Spatiotemporal Differentiation and Driving Factors of Green Development in Xinjiang' s Urbanization (Postprint)

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Abstract

As a key focus of the Western Development Strategy and a core area of the Belt and Road Initiative, Xinjiang' s urbanization exhibits distinct regional characteristics and geopolitical attributes. Scientifically diagnosing and identifying the driving factors of green urbanization development can provide empirical evidence for coordinating borderland development and security patterns. Based on green development and spatial structure theories, and employing the entropy method, geostatistical analysis, and exploratory spatial data analysis methods on the ArcGIS spatial analysis platform, this study examines the spatiotemporal differentiation patterns of green urbanization development across 14 prefecture-level cities in Xinjiang from 2008 to 2018. The results indicate that: (1) Xinjiang' s green urbanization development level is low with slow growth, spatial dependence and heterogeneity are weak, core-periphery differentiation centered on differences between southern and northern Xinjiang is significant, demographic, economic, social, and ecological urbanization development is uncoordinated, localized and introverted functions such as land bridges and resources are prominent, while globalized and open geopolitical functions like ports and corridors are not evident. (2) Urban population size and ecological endowment have greater influence on the spatiotemporal differentiation of green urbanization than economic growth, while social urbanization is notably weak; however, economic and social functions show clear growth momentum, and homogenization and isomorphic trends in the spatiotemporal differentiation of urbanization are gradually strengthening. (3) Per capita GDP is the core driver of spatiotemporal differentiation in green development, and quality and efficiency is the most important impetus for promoting green urbanization development in Xinjiang; investment scale and efficiency, along with education, culture, and healthcare development, are effective pathways for green development. However, functions such as foreign trade, population agglomeration, and structural upgrading are weak and grow slowly. Efforts should be made to cultivate new capacities and

new drivers for green urbanization development, actively participate in global and regional economic and trade cooperation, accelerate integration into domestic and international dual circulation, and improve infrastructure and public service provision levels.

Full Text

Spatial and Temporal Differentiation and Driving Factors of Green Development in Xinjiang' s Urbanization

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Abstract: As a key region in China' s western development strategy and the core area of the "Belt and Road" Initiative, Xinjiang' s urbanization exhibits distinct regional characteristics and geopolitical attributes. Scientific diagnosis and identification of the driving factors behind green urbanization development can provide empirical evidence for coordinating border development and security patterns. Based on green development and spatial structure theories, this study employs the entropy method, geostatistical analysis, and exploratory spatial data analysis within the ArcGIS platform to examine the spatiotemporal differentiation patterns of green urbanization development across 14 prefectures and cities in Xinjiang from 2008 to 2018. The results indicate: (1) Xinjiang' s urbanization green development level is low with slow growth, weak spatial dependence and heterogeneity, and significant core-periphery differentiation between southern and northern Xinjiang. The development of population, economic, social, and ecological urbanization remains uncoordinated, with localized and introverted functions such as land bridges and resource exploitation being prominent, while globalized and open functions like ports and corridors are underdeveloped. (2) Urban population scale and ecological endowments exert greater influence than economic growth on the spatiotemporal differentiation of urbanization green development, while social urbanization is notably weak. However, economic and social functions have shown significant enhancement, with homogenization and isomorphic trends in urbanization spatiotemporal differentiation gradually strengthening. (3) Per capita GDP constitutes the core driver of green development spatiotemporal differentiation, with quality and efficiency representing the most important forces propelling Xinjiang' s green urbanization. Investment scale and efficiency, along with education, culture, and medical infrastructure construction, serve as effective pathways for green development. Conversely, foreign trade, population agglomeration, and structural upgrading demonstrate weak functions and slow growth. The study concludes that policymakers should focus on cultivating new productive capacities and driving forces for green urbanization, actively participate in global and regional economic cooperation, accelerate integration into domestic and international dual circulation patterns, and improve infrastructure and public service guarantee levels.

Keywords: green development; spatiotemporal differentiation; driving factors; geographic detector; northern and southern Xinjiang

1 Introduction

Green development represents a comprehensive integration of ecological industries and circular economies, serving as a practical model for improving urbanization quality, efficiency, and high-quality development. It emphasizes mutually beneficial symbiosis between new urbanization and the ecological environment, promotes the transformation from industrial to ecological civilization, and constructs a comprehensively coordinated and stably balanced human-land regional system. Since the 18th National Congress of the Communist Party of China established "green development" as a basic national policy, and the 19th Congress launched a new era of ecological civilization construction, the coordinated development and security pattern has become fundamental to new urbanization. In 2020, the proposal to build a "dual circulation" development pattern further elevated green growth to a core principle for coordinating development and security.

Urbanization is fundamentally a regional spatial process that manifests both physical expansion of urban scale and form, and dynamic evolution of urban functions and roles. It represents the coupling and coordination between urban activities and supporting environments—the spatial expression of human-land regional systems. Beyond internal (inward) spatial agglomeration of population and economy, urbanization involves material, energy, and information exchange with background environments. In the 21st century, rapid urbanization intertwined with global change has heightened concerns about vulnerability and risk prevention in sensitive regions, focusing attention on spatiotemporal differentiation across various characteristics, states, and manifestations. Scholars have employed Green Development Performance Index (GDPI) to evaluate urbanization development, used DEA models to measure correlations between urbanization and green development efficiency based on comprehensive energy and environmental efficiency, and applied exploratory spatial data analysis to study spatial correlations of industrial green development in developed cities. Classic theories including push-pull theory, population migration theory, dual economy models, core-periphery theory, and regional urban structure theory have been used to construct urbanization-environment evolution models, yielding empirical models such as the "U-shaped" curve, logarithmic curves, and the Environmental Kuznets Curve. The OECD's Pressure-State-Response (PSR) model has been widely applied. Since the 21st century, urbanization green evaluation based on "spatiotemporal structure theory," "spatiotemporal geography," and spatial analysis methods has become a research focus.

Domestic research primarily draws on developed country experiences to address Chinese realities, emphasizing problem orientation, policy guidance, and empirical induction. System theories including human ecology, regional structure theory, new economic geography, and spatial self-organization, along with methods such as system dynamics, cellular automata, and spatiotemporal spatial analysis, have been extensively applied. Flow space, balanced networks, and spatial information systems with Chinese characteristics provide differentiated research frameworks for urbanization issues across scales, levels, and types. However, existing research on Xinjiang' s urbanization has focused on single-factor analysis and causal relationships, emphasizing micro-analysis of individual cities and internal urban environments while lacking macro-level quantitative studies from strategic perspectives. Influenced by natural location conditions and historical development foundations, Xinjiang' s urbanization is characterized by small urban scales, weak agglomeration capacity, low development quality, and scattered spatial distribution. The urban system suffers from incomplete functions and irrational layout, with urbanization remaining in the primary stage of dispersed development. Therefore, studying Xinjiang' s urbanization green development requires moving beyond traditional factor and investment-driven, resource-environment constraint models. Instead, research should focus on systematic development and comprehensive balance, innovating development models by leveraging geographical, geopolitical, and resource-environment advantages, and optimizing urban geographical functions and network systems from a strategic height to achieve balanced green development foundations.

2 Study Area and Methods

2.1 Study Area and Data 2.1.1 Analytical Units and Data Indicators

Prefecture-level administrative units represent relatively stable and functionally important units in China' s provincial administrative sequence. Since the late 20th century, the "city-leading-county" model has accelerated urbanization, and early 21st-century modernization has prioritized urban agglomerations, making prefectures the primary administrative units for organizing urban-rural economic development and implementing national strategies. Using prefectures (cities) as analytical units reduces uncertainties from administrative adjustments and urban-rural population mobility. This study examines 14 prefectures and cities in Xinjiang across four dimensions: population, economy, society, and ecology, constructing a comprehensive evaluation index system based on Xinjiang' s urbanization characteristics and relevant literature.

2.1.2 Data Sources and Processing

All socioeconomic statistical data were obtained from the *China Statistical Yearbook*, *China County (City) Statistical Yearbook*, *China Urban Statistical Yearbook*, *Xinjiang Statistical Yearbook*, and related survey and census data. The entropy method was applied to original data after dimensionless and standardization processing. Basic geographic data including raster, vector, and digital elevation model (DEM) were sourced from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn) and Geospatial Data Cloud (http://www.gscloud.cn). ArcGIS was used for spatial analysis, classical geostatistical analysis calculated urbanization sustainable development levels, and GeoDa performed spatial autocorrelation analysis for spatiotemporal differentiation patterns.

2.2 Methods 2.2.1 Indicator System Construction

Traditional research tends to measure urbanization levels using population or economic attributes, while green development emphasizes people-oriented, comprehensive coordination. This study adopts population, economy, society, and ecology indicators to reflect urbanization's comprehensive attributes. Secondary indicators include urbanization rate, per capita GDP, per capita investment, and others to characterize urban system functions (Table 1). All dimensional indicators use mean values (per capita) to represent urbanization green development efficiency, with per capita water resources and per capita cultivated land representing ecological dimensions to highlight oasis urbanization regional characteristics. Population urbanization emphasizes population scale and urbanization level differences among prefectures; economic urbanization highlights economic development, industrialization, and per capita level differences; social urbanization focuses on fixed asset investment, social consumption, and budget income level differences; and ecological urbanization emphasizes natural capital and ecological endowment differences. Population and economic urbanization constitute the core, while social and ecological urbanization form the foundation, jointly comprising green development capacity.

Table 1 Evaluation index system of urbanization green development

Dimension	Indicator	Unit
Population urbanization	Prefecture population density (X_1)	persons · km^{-2}
	Urban population density (X_2)	persons · km^{-2}
	Urbanization rate (X_3)	%
	Natural population growth rate (X_4)	%
Economic urbanization	Secondary industry proportion (X_5)	%
	Tertiary industry proportion (X_6)	%
	Per capita total import-export value (X_7)	10^4 yuan · $person^{-1}$
Social urbanization	Per capita fixed asset investment (X_8)	10^4 yuan · $person^{-1}$

Dimension	Indicator	Unit
	Per capita retail sales of consumer goods (X_9)	10^4 yuan · person^{-1}
	Per capita education level (X_{10})	10^4 yuan · person^{-1}
	Per capita medical level (X_{11})	10^4 yuan · person^{-1}
Ecological urbanization	Per capita cultivated land area (X_{12})	10^2 · person^{-1}
	Per capita water resources (X_{13})	10^3 · person^{-1}

2.2.2 Entropy Method for Weight Calculation

The entropy method is a relatively objective multi-indicator weighting approach suitable for comprehensive weighting of multiple indicators. It calculates information entropy to determine indicator weights—smaller information entropy indicates greater variability or dispersion, thus greater indicator importance.

For the i-th indicator, entropy value e is calculated as:

$$e_i = -\frac{1}{\ln n}\sum_{j=1}^{n} P_{ij}\ln P_{ij}$$

where P   is the standardized value of indicator i for region j, and n is the number of evaluation indicators.

The information entropy g is:

$$g_i = 1 - e_i$$

The weight W of indicator i is:

$$W_i = \frac{g_i}{\sum_{i=1}^{m} g_i}$$

2.2.3 Urbanization Development Level

The comprehensive index method calculates each dimension's urbanization green development level. The score S   for prefecture j at time t is:

$$S_{tj} = \sum_i X_{ij}W_i$$

2.2.4 Spatial Autocorrelation Analysis

Spatial autocorrelation expresses spatial dependence and heterogeneity arising from geographical location or adjacency relationships, statistically analyzing spatial distribution structures of regional system elements. Global Moran' s I measures overall spatial clustering patterns:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

where n is the number of elements, W is the spatial weight between elements i and j, x and x are attribute values, and $\bar{x}$ is the mean value.

2.2.5 Inverse Distance Weighting (IDW) Interpolation
IDW estimates values at unsampled locations using weighted averages of nearby sample points, with weights inversely proportional to distance. For any point p:

$$Z(p) = \frac{\sum_{i=1}^{n} Z_{iW} i}{\sum_{i=1}^{n} W_i}$$

where Z(p) is the estimated value, Z are surrounding point values, and W are weight values. ArcGIS IDW analysis was applied with output raster cell size of 100 km and default search radius settings, followed by mask extraction.

2.2.6 Geographic Detector
Geographic detectors identify spatial stratified heterogeneity characteristics of geographical phenomena, addressing scale-dependent spatial dependence and heterogeneity issues that traditional statistics cannot resolve. It measures stratified heterogeneity, detects spatial differentiation patterns, and estimates nonlinear spatial causal relationships. The q-value measures the degree to which factor X explains variable Y' s spatial differentiation:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where h is the stratification number, N and σ ^{2} are the unit count and variance within stratum h, and N and σ^2 represent total units and variance. The q-value ranges [0,1]; larger values indicate stronger explanatory power of X on Y' s spatial differentiation.

3 Results

3.1 Spatial Differentiation Characteristics Natural breaks in ArcGIS classified urbanization comprehensive development levels of 14 prefecture-level cities into five grades: low, relatively low, medium, relatively high, and high. High-value centers are distributed in Karamay, Urumqi, and Altay, while low-value centers concentrate in border prefectures of southern Xinjiang: Kizilsu Kirghiz Autonomous Prefecture (Kizilsu) and Hotan Prefecture, as well as eastern Xinjiang. High-value areas are small in scope, while medium-low value areas are widely distributed. Significant differences exist between northern and southern Xinjiang, with clear core-periphery differentiation that remained stable between 2008 and 2018. This indicates that the core area of the Tianshan North Slope Economic Belt remains the polarized growth center, while border prefectures in southern and eastern Xinjiang maintain low urbanization levels. The urban system spatial structure is relatively stable, with traditional functions like land bridge economy and corridor roles being prominent, while globalized and open geopolitical functions such as ports and passages remain underdeveloped.

3.2 Spatial Differentiation Patterns 3.2.1 High Urbanization in Northern Xinjiang with Significant Differentiation; Low but Structurally Balanced Urbanization in Southern Xinjiang

In 2008, high-value urbanization centers were located in Karamay and Ili Kazak Autonomous Prefecture (Ili), while low-value centers were in Hotan, Kizilsu, Turpan, and Hami. High-value areas clustered in the Eurasian Continental Bridge core zone, while low-value areas were contiguously distributed in southern and eastern Xinjiang. By 2018, Urumqi and Altay became high-value centers, with low-value centers concentrating in Hotan and Turpan. The high-value area contracted while the low-value area expanded. High-value centers consistently remained in northern Xinjiang, but internal differentiation within northern Xinjiang is substantial. Low-value centers persistently located in southern and eastern Xinjiang, where internal differentiation is relatively small (Figure 2).

3.2.2 Significant Core-Periphery Differentiation in Population Urbanization

In 2008, high-value population urbanization centers were in Kashgar, Ili, and Urumqi, while low-value centers concentrated in western and northern border prefectures: Hotan, Kizilsu, Bortala Mongol Autonomous Prefecture (Bortala), Turpan, and Hami. By 2018, the pattern remained largely unchanged, though Urumqi and southern Xinjiang prefectures showed faster growth. This indicates clear core-periphery differentiation in Xinjiang's population urbanization. Cities along the "Belt and Road"—Kashgar, Ili, and Urumqi—consistently serve as high-value centers, while western and northern border prefectures form contiguous low-value areas with stable spatial structures over the past decade.

3.2.3 Economic Urbanization Shows Significant North-South Differentiation

In 2008, high-value economic urbanization centers were in Urumqi and Bayingolin Mongol Autonomous Prefecture (Bayingolin) within the core zone, while low-value areas concentrated in Hotan and surrounding regions, showing clear north-south differences. By 2018, Urumqi became the sole high-value center, with low-value areas expanding contiguously around Hotan and Turpan. The high-value area shrank while the low-value area expanded, demonstrating significant north-south differentiation.

3.2.4 Inconsistent Patterns Between Urbanization Development and

Ecological Evolution
Xinjiang' s ecological environment high-value areas are in border prefectures: Altay, Ili, Kizilsu, and Hotan, while low-value centers are in Urumqi, Karamay, Turpan, and Kashgar. The ecological environment in northern and western border cities is significantly superior to the "Belt and Road" core zone. Between 2008 and 2018, high-value ecological areas remained in Altay and Kizilsu, while low-value areas expanded contiguously. Medium-high value areas contracted, with low-value zones forming contiguous patches along the Eurasian Continental Bridge where urbanization levels are high, while high-value ecological areas are distributed in border prefectures with low urbanization levels (Figure 3).

3.3 Driving Factor Detection 3.3.1 Dominant Factor Detection

Stratified heterogeneity factor detection quantitatively identifies factors influencing spatial stratified heterogeneity and detects relative importance and relationships between independent and dependent variables. To obtain optimal stratification results, this study combined empirical knowledge, expert decision-making, and natural breaks methods to classify various impact factors. Using urbanization level as the dependent variable and population, economic, social, and ecological urbanization as independent variables, the analysis detected each factor' s explanatory power for urbanization spatial differentiation.

Results show that among primary differentiation factors, only per capita GDP (X_5) passed significance testing at the 95% confidence level, with a q-value of 0.928, indicating the strongest explanatory power for spatial differentiation. Other indicators showed weaker relationships. Among secondary differentiation factors, per capita GDP (q=0.818), per capita fixed asset investment (X_8, q=0.711), and per capita education level (X_{10}, q=0.501) all showed q-values >0.5, indicating significant contributions to spatial differentiation. These factors constitute the main drivers of Xinjiang's urbanization spatial differentiation.

3.3.2 Interaction Detection

Interaction detection revealed that q-values for any two-factor interaction were significantly greater than single-factor effects, with linear enhancement being the primary interaction type. The interaction q-values reached 0.957 and 0.938, indicating that dual-factor interactions substantially influence Xinjiang's urbanization spatial differentiation. Specifically, the interaction between education level and fixed asset investment, and between education level and per capita income, showed the most significant spatial spillover effects.

3.3.3 Dynamic Changes in Factor Effects

Analysis of q-value trends for primary and secondary differentiation factors from 2008-2018 shows that the effects of economic, social, and population urbanization factors all increased, with cumulative intensity increases of 75.20%, 31.02%, and 34.34% respectively. Conversely, ecological endowment effects continuously declined by 41.54%. This indicates that human factors increasingly influence Xinjiang' s urbanization green spatial differentiation, while environmental impacts are weakening. Economic development shows the strongest increasing influence, followed by social urbanization, while population urbanization is relatively weaker. Water and land resources show insignificant effects on spatial differentiation.

Among secondary factors, per capita education level showed the most significant increase (192.57%), followed by per capita medical level (316.85%) and per capita fixed asset investment (320.13%). In contrast, per capita total import-export value decreased by 95.49%, prefecture population density by 88.91%, and per capita cultivated land area by 52.04%. This demonstrates that social development levels (education, healthcare) and economic development quality (investment attraction) are strengthening, while foreign trade, urban population scale, and industrial structure effects are weakening.

3.3.4 Driving Mechanism Detection

Among primary differentiation factors, population and ecological urbanization show relatively strong effects, with urban population scale and ecological endowments influencing green development more than economic growth, while social urbanization effects are notably weak. With reform and modernization, economic and social functions have become increasingly significant, with homogenization and isomorphic characteristics of urbanization spatiotemporal differentiation gradually strengthening.

Per capita GDP is the core driver of Xinjiang’ s urbanization spatial differentiation. Developing urban economies, improving industrialization levels, and increasing high value-added production capacity remain the most important factors for advancing Xinjiang’ s urbanization. Expanding investment scale and efficiency, and continuously improving education, culture, and medical standards, are also effective pathways. Analysis of changing trends reveals that public services such as culture, education, and healthcare have most significantly enhanced their influence on spatial differentiation. Therefore, accelerating infrastructure construction and expanding balanced public service layouts, along with improving economic development quality and investment scale, are effective means for rationally structuring the urban system.

4 Conclusions

Based on comprehensive development and regional equilibrium theories, this study designed an evaluation model for urbanization green development and examined spatiotemporal differentiation patterns across comprehensive, dimensional, and elemental scales in Xinjiang from 2008-2018. The main conclusions are:

(1) Significant development differences exist between the “Belt and Road” core zone and border prefectures, presenting a core-periphery differentiation pattern. Northern Xinjiang shows relatively higher urbanization levels with significant spatial differentiation but slower recent growth, narrowing the gap with southern Xinjiang. Southern Xinjiang exhibits lower urbanization levels with small spatial differences but recent rapid growth,

with intra-regional differences narrowing.

(2) Population, economic, social, and ecological urbanization development remains uncoordinated. Southern Xinjiang' s population urbanization outperforms northern Xinjiang, with Urumqi, Ili, and Kashgar along the "Belt and Road" consistently serving as high-value centers with stable spatial structures. Northern Xinjiang' s economic urbanization surpasses southern Xinjiang, with low-value centers persistently in southern Xinjiang and the medium-low value area expanding over the decade, showing converging spatial differences. Social urbanization demonstrates the greatest change and fastest growth, with unstable differentiation patterns. Urbanization development and ecological differentiation show inconsistent patterns, with high urbanization areas showing contiguous low ecological values and low urbanization areas showing high ecological value clusters.

(3) Per capita GDP, per capita fixed asset investment, and per capita education level are core drivers of Xinjiang' s urbanization green development, with other factors showing weaker relationships. Education level, fixed asset investment, and per capita income show the most significant interactive effects and spatial spillover benefits. Over the past decade, economic development' s effect on spatial differentiation has strengthened most significantly, followed by social urbanization, while ecological factors show insignificant influence. Education, healthcare, economic development quality, and investment attraction have grown markedly, while foreign trade, population scale, and industrial structure effects have continuously weakened.

Therefore, policymakers should seize the historical opportunity of "Belt and Road" core zone construction, adhere to people-oriented, ecology-first, balanced and coordinated green development principles, and focus on consolidating ecological foundations and building harmonious cities. Efforts should promote functional coupling and coordinated development among population, society, economy, and ecology, improve infrastructure and public service guarantee levels, optimize urban geographical functions and spatial structures, and systematically enhance green development efficiency of factor inputs and economic growth.

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Figures

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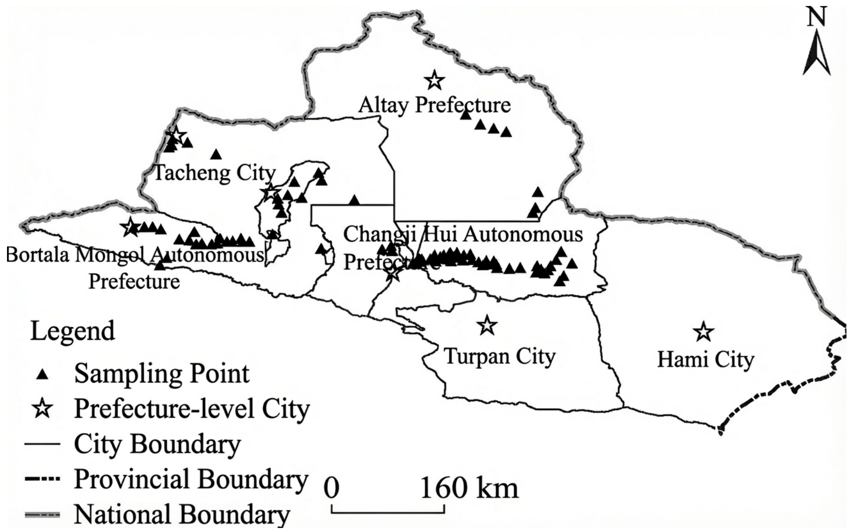

Figure 1: Figure 1

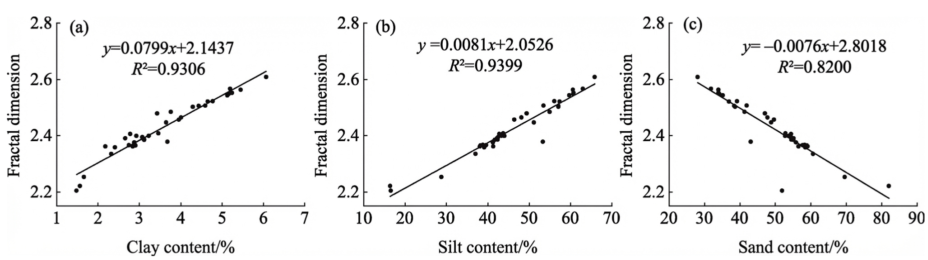

Figure 2: Figure 2