{\mathrm{ES}_{\mathrm{max}} - \mathrm{ES}_{\mathrm{min}}}$$

where ES_i is the i-th ecosystem service; $\mathrm{ES}_{\mathrm{max}}$ and $\mathrm{ES}_{\mathrm{min}}$ are the maximum and minimum values of the ecosystem service; and $\mathrm{ES}_{\mathrm{std}}$ is the normalized ecosystem service value. Larger RMSD values indicate greater trade-off intensity.

3 Results and Analysis

3.1 Spatiotemporal Characteristics of Grain Production Space Reconstruction

To clearly express GPSR characteristics in Yulin from 2000 to 2018, land use data for the two periods were overlaid and analyzed in ArcGIS 10.2. Spatial patterns of GPSR pathways—including Grain-for-Green (cultivated land → forest/grassland), deforestation for cultivation (forest/grassland → cultivated land), urban expansion (cultivated land → construction land), and others (cultivated land → water bodies; construction land, water bodies → cultivated land)—were extracted (Figure 2). Results show that from 2000 to 2018, due to Grain-for-Green implementation, 1,462.17 km^2 of cultivated land converted to forest/grassland, accounting for 61.30% of grain production space transfer area. Concurrently, urbanization converted 239.56 km^2 of cultivated land to construction land (10.04% of transfer area). To protect cultivated land and ensure food security, Yulin reclaimed 683.54 km^2 of forest/grassland, comprising 75.48% of new grain production space. The Grain-for-Green area was 6.1 times and 2.1 times the urban expansion and deforestation areas, respectively.

Spatially, Grain-for-Green ecological project areas were widely distributed in the central and eastern Yellow River coastal regions; deforestation for cultivation concentrated in the southwestern traditional agricultural zone, gradually expanding northeastward; urban expansion areas were scattered without large-scale concentration. Thus, Grain-for-Green was the dominant pathway driving quantitative and structural GPSR in Yulin.

3.2 Spatiotemporal Variation Characteristics of Ecosystem Services

Analysis results indicate that under constant climate conditions, GPSR in Yulin from 2000 to 2018 improved carbon sequestration and soil conservation while negatively affecting food supply and water yield services. Specifically (Table 1), in 2018, the average carbon sequestration service in GPSR areas was 314.50 g $C \cdot m^{-2}$, an increase of 318.11 g $C \cdot m^{-2}$ compared with 2000. Correspondingly, soil conservation capacity increased by 2.88 times. Conversely, food supply and water yield services declined slightly: food supply decreased from 1,088.77 $kg \cdot hm^{-2}$ in 2000 to 1,088.55 $kg \cdot hm^{-2}$ in 2018 (a reduction of only 0.22 $kg \cdot hm^{-2}$), while water yield capacity decreased by 0.22 $mm \cdot a^{-1}$.

Spatially (Figure 3), carbon sequestration service increased significantly in eastern Yellow River coastal Grain-for-Green areas, with marked food supply declines and minimal water yield and soil conservation changes. In southwestern deforestation areas, food supply service improved while other services declined. In 2000, high water yield areas were widespread across GPSR regions, but by 2018, water yield capacity decreased in all reconstruction areas except urban expansion zones, with the most pronounced decline in southwestern deforestation areas.

3.3 Characteristics of Ecosystem Service Trade-off Changes

RMSD calculations for service pairs reveal that (Figure 4) from 2000 to 2018, trade-offs between carbon sequestration and soil conservation and between food supply and water yield decreased during GPSR, while trade-offs between other service pairs increased. The largest increase occurred in food supply vs. soil conservation (0.042), followed by carbon sequestration vs. food supply (0.036). The most significant decrease was in food supply vs. water yield (0.016).

Comparative analysis of ecosystem service changes caused by different GPSR pathways shows varying patterns across pathways (Table 1). After Grain-for-Green implementation, carbon sequestration, soil conservation, and water yield services increased, while food supply declined most significantly—2018 food supply in these areas was only 40.96% of 2000 levels, primarily because forest/grassland provide greater ecological regulation services but far less food than cultivated land. Urban expansion reduced carbon sequestration, soil conservation, and food supply services, with food supply showing the most significant decline, indicating that urban expansion weakened both ecological regulation and food provision capacities. However, water yield capacity increased significantly after urban expansion due to impervious surfaces reducing water infiltration. Deforestation for cultivation markedly improved food supply service but reduced carbon sequestration and soil conservation, demonstrating that this reclamation approach, while ensuring food production, is detrimental to ecosystem balance.

Different GPSR pathways exhibited distinct characteristics in service pair trade-offs. Grain-for-Green increased trade-offs between carbon sequestration vs. food supply, food supply vs. soil conservation, and soil conservation vs. water yield, with the largest increase in carbon sequestration vs. food supply (0.072). Trade-offs between carbon sequestration vs. soil conservation, food supply vs. water yield, and carbon sequestration vs. water yield decreased. After urban expansion, trade-offs between carbon sequestration vs. food supply and carbon sequestration vs. soil conservation strengthened, while other service trade-offs weakened, with the largest increase in carbon sequestration vs. food supply (0.061) and the most significant decrease in carbon sequestration vs. water yield (0.028). Deforestation for cultivation increased trade-offs between carbon sequestration vs. soil conservation, carbon sequestration vs. water yield, and food supply vs. water yield, while decreasing trade-offs between carbon sequestration vs. food supply, food supply vs. soil conservation, and soil conservation vs. water yield.

Overall, GPSR-induced trade-off changes from 2000 to 2018 differed from pathway-specific changes. RMSD analysis effectively reveals reasons for these differences. In Yulin' s GPSR process, carbon sequestration consistently held relative benefit advantages in its trade-offs with other services. Although deforestation and urban expansion improved food supply and water yield benefits, reducing their trade-offs with carbon sequestration, they did not change the benefit-dominant service. Carbon sequestration vs. soil conservation trade-offs were most stable during GPSR, approaching zero. Grain-for-Green and deforestation most significantly affected trade-offs among carbon sequestration, soil conservation, and food supply, while urban expansion prominently influenced trade-offs involving water yield. This occurs because the three reconstruction pathways differentially expanded or narrowed relative benefit differences among services, continuously affecting the dynamic balance of relative benefits and thereby generating positive or negative trade-off changes.

4 Discussion

Grain production space reconstruction focuses on areas where grain production space interacts intensely with urban-rural development space and ecological service space, concentrating the principal contradictions in land system change. Investigating ecosystem service trade-off characteristics during GPSR helps clarify reconstruction effects and mechanisms, providing information for land resource management decisions. This study first overlaid land use data from 2000 and 2018 to characterize GPSR spatiotemporal patterns in Yulin. From 2000 to 2018, urban expansion and Grain-for-Green accounted for 71.34% of grain production space transfer area; deforestation for cultivation accounted for 75.48% of new grain production space. During this process, Grain-for-Green improved regulating services (carbon sequestration, soil conservation) but negatively affected provisioning services (food supply, water yield). Deforestation for cultivation, as the reverse process, had opposite effects on all services except water yield. Urban expansion generally weakened regional carbon sequestration, soil conservation, and food supply capacities but promoted water yield. The contradictions among grain production space, urban-rural development space, and ecological service space have intensified.

Most current ecosystem service trade-off research evaluates single land-use change processes, where trade-off relationships are relatively simple to discriminate. However, systematic analysis of comprehensive processes reveals varying patterns and characteristics. This study used ecosystem service evaluation models and RMSD to analyze spatiotemporal patterns and trade-off dynamics of ecosystem services across different GPSR pathways in Yulin from 2000 to 2018. Average climate data (2000–2018) were used to represent constant climate conditions, highlighting GPSR impacts on service trade-offs. RMSD accurately quantified service trade-offs, intuitively reflecting their changing characteristics during GPSR. When GPSR results in dramatic increases in ecological service space, it disrupts constraint threshold effects among ecosystem services, strengthening trade-offs. Grain-for-Green and deforestation most significantly affected trade-offs among carbon sequestration, soil conservation, and food supply, while urban expansion prominently influenced trade-offs involving water yield.

This study' s limitations include: (1) Despite multiple model parameter corrections based on Yulin' s actual conditions, low soil data availability and grid scale conversion issues may have reduced precision of soil-related model results. (2) Grain production space refers to land systems primarily functioning for grain production. This study used cultivated land to represent grain production space, but land has multi-functional attributes in reality, and cultivated land is not perfectly coupled with grain production space, potentially causing bias. Future research should employ more rigorous land use classification systems to delineate grain production, urban-rural development, and ecological service spaces. Additionally, further investigation is needed on how to use ecosystem service trade-off analysis to reveal GPSR effects and mechanisms.

5 Conclusion

Using 2000 and 2018 data, this study analyzed spatiotemporal variation characteristics of carbon sequestration, food supply, soil conservation, and water yield services during GPSR in Yulin, quantified trade-offs among these four services, and discussed GPSR impacts on ecosystem service trade-offs. Main conclusions are:

(1) From 2000 to 2018, Grain-for-Green, urban expansion, and deforestation for cultivation were the main GPSR pathways in Yulin. Construction land expansion and Grain-for-Green accounted for 71.34% of grain production space transfer area; deforestation for cultivation accounted for 75.48% of new grain production space.

(2) From 2000 to 2018, GPSR in Yulin significantly improved regulating ecosystem services (carbon sequestration, soil conservation) while reducing provisioning services (food supply, water yield). Grain-for-Green markedly enhanced carbon sequestration and soil conservation but reduced food supply. Deforestation for cultivation had opposite effects on all services except water yield. Urban expansion generally weakened carbon sequestration, soil conservation, and food supply but enhanced water yield capacity.

(3) During GPSR, trade-offs between carbon sequestration and soil conservation and between food supply and water yield decreased, while other service pair trade-offs increased. Grain-for-Green and deforestation most significantly affected trade-offs among carbon sequestration, soil conservation, and food supply, while urban expansion prominently influenced trade-offs involving water yield. Different reconstruction pathways differentially altered relative benefit differences among services, affecting their dynamic balance and generating divergent trade-off patterns.

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Figures

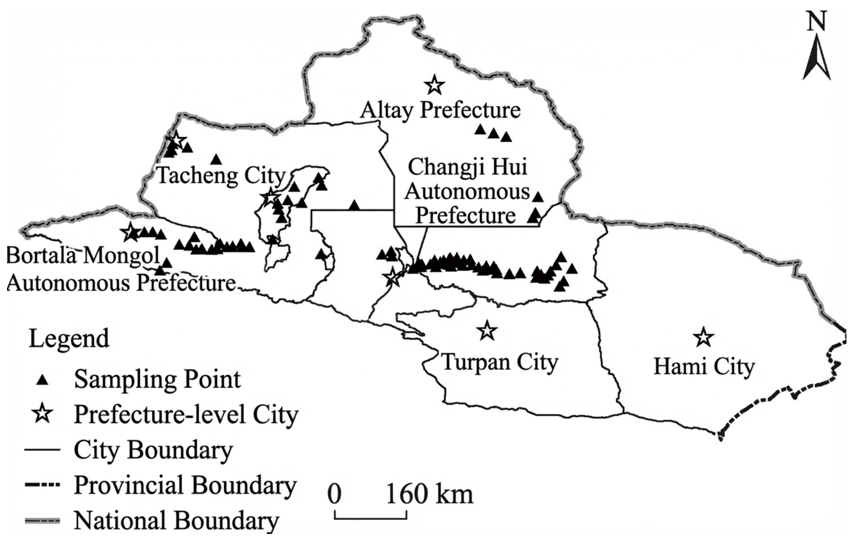

Figure 1: Figure 1

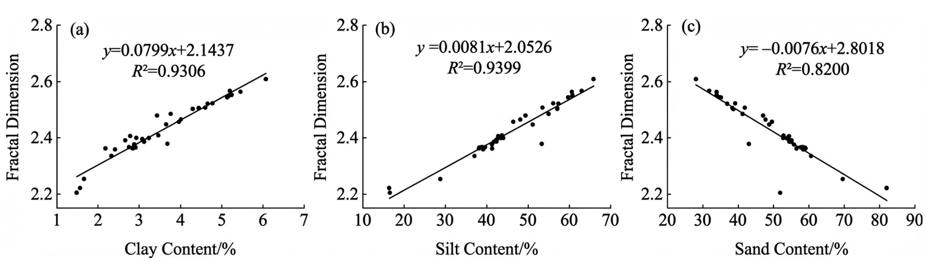

Figure 2: Figure 2

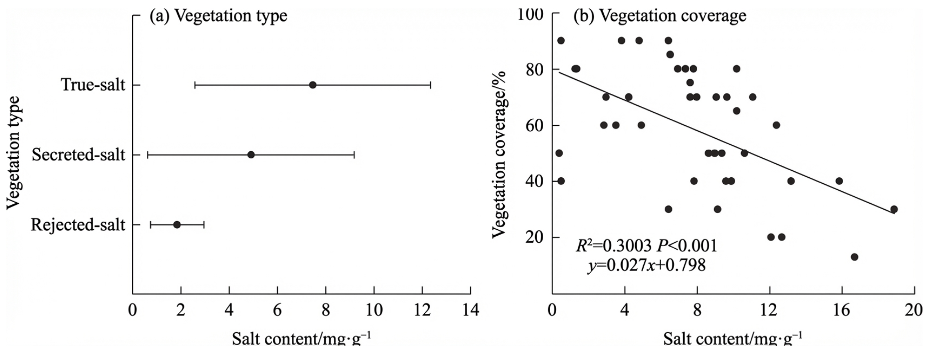

Figure 3: Figure 5

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