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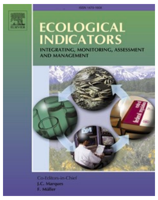

Original Articles

A geographic identification of sustainable development obstacles and countermeasures in drylands: A case study in Inner Mongolia, China

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ABSTRACT

Drylands cover about 41% of the Earth's land surface and are inhabited by more than two billion people, who rely on the diversified ecosystem services provided by drylands for their livelihoods. Achieving sustainable livelihoods (SLs) is a key component of achieving the sustainable development goals set by the agenda in 2030. Although it has aroused extensive interest, research on SLs in drylands at a regional scale is still limited. This paper aims to address this research gap by evaluating SLs through a geographic gradient of aridity in Inner Mongolia. A sustainable livelihood index (SLI) was developed using a wide range of indicators in a sustainable livelihood framework (SLF). The weight of the indicators was determined by the entropy weight method, and the characteristics of the spatial distribution of the SLI were analyzed. The results showed that the SLI varies greatly across aridity zones. In terms of livelihood assets, the SLI in the dry sub-humid zone was 15% higher than in the arid zones, while, surprisingly, semi-arid zones were found to have the most vulnerable livelihoods (rather than the arid zones). The reason for this is that land management and planning approaches are necessary in drylands. In further detail, Moran's I index illustrated that the overall performance of the SLI of each league or city has a positive spatial correlation, while through local spatial correlation it was found that Hinggan and Chifeng are hot spot areas and Hohhot is a cold spot area. The lack of physical and social capital is an important obstacle for SLs. Based on the analysis of SLs in Inner Mongolia, the characteristics of the sustainable development of local residents were revealed. In this paper, we call for an integrated (i.e., focusing on natural and human capital) land management and planning approach for drylands to reflect the nature of the tightly coupled socio-ecological systems.

1. Introduction

Sustainable development (SD), as a visionary and forward-looking development paradigm, is currently one of the most important global challenges (Abubakar, 2017; Cerin, 2006; Kaivo-oja et al., 2014; Mensah, 2019). Since the Brundtland Commission in 1987 (Borowy, 2013), the concept of SD has attracted significant attention and stimulated a great deal of research worldwide (Martha G. Roberts, 2003). However, due to the complexity and context-specificity of the concept, the question of how to achieve SD is still a major concern around the world and a topic of major interest for researchers. Commonly used methodological frameworks for achieving SD rely on the sustainable livelihoods concept (Mensah, 2019). In this concept, sustainable livelihoods (SLs) refer to a combination of resources for which the necessary capabilities, assets,

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and activities are required in order to maintain a sustainable means of living (Chambers, 1991) and that can respond to and recover from pressures and shocks without destroying the natural resource base (Serrat, 2017). SLs are an important part of the Sustainable Development Goals (SDGs) 2030, which is a global development agenda set by the United Nations in 2015 (United Nations General Assembly,2015). Studies on SLs will directly impact the realization of the SDGs (Editorial, 2018; Fu et al., 2021).

Among those frameworks, in recent years the sustainable livelihoods approach (SLA) has received widespread attention as a critical tool for advancing SD (Hahn et al., 2009), with the goal of understanding the process and dynamics of livelihood assets and vulnerability contexts. The SLA originated from the deepening of the understanding of the attributes of poverty in the 1980 s and early 1990 s and from the recognition that the lack of ability to choose and complete basic livelihood activities is a major poverty factor (Chambers, 1991; DFID, 1999; Regmi and Weber, 1996; Scoones, 1998). At present, a variety of SLA implementation methods coexist. Among them, the sustainable livelihoods framework (SLF), originally proposed by the Department for International Development (DFID) of the United Kingdom, has been widely used by many development organizations and researchers (Carney, 2002; DFID, 1999; Knutsson, 2006; Morse et al., 2013; Serrat, 2017). As shown in Fig. 1, the SLF is structured into five main components: vulnerability contexts, livelihood assets, transforming structures and processes, livelihood strategies, and outcomes (Carney, 2002; DFID, 1999). The vulnerability context refers to the external variable environment, which is out of an individual's control, and takes into account shocks, trends, and seasonality. Within this context, individuals have access to a range of livelihood assets, including human (H), physical (P), social (S), financial (F), and natural (N) ones. The assets' relevance is weighted according to the prevailing social and institutional structures and processes (Carney, 2002; DFID, 1999). All this, in turn, influences the decisions that people can make and the activities that people endeavor to complete to attain their goals, which are described as livelihood strategies (Zhao et al., 2020; Zhao et al., 2019). Furthermore, the SLF depicts stakeholders as operating in a context of vulnerability, within which they have access to certain assets. Assets gain weight and value through the prevailing social, institutional and organizational environment (policies, institutions and processes). This context decisively shapes the livelihood strategies that people may use in pursuit of their self-defined beneficial livelihood outcomes. Therefore, SLF is an important analytical tool for solving the problem of poverty and achieving SD (Borowy, 2013).

Considering that global climate and environmental changes are leading to an increase in the frequency of natural disasters and weather extremes, improving the characterization of SLs with respect to the vulnerability context and its spatial and temporal variability is a key requirement for achieving SLs; thus, this a major area of research interest. Early studies by Siegel et al. (2005) proposed a conceptual framework for assessing the relationship between the vulnerability context, livelihood assets, livelihood strategy, and livelihood outcomes and pointed out that this approach can be used at different levels (such as the levels of individuals, families, villages, small watersheds, regions, or countries). Several international institutions and researchers have carried out studies aiming to evaluate different fragile environments at different assessment levels using this framework. The International Centre for Integrated Mountain Development (ICIMOD), for example, applied it to assess the impact of the environmental conditions of the India-Kashh Himalayas on the livelihoods of poor people living in the mountains (Gerlitz et al., 2017). The Assessments of Impacts and Adaptations to Climate Change (AIACC) project assessed the resilience of farmers' livelihood capital to the adverse effects of natural disasters in Sudan (Bebbington, 1999). Hahn et al. (2009) estimated the vulnerability to natural disasters in Mozambique and proposed a livelihood vulnerability assessment index system to quantitatively analyze societies' adaptability to environmental changes. Some scholars have also evaluated and studied SLs in the disaster vulnerability context at the county and district levels in China's Qinghai-Tibet Plateau (Zhao et al., 2020; Zhao et al., 2019). Other studies have focused on the evaluation of SLs at a household livelihood capital scale (Chambers, 1991; Li et al., 2020; Martha G. Roberts, 2003; Serrat, 2017) in the vulnerability context. Li et al. (2013) used livelihood assets as indicators in order to explore the SLs of small farmers in the context of climate variability based on questionnaires and focus group discussions (Li et al., 2013), while Chen et al. (2018) evaluated the adaptation of farmers' livelihoods to environmental changes in the arid region of Xinjiang, China.

While there is a vast amount of literature that focuses on assessing SLs at different levels, drylands have received limited attention, likely because of the lack of assessment data available. Drylands account for about 41% of the global land surface area (Van Loon et al., 2016; Fu et al., 2021) and are home to more than 38% of the global population (Reynolds et al., 2007; Huang et al., 2016). The fifth report of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) pointed out the increasing vulnerability of drylands to drought shocks and these shocks' dramatic impacts on food security and the livelihoods of farmers and herders, thus highlighting the need for vulnerability assessment methodologies. At the same time, SL evaluation methods mostly concentrate on the farm household scale or the national scale based on the above analysis; thus, there is still a knowledge gap regarding regional scale assessment approaches.

Considering these gaps, this research aims to present a case study to (1)e valuate the various SLs and the spatial differences in all leagues or cities in Inner Mongolia of China, (2) assess the tradeoffs between the region development and SL goals, (3) provide SD strategies from a social–economic–ecological perspective across a gradient of aridity in dryland systems. Better understanding the variability of SLs through the

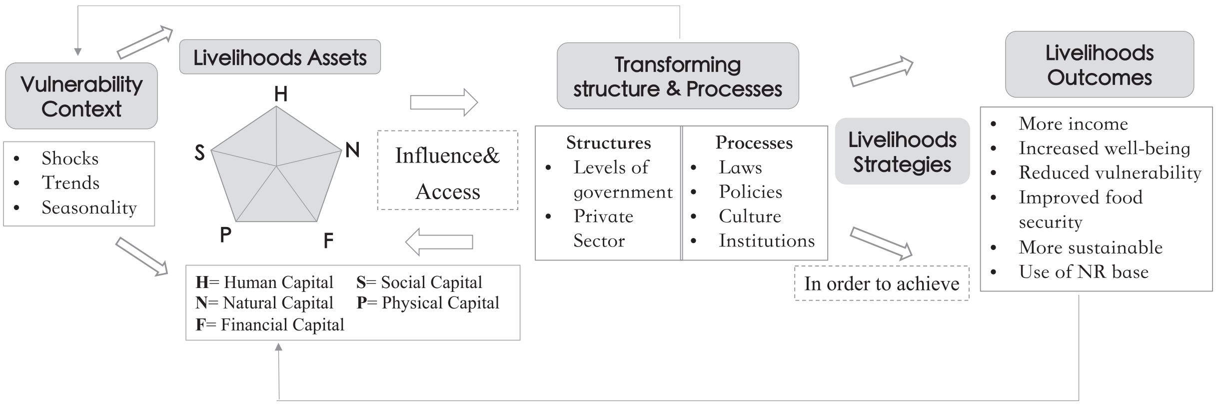

Fig. 1. The sustainable livelihoods framework of the United of Kingdom's Department for International Development (DFID).

use of aridity gradients could help us to improve drought risk management planning and promote SL options.

The case study focuses on the arid, semi-arid, and dry sub-humid regions of China, which are mainly concentrated in the northern region (Xu et al., 2021) and account for about 52% of the total land area of the country. This region is dominated by grasslands and has scarce precipitation, few water resources, and fragile habitats (Gong et al., 2004; Yin et al., 2019). The environment is sensitive to the regional climate, particularly to precipitation, and is also very vulnerable to global climate change (Christensen et al., 2004; Li et al., 2018). Due to the huge changes in precipitation and the increase in the level of human activity in this area, this agro-pastoral transition zone is also considered as an area at high risk of desertification. The shortage of water resources and the deterioration of the ecosystem have had significant impacts on regional food production and socio-economic development (Simelton et al., 2012; Simelton et al., 2009; Van Loon et al., 2016), which has seriously restricted the livelihood development of local residents (Rogers and Xue, 2015; Zhang et al., 2019; Zhao et al., 2019). In this study, we took Inner Mongolia, a farming-grazing zone in Northern China, as an example. This region plays an important role in the ecological barrier function zone in Northern China.

2. Materials and methods

2.1. Study area

As shown in Fig. 2, the Inner Mongolia Autonomous Region (37°24′–53°23′N, 97°12′–126°04′E) is located in the north of China and includes 12 leagues or cities. A league is a the level of administrative units specifically used in Inner Mongolia, China. It roughly corresponds to a city in other provinces, above banner (i.e., county). The total area covered is 1,183,000 km^2. The main landscape is a high plateau, most of which is located on the Mongolia Plateau, and has an average altitude of 1000 m. Most of the land in this region is natural grassland. The grassland area in the Inner Mongolia Autonomous Region is 86,667,000 ha, accounting for 73.26% of the total land area in the region and 22% of the total grassland area in China, which is an important part of the Eurasian grassland (Lu, 2018; Wang et al., 2012; Wei and Zhen, 2020; Xu et al., 2020).

The climate of the region is complex and diverse because of the geographical location and topography variability. Most of the region is dominated by a temperate continental climate. The annual average precipitation is between 50 mm and 450 mm, showing a strong decreasing gradient from the northeast to the southwest, while the average annual temperature increases gradually, showing obvious zonal characteristics. From the east to the west, the climate changes from dry sub-humid to semi-arid and arid. The land cover changes from east to west and includes forest, grassland, and desert. Therefore, Inner Mongolia encompasses most of the forestry–grazing transitional zone, farming–grazing transitional zone, grazing zone, and dryland farming zone in China and is very sensitive to climate fluctuation and anthropogenic impacts. The population is over 24,490,000, with a density of about 21 persons/km^2.[1] The desertification of the land, resulting from human activity and climate change, is one of the biggest challenges for SD and it is exacerbated by drought events (Chen and Yang, 2013; Song and Zhang, 2007).

Inner Mongolia is a drought-prone region. In 2017, the area of crops affected by drought in the Inner Mongolia Autonomous Region was 167,700 ha, of which 106,300 ha were seriously affected. These areas are mainly distributed in Hulunbuir, Tongliao, Ulanqab, and Chifeng. In addition, 264,000 ha of pastoral areas, mainly distributed in Xilin Gol and Hulunbuir, were also affected. Furthermore, the life and production of 4,340,000 people in 66 counties of 10 cities or leagues were impacted, resulting in drinking water difficulties for 130,000 people and 2,350,000 livestock[2].

2.2. Data source

This paper makes use of a top-down data collection method (Mereu et al., 2017). All socio-economic data were collected from official statistical sources[3]. Evapotranspiration data were extracted from the MODIS global surface evapotranspiration product (mod16a2) monthly data from 2016 with a spatial resolution of 1 km. Precipitation was calculated based on the China Meteorological Data Network[4]. The precipitation data of stations in 2016 were obtained by spatial interpolation, based on extrapolating the data of the whole region from the data of known stations. It has been stated that “Top-down data collection methods involve creating an overarching system of data collection and analysis before detailing and fleshing out subsystems under it[5]. The top-down research method is convenient and effective for large-scale research and comparative evaluation and is considered to be a useful method for revealing the different impacts of climate on society.

2.3. Analysis framework

The analysis framework was constructed in two main steps. First, a sustainable livelihood index (SLI) was defined by identifying and selecting key indicators and using SLF as a reference. Then, multiple analytical methodologies were used to evaluate the weight of each indicator, analyze the SLI spatial patterns, and evaluate the obstacle factors.

2.3.1. Definition of the sustainable livelihoods index (SLI) and its indicators

The identification and selection of key attribute variables is an important step in the construction of an SLI, which plays an important role in evaluating the whole process of SD. Based on the SLF, previous studies (Li et al., 2019; Liu and Xu, 2016; Qiu et al., 2018; Zhao et al., 2020; Zhao et al., 2019)), and the characteristics of study area, an index for SLs in Inner Mongolia was constructed (see Table 1). As mentioned previously, livelihood assets, including human assets, natural assets, physical assets, social assets, and financial assets, are the key components according to the SLA and thus were chosen in analysis. Moreover, a livelihood strategy is one of the components developed in the SLA. Therefore, according to the framework of the SLA, 15 key indicators were selected for further analysis. We chose the three key indicators to reflect the human assets, with them being the number of laborers (I_1), the education time per capita (I_2), and the number of doctors per 10^3 residents (I_3). Population density is a measure of population distribution, which is equal to the number of permanent residents in an area divided by the administrative area of the region. It can be used to reflect the basic distribution of the labor force across a region. The education level per capita reflects the educational level of the population. People with a higher educational level usually have better economic income and wider access to information and other types of resources, meaning that they may employ better risk management strategies when facing the risk of drought. The medical level is an indicator used to measure the degree of medical services provided to residents in a region and can effectively reflect the health status of the local labor force. In terms of natural capital, the area of grassland (I_4), area of sowing crops (I_5), and total water consumption (I_6) are important indicators used to reflect the degree of dependence and ownership of local farmers and herders on a region’s natural capital.

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[1] Inner Mongolia Autonomous Region Bureau of Statistics, 2019.

[2] Inner Mongolia Autonomous Region Bureau of Statistics, 2019.

[3] Inner Mongolia statistical yearbook 2007-2017, Inner Mongolia water resources bulletin 2006-2016.

[4] https://data.cma.cn/.

[5] https://taroworks.org/data-collection-methods/.

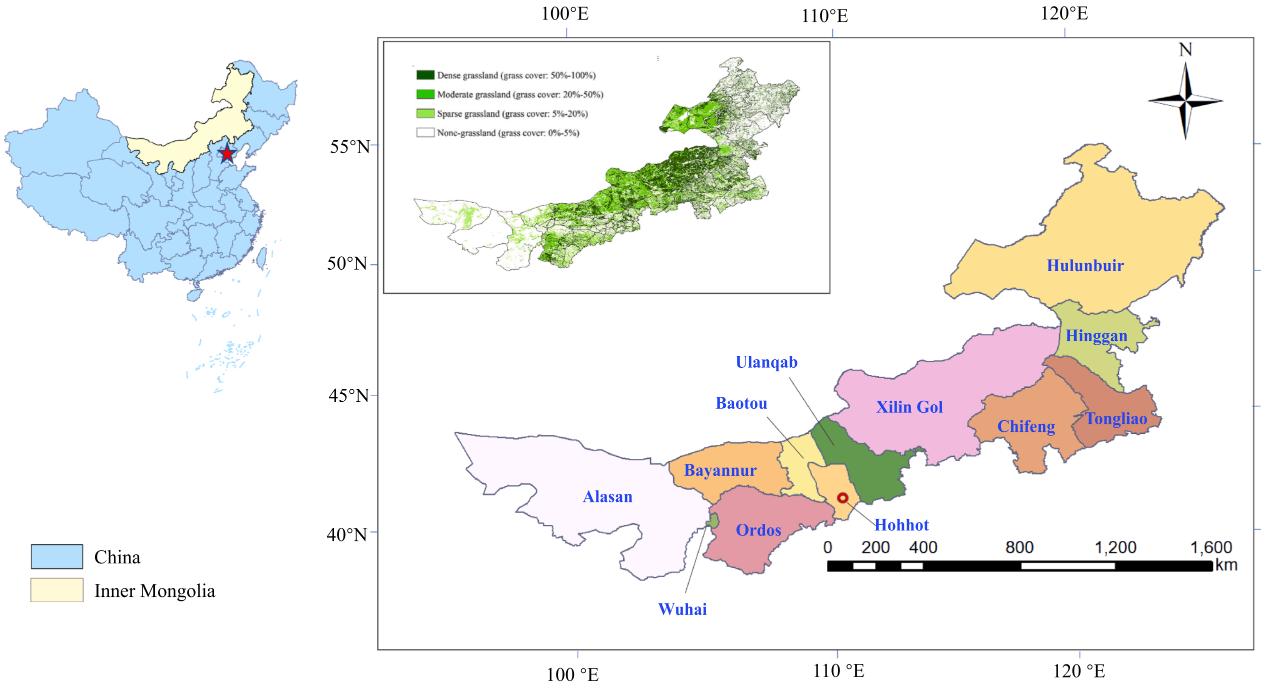

Fig. 2. Location of the study area in China and the main eco-types.

Table 1
Indicators and sub-indicators for the SLI.

Major Components	Indicators	Proxy Indicators	Descriptions	Positive / Negative
Household livelihoodsassets	Human assets (H)	Number of laborers (I_1)	Population density	+
		Education time per capita (I_2)	Education level	+
		Doctors per 10^3 residents (I_3)	Medical level	+
	Natural assets(N)	Area of grassland (I_4)	Area (10^3 hm^2)	+
		Area of sowing crops (I_5)Total water consumption (I_6)	Crop resourcesWater resources	+-
	Social assets (S)	Highway density (I_7)Proportion of communication and transportation costs out of total expenditure (I_8)	Traffic accessibility Communication level	++
	Financial assets (F)	Per capita disposable income (I_9)	Disposable income	+
		Per capita saving (I_{10})	Saving level	+
	Physical assets (P)	Proportion of villages with tap water (I_{11})	Infrastructure construction level	+
		Livestock assets per capita (I_{12})	Livestock assets	+
Livelihood strategies	Diversification of livelihoods	Number of livelihood activities (I_{13})		+
	Non-agricultural livelihoods	Proportion of primary industry employees (I_{14})		–
Vulnerability context	Aridity gradient	Aridity index (I_{15})		–

Highway density (I_7) and the proportion of communication and transportation costs out of total expenditure (I_8) can reflect the level of social capital in an area. The density of the highway network represents the administrative unit's ability to contact the market and other places. The higher the density of the highway network is, the better it will enable the transportation of agricultural and animal husbandry products and tourism development. The proportion of communication cost and transportation cost out of the total expenditure represents the communication level. A higher communication level means that people have more ways to obtain information and help when drought occurs. Per capita disposable income (I_9) and per capita savings (I_{10}) are vital indictors of financial capital. Disposable income can represent the economic and living standards of residents. Residents with a high per capita savings will have better financial ability to cope with the risk of drought and recover their livelihood. Meanwhile, the following two variables were selected to reflect the physical assets of herders: the proportion of villages with tap water (I_{11}) and livestock assets per capita (I_{12}).

The variables of the number of livelihood activities (I_{13}) and the proportion of primary industry employees (I_{14}) were chosen to represent the livelihood strategy of a region. Livelihood strategies are important manifestations of livelihood activities. The richer the types of employment available are, the fewer people engaged in the first industry there are, and the higher the level of social development is, the higher the sustainability of livelihoods will be. Aridity can reflect the environmental stress and disturbance faced by Inner Mongolia. The Aridity Index (AI), which determines whether the climate is suitable for crop growth and animal husbandry development, can represent the degree of vulnerability of each league or city to drought. To construct an aridity gradient, we used spatially explicit rainfall and potential evapotranspiration data of Inner Mongolia from the year 2012 to 2016. The aridity index was calculated as the ratio of annual rainfall to potential evapotranspiration according to the United Nations Environment Programme (UNEP). The average value over the five years was taken as the aridity index (I_{14}) for a league or city. Aridity levels were then assigned based on the UNEP's aridity classification.

2.4. Methods

In this study, three main methods were utilized: The entropy weighting method was used for calculating the SLI and assigning weights to the selected indicators. Spatial autocorrelation and local autocorrelation analyses were used to characterize the SLI patterns in the study region. Finally, obstacle degree analysis was used to identify obstacle factors for the SLI. The three methods are described in the following paragraphs.

2.4.1. Entropy weight method

The entropy weight method was chosen to be used as an alternative approach in this study. The entropy weight method reflects the information entropy of data according to the dispersion of the data so as to determine the weights of indicators. Specifically, the smaller the dispersion of an indicator is, the smaller the amount of information needed to determine it is and the greater the information entropy will be; similarly, the smaller the dispersion of an indicator is, the smaller the influence (i.e., weight) of the indicator on the overall evaluation will be (Rocha et al., 2012; Yan et al., 2014). This not only overcomes the problem of the randomness assumption but also effectively solves the problem of information overlapping among multiple index variables (Chu et al., 2015; Yan et al., 2014). The most common approaches used to assign weights to indicators, such as the Delphi method and analytic hierarchy process (AHP), are used because of their simplicity (Aminbakhsh et al., 2013; Stefanidis and Stathis, 2013), but they have the limitation of a high degree of subjectivity (Chu et al., 2015). Thus, the entropy weight method is a more objective method based on probability theory that measures the relative importance of the variables involved (Chu et al., 2015; Chu et al., 2014; You and Zhang, 2017) and represents the average internal information of the decision (Hirche, 1978). The concept of entropy is to measure the relative intensities of contrasting criteria to represent the average intrinsic information for use in decision making. According to the characteristics of entropy (Robinson, 2008), we can evaluate the randomness and disorder degree of an event by calculating the entropy value, and we can also evaluate the degree of dispersion of an index using the entropy value. The greater the dispersion degree of an index is, the greater the influence of the index on the comprehensive evaluation will be.

The entropy weight method first calculates the variation degree of indicators, then calculates the entropy weight, then corrects each indicator according to the entropy weight. The specific process of using the entropy method to determine the weight is as follows:

(1) Data standardization:

Firstly, all indicators were standardized to cause their values to range from 0 to 1 so as to allow us to compare various variables. According to Equation (1) and Equation (2):

For the factors positively related to SLs:

$$Z_{ij} = \frac{X_{ij} - X_{jmin}}{X_{jmax} - X_{jmin}} \tag{1}$$

For the factors negatively related to SLs:

$$Z_{ij} = \frac{X_{jmax} - X_{ij}}{X_{jmax} - X_{jmin}} \tag{2}$$

Due to the fact that the entropy method uses logarithm operation, the standardized value cannot be calculated directly. In order to solve the influence of negative number or 0 on the operation, the standardized value is transformed into:

$$Z_{ij}^{'} = Z_{ij} + A \tag{3}$$

Each index is then quantified according to the same scale, where the proportion of the *i*th league or city and the *j*th indicator is:

$$Y_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} \tag{4}$$

The value of the information entropy is:

$$e_j = \left(-\frac{1}{\ln n}\right) \times \sum_{i=1}^{n} Y_{ij} \ln Y_{ij} \tag{5}$$

If$Y_{ij} = 0$, then$Y_{ij}\ln Y_{ij} = 0$ (Yan et al., 2014) , $0 \le e_j \le 1$.

The redundancy value of information entropy is:

$$d_j = 1 - e_j \tag{6}$$

The difference coefficient is normalized, and the index weight is:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{7}$$

The score of a single index in the kth group is:

$$S_{kj} = \sum w_j Z_{kj} \tag{8}$$

The comprehensive SLs score in the kth group is:

$$S_K = \sum_{1}^{n} S_{kj} \tag{9}$$

Here, X_{ij} represents the original value of the ith leagues or cities and the jth indicator; X_{jmin}andX_{jmax} represent the minimum and maximum value of the factor among all leagues or cities in the current year; Z_{ij} represents the data after dimension elimination and represents the standard value of the ith league or city in the jth indicator; I = 1, 2, …, m, m is the number of evaluation indicators; j = 1, 2, …, n, n is the number of leagues or cities to be evaluated; $Z'_{ij}$is the converted value; and A is the converted amplitude; $Z_{kj}$is the standardized indicators in the kth group; m is the number of leagues or cities being assessed; and n is the number of the indicators. Here, m = 15 and n = 12. Table 2 shows the specific weights of the 15 indicators.

2.4.2. Analysis of spatial patterns

To evaluate the spatial variability of SLI in Inner Mongolia, spatial autocorrelation and local spatial analysis (hot spot) were used.

To measure and analyze the spatial correlation and difference characteristics of all regions in Inner Mongolia, we used global spatial autocorrelation, which is represented by Moran's I index. As shown in Formula (10):

$$\mathrm{I} = \frac{n^{*}\sum_{i=1}^{n}[w_{i,j}{}^{*}(X_i - \overline{X})(X_j - \overline{X})]}{[\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j} \sum_{i=1}^{n} w_{ij}{}^{*}\left(X_i - \overline{X}\right)^2]} \tag{10}$$

Here, n is the number of evaluation indicators. $W_{i,j}$ is the i's and j's space weight matrix, which is the space weight defined based on the distance method, which calculates the straight line distance between two points (**Euclidean Distance Metric**). $X_i$andX_j are used to represent the SLI of two different regions, i and j, and $\overline{X}$ represents the average value of this index in the two regions. Moran's I greater than 0 indicates a positive spatial correlation. The larger the value is, the more obvious the spatial correlation is. Moran's I less than 0 indicates a negative spatial correlation; the smaller the value is, the greater the spatial difference will be. When Moran's I = 0, the space is random.

When analyzing the spatial aggregation characteristics of the local spatial attributes in Inner Mongolia, the measurement index that can be used is the local spatial autocorrelation index, expressed by the local G_I* index, which is the hot spot analysis method. This is shown in (11):

$$G_i{}^{*} = \frac{\sum_{j=1}^{n} W_{ij}{}^{*} X_j}{\sum_{j=1}^{n} X_j} \tag{11}$$

Here, X_j is the SLI of area j and $G_i{}^{*}$ is the local $G_i{}^{*}$ index. If $G_i{}^{*}$ is greater than 0, this indicates that the spatial agglomeration is high and

Table 2
The value of the information entropy and weight of the 15 indicators.

y	I1	I2	I3	I4	I5	I6	I7
information entropy	0.2413	0.1394	0.0378	0.1694	0.1434	0.0889	0.0595
weight	0.1409	0.0814	0.0221	0.0989	0.0837	0.0519	0.0482
I8	I9	I10	I11	I12	I13	I14	I15
0.0825	0.1209	0.1205	0.1469	0.1710	0.0650	0.0761	0.0504
0.0706	0.0704	0.0857	0.117	0.0998	0.0380	0.0444	0.0294

belongs to the hot spot area; if G_i^* is less than 0, this indicates that the spatial agglomeration is low and belongs to the cold spot area. In order to clearly find the obstacle factors that limit the development of SLI in Inner Mongolia, we introduced obstacle degree analysis.

2.4.3. *Obstacle factor analysis*

To evaluate the obstacle factors and degree of the obstacle limiting the SLI in in Inner Mongolia and identify the main obstacle factors in achieving SD, obstacle factors analysis, which is an important method for ecological index analysis, was used. This analysis is a particularly efficient way to help researchers quickly identify the key impact factors among many different indicator factors. This is an important factor helping in the identification of geographic key factors and the expression of key features.

The obstacle factor analysis model contains three main indicators. These three main indicators can be used to summarize and analyze the obstacle model. They are factor contribution degree, indicator deviation degree, and obstacle degree. The degree of contribution of each influence factor to the overall target can be expressed by the factor's contribution degree. The factor contribution degree represents the weight of each indicator w_j. The index deviation degree O_{ij} is used to analyze the difference between the maximum target and the single index, Z_{ij} represents the livelihood index of a single indicator, I_{ij} represents the degree to which a single regional indicator is an obstacle to the SLs, and S_{ij} refers to the obstacle degree of the criterion level. The specific calculation formulas for the three indexes are as follows:

$$O_{ij} = 1 - Z_{ij} \tag{12}$$

$$I_{ij} = \frac{O_{ij}{*}w_j}{\sum_{j=1}^{n} O_{ij}{*}w_j}{*}100\% \tag{13}$$

$$S_{ij} = \sum_{j=1}^{n} I_{ij} \tag{14}$$

3. Results

In this section, the indexes are organized into three main sub-parts. The first sub-part contains the aridity analysis, the second one contains the spatial analysis of the SLI, and the third contains the analysis of the barrier factors affecting the SLs.

3.1. *Aridity analysis*

3.1.1. *Aridity gradient*

The Aridity Index (AI) reflects the spatial distribution of the climate in Inner Mongolia. The results suggest that the spatial variability of the AI within Inner Mongolia is much higher than the interannual variability within each league or city, and no trends can be highlighted in the study period toward an increasing level of aridity (Fig. 3). According to the AI, the Inner Mongolia drylands were classified into three main zones, as shown in Table 3.

3.1.2. *Variation in livelihood assets with aridity*

The weight vector was obtained by the entropy weight method, then the indicators' weights could be obtained. The most important variables driving SLI and ranked in the top four were I_1 (0.1409), I_{11} (0.117) I_{10}

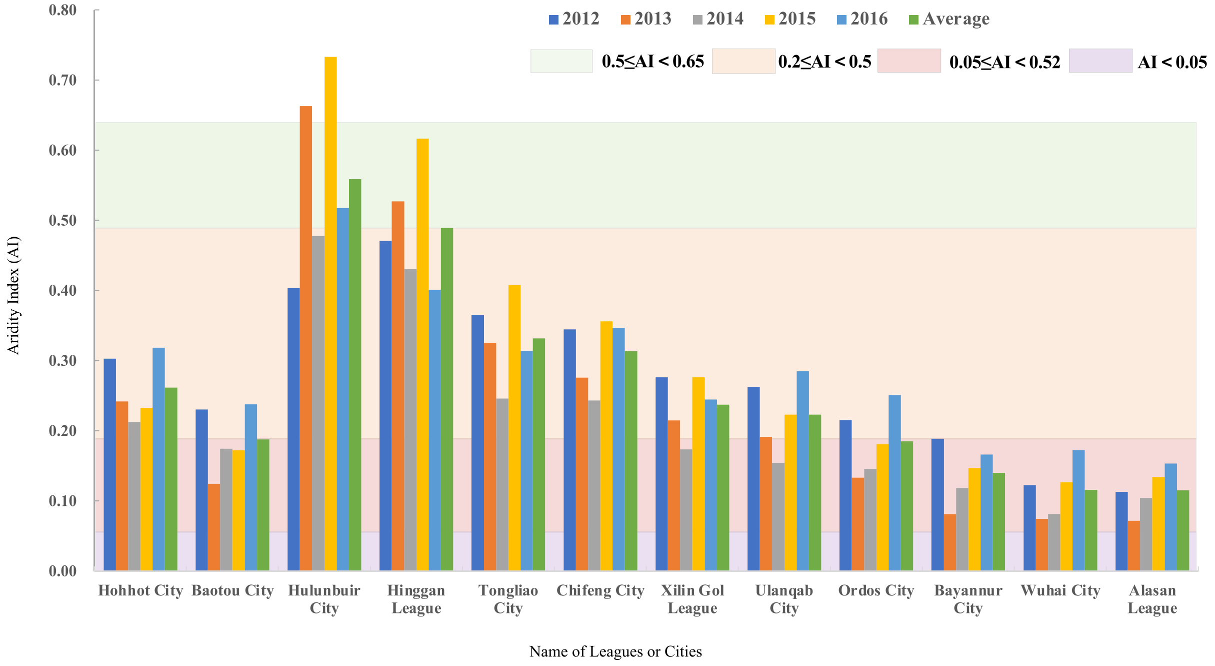

Fig. 3. The temporal change in the AI in the leagues or cities of Inner Mongolia from 2012 to 2016.

Table 3
Leagues' or cities' distribution according to the AI in Inner Mongolia.

Zone Type	Classification	Leagues or Cities
Arid zone	($0.05 \leq AI < 0.2$)	Baotou, Bayannur, Ordos, Alasan, Wuhai;
Semi-arid zone	($0.2 \leq AI < 0.5$)	Hohhot, Tongliao, Xilin Gol, Ulanqab, Hinggan, Chifeng;
Dry sub-humid zone	($0.5 \leq AI < 0.65$)	Hulunbuir;

(0.0998), and I_4 (0.0989); see the appendix for details.

The results showed that the SLI of the dry sub-humid zone was 15% higher than that of the arid zone (Fig. 4), the physical capital of the dry sub-humid zone contributed the most to the SLI (0.1255), and the contribution of physical capital to SLI in the arid area was the least (0.0352) (Table 4).

3.1.3. *Livelihood strategy*

From the perspective of the contribution of a livelihood strategy to the SLI, the results indicated that the semi-arid zone has the greatest contribution to the livelihood strategy, rather than the dry sub-humid zone, as shown in Table 5.

The results shown in Table 6 demonstrate that the maximum value of the SLI occurs in the dry sub-humid zone. In contrast, the value in the semi-arid zone is smaller than that in the arid zone (Table 7).

3.2. *Spatial pattern analysis of SLI*

3.2.1. *Spatial pattern of SLI in Inner Mongolia in 2017*

These results reveal that the SLI of 12 leagues or cities in Inner Mongolia in 2017 ranged from 0.2063 to 0.4621, with significant differences among regions (Fig. 5). The maximum value appears in Xilin Gol (0.4621), which is part of the semi-arid area, while the minimum value appears in Baotou (0.2063), which is arid. The SLIs of other regions are: Wuhai (0.2966), Ulanqab (0.3107), Hinggan (0.3455), Ordos (0.3465), Bayannur (0.3835), Hohhot (0.3855), Alasan (0.4251), Hulunbuir (0.4501), Chifeng (0.4520), Tongliao (0.4564), and Xilin Gol (0.4621). Fig. 6 used the ratio of SLI and AI, i.e., SLI/AI, thus representing specific SLI to explore further the spatial pattern of SLI with partial control of the effect of non-uniform AI values in the leagues or cities.

Based on the characteristics of the data reflected in the evaluation results, the SLI can be divided into four grades to represent the degree of vulnerability of SLs—namely, extremely unsafe (I), slightly unsafe (II), safe (III), or relatively safe (IV) (Lindenberg, 2002)[6]. Under the condition of SLI = 1, where the vulnerability is the lowest for each league or city, SLs can enter an optimal state; under the condition of SLI = 0, where the vulnerability is the highest, the SLs will face a high level of risk. According to the classification criteria, most leagues or cities are in (II) and (III).

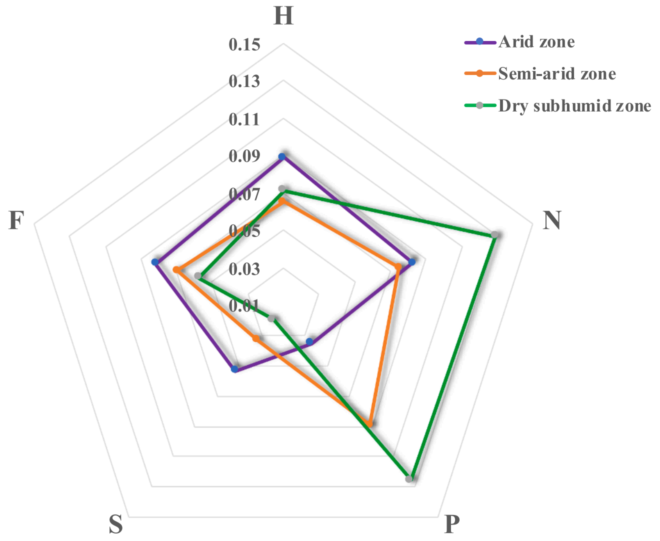

Fig. 4. Livelihood assets of each arid zone in 2017 (H: human; P: physical; N: natural; F: financial; S: social).

3.2.2. *Spatial clustering and hot spot analysis*

Using the spatial autocorrelation analysis method, the global Moran's I index of Inner Mongolia's SLI in 2017 was calculated. Based on the local spatial autocorrelation analysis method for cold and hot spots, these results indicate that the Moran's I index is generally positive and significant at the 95% confidence level. The results for Moran's I index, the Z-score, and the p-value of Inner Mongolia's SLI are 0.28, 2.147, and 0.043, respectively. A value of 0.28 for Moran's I index indicates that the SLI of each league or city has an overall status of positive spatial correlation, which means that the SLI clusters together with a high/low value in the map.

As shown in Fig. 7, the results demonstrate that hot spots occur in Hinggan and Chifeng. In contrast, Hohhot represents a cold spot. Furthermore, these results indicate that Xilin Gol and Tongliao have a higher SLI; Hulunbuir and Tongliao have a higher SLI; and Ordos, Baotou, and Ulanqab have a lower SLI. The local spatial correlation shows that the number of specific leagues or cities that have a higher SLI show a trend of increase in semi-arid and dry sub-humid regions. In contrast, the leagues or cities with a lower SLI in arid and semi-arid areas have shown a trend of decrease, with great effects.

3.3. *Analysis of obstacle factors*

3.3.1. *Obstacle degree factor analysis based on different aridity regions*

Based on the indicator layers of sustainable livelihood assets, the indicator barriers in different aridity zones were analyzed, as shown in Fig. 8. The results indicate that the three arid regions in Inner Mongolia have the smallest barriers to social capital at less than 12%, which is significantly lower than the barriers for other capital indicators. Human capital has the largest barriers, with the three arid regions all having more than 25%. Among the natural capital indicators, semi-arid regions have the largest barriers, reaching 27%. The difference in the barriers of physical capital indicators is the most significant. Specifically, as shown in Fig. 9, among the 12 specific sustainable livelihood indicators in Inner Mongolia, I_1(the number of laborers), I_4 (the grassland area), I_{12} (the number of livestock), I_5 (the total amount of water resources), and I_2 (the highest level of education) are the main obstacle factors. Meanwhile, I_3 (medical level) represents the lowest obstacle to SLs. In areas with different levels of aridity, the impact of each obstacle factor is different. I_1 (the number of laborers) is the largest obstacle factor in semi-humid areas, representing about 25%. In addition, I_9 (disposable income per capita), I_{11} (infrastructure), and I_{12} (the number of livestock) are typical obstacles in arid areas, with the obstacles at levels of 8.07%, 9.73%, and 13.81%, respectively. I_2 (education level) and I_4 (grassland area) are important in arid and semi-arid areas, accounting for 9.73%, 9.61%, 10.25%, and 11.53%, respectively. The total amount of I_5 (water resources) is the main obstacle factor in semi-arid and semi-humid areas, with the obstacle degree reaching 10.77% and 10.42%, respectively.

3.3.2. *Analysis of obstacle factors in different leagues or cities*

We selected all obstacle factors for each league or city in Inner Mongolia for subsequent analyses, as shown in Fig. 10. A macroscopic analysis of the heat map clearly indicated that the main obstacle degree factors are I_1, I_2, I_4, I_{12}, and I_{10}. The most unimportant obstacle factors

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[6] Grade (I) is SLI < 0.25, grade (II) is $0.25 \leq SLI < 0.35$, grade (III) is $0.35 \leq SLI < 0.45$, grade (IV) is $SLI \geq 0.45$.

Table 4
Distribution of livelihoods assets' according to the aridity gradient in Inner Mongolia.

Group	HumanAssets	NaturalAssets	PhysicalAssets	SocialAssets	FinancialAssets	LivelihoodsAssets
Arid zone	0.0889	0.0826	0.0352	0.0534	0.0817	0.3418
Semi-arid zone	0.0650	0.0749	0.0890	0.0334	0.0695	0.3959
Dry sub-humid zone	0.0712	0.1290	0.1255	0.0195	0.0577	0.4030

Table 5
Results of livelihood strategies' distribution according to the aridity gradient in Inner Mongolia.

Group	Contribution of livelihood strategy to SLI
Arid zone	0.0399
Semi-arid zone	0.0668
Dry sub-humid zone	0.0468

Table 6
Results of the SLI in regions of different aridity.

Group	SLI
Arid zone	0.4145
Semi-arid zone	0.4020
Dry sub-humid zone	0.4501

are I_6 and I_8. Since there are many sub-indicator-level factors involved in livelihood capital, in order to more clearly determine the main obstacle factors for each league or city, only the top five obstacles with the largest degree of obstacles (cumulative obstacles exceeding 55%) were selected as the main obstacle factors (Table 8). The study results suggested that, except for the cities of Hohhot and Wuhai, the main obstacle factor for SLs in Inner Mongolia was the number of laborers. The largest obstacle factor occurred in Xilin Gol (25.64%) and the smallest in Baotou (12.13%). With the increase in the AI, the same obstacle index did not show a regular decrease in the degree of urban obstacles, indicating that the relationship between SLs and obstacle indicators is a more complex social-economic-ecological issue that requires more in-depth exploration. Among the 12 leagues or cities, the obstacle factor ranked 2nd and 3rd, and the most frequent ones were grassland area (I_4) and the number of livestock (I_{12}).

For Alasan and Wuhai, where the AI were the smallest, the main obstacle factors were I_1 (24.10), I_{12} (16.22), I_5 (11.26), I_2 (9.21), I_9 (9.18), I_{12} (14.01), I_4 (13.88), I_{11} (12.04), I_5 (11.77), and I_2 (11.41). As the only one city in the semi-humid zone, Hulunbuir's sustainable livelihood obstacle factors were 0.56 I_1 (24.77), I_5 (10.42), I_{10} (9.57), I_{10}

Table 7
Results for the obstacle degree (%) of SLI from I_1 to I_{12}.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}
Arid zone	15.46	9.73	1.28	10.25	8.23	6.44	2.93	3.07	8.07	3.10	9.73	13.81
Semi-arid zone	19.55	9.61	2.29	11.53	10.77	4.58	3.59	4.74	3.25	8.86	8.64	7.67
Dry sub-humid zone	24.77	5.05	1.52	8.78	10.42	4.10	5.63	5.91	5.57	9.57	2.84	8.08
Sum	59.79	24.39	5.09	30.56	29.43	15.02	12.15	13.72	16.88	21.53	21.21	29.56

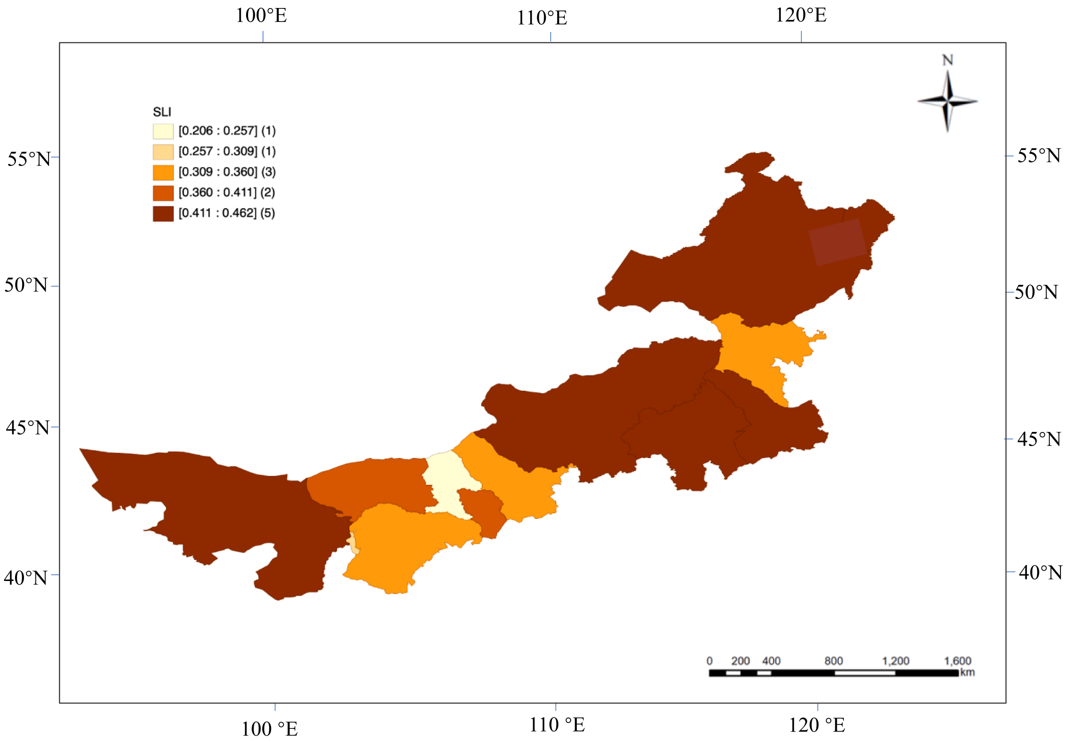


Fig. 5. SLI according to the league or city level in Inner Mongolia in 2017.

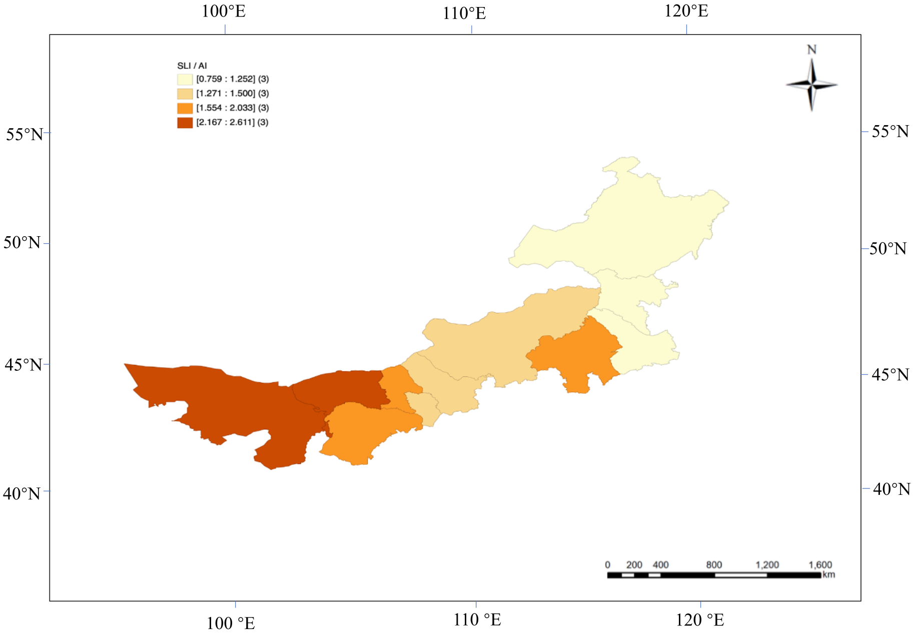


Fig. 6. SLI/AI according to the league or city level in Inner Mongolia in 2017.

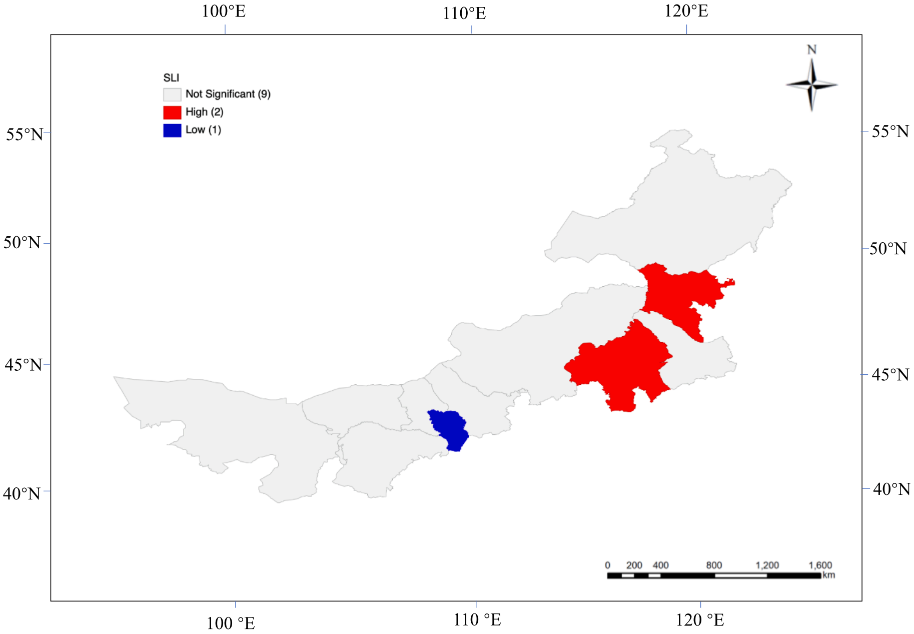


Fig. 7. Spatial distribution of hot spots and cold spots of Inner Mongolia's SLI in 2017.

(8.78), and I_{12} (8.78).

4. Discussion

4.1. SLI and spatial analysis

According to the UN aridity index classification criteria, the 12 regions in Inner Mongolia were classified into three different aridity zone types. With the increase in the number of types of aridity, the livelihood assets also increased. In contrast, in terms of livelihood strategies, maximum values were found in the semi-arid zone. The semi-arid areas had the most vulnerable livelihood (rather than the arid ones), and this suggests that while the environmental and climate context is important, socio-economic planning can play a critical role in determining SL outcomes. This calls for integrated (i.e., focusing on natural and human capital) land management and planning approaches in drylands, reflecting their nature of tightly coupled socio-ecological systems.

The SLI was similar in the arid and semi-arid zones. In contrast, the SLI was higher in dry sub-humid zones than in other areas with a higher aridity. However, since there was only one city in the dry sub-humid zone, this relationship needs to be further investigated. The lowest SLI value among the three arid zone types was for social capital, which indicated that there is a need to improve this aspect in Inner Mongolia. The results of the livelihood strategies for the SLI further reveled that aridity (appropriate ecological stress) can promote the optimization of livelihood strategies to some extent and promote the development of SLs.

Specifically, the spatial distribution of the SLI demonstrated a

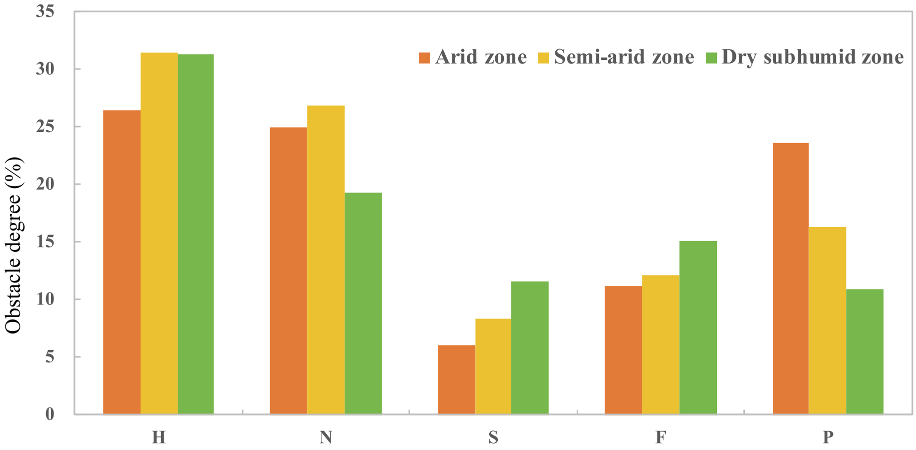
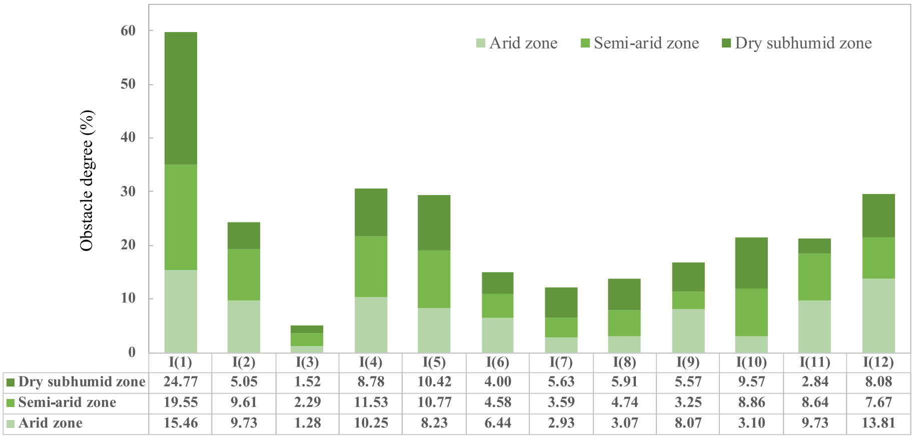


Fig. 8. Obstacle degree (%) of livelihood asset indicators for each aridity zone in 2017 (H: human; P: physical; N: natural; F: financial; S: social).



	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)	I(11)	I(12)
Dry subhumid zone	24.77	5.05	1.52	8.78	10.42	4.00	5.63	5.91	5.57	9.57	2.84	8.08
Semi-arid zone	19.55	9.61	2.29	11.53	10.77	4.58	3.59	4.74	3.25	8.86	8.64	7.67
Arid zone	15.46	9.73	1.28	10.25	8.23	6.44	2.93	3.07	8.07	3.10	9.73	13.81

Fig. 9. Obstacle degree (%) based on livelihood assets' sub-indicators for each aridity zone in 2017 (I (1)-I (12) refer to the sub-indicators and are equal to I_1).

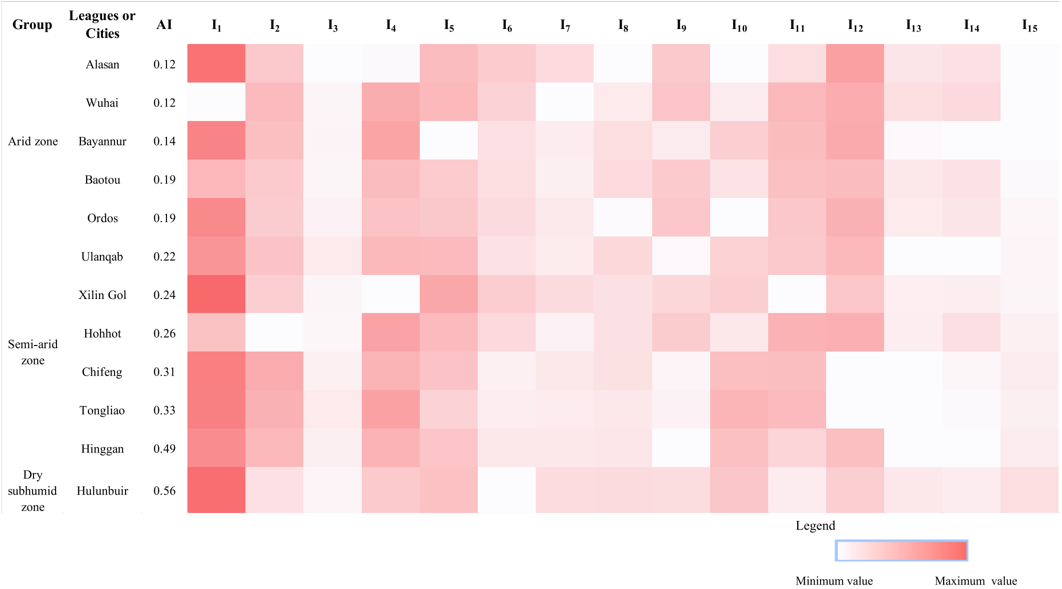


Fig. 10. Heat map of the distribution of obstacle factors in different leagues or cities (colors represent the values of the obstacle degree for different indicators among the different leagues or cities).

Table 8

Main obstacle factor degree (%) based on the SL assets among the different leagues or cities in inner Mongolia in 2017.

group	Leagues or Cities	AI	Ranking of obstacle degree				
			1	2	3	4	5
Arid zone	Alasan	0.12	I_1(24.10)	I_{12}(16.22)	I_5(11.26)	I_2(9.21)	I_9(9.18)
	Wuhai	0.12	I_{12}(14.01)	I_4(13.88)	I_{11}(12.04)	I_5(11.77)	I_2(11.41)
	Bayannur	0.14	I_1(20.95)	I_4(15.45)	I_{12}(14.33)	I_{12}(11.34)	I_2(10.71)
	Baotou	0.19	I_1(12.13)	I_{12}(11.26)	I_4(11.24)	I_{11}(10.62)	I_2(8.84)
	Ordos	0.19	I_1(19.94)	I_{12}(13.24)	I_4(10.12)	I_{11}(9.34)	I_9(9.27)
Semi-arid zone	Ulanqab	0.22	I_1(18.03)	I_{12}(11.86)	I_4(11.86)	I_5(11.39)	I_2(10.10)
	Xilin Gol	0.24	I_1(25.64)	I_5(14.84)	I_{12}(9.42)	I_6(8.26)	I_{10}(8.12)
	Hohhot	0.26	I_4(15.55)	I_{12}(13.31)	I_{11}(13.09)	I_5(11.39)	I_1(10.30)
	Chifeng	0.31	I_1(21.93)	I_2(14.17)	I_4(12.74)	I_{11}(10.99)	I_{10}(10.85)
	Tongliao	0.33	I_1(21.70)	I_4(16.06)	I_2(13.15)	I_{10}(12.50)	I_{11}(11.56)
	Hinggan	0.49	I_1(18.03)	I_4(12.79)	I_2(12.02)	I_{12}(10.88)	I_{10}(10.64)
Dry subhumid zone	Hulunbuir	0.56	I_1(24.77)	I_5(10.42)	I_{10}(9.57)	I_{10}(8.78)	I_{12}(8.78)

pattern of “high at both ends and low in the middle”, with Baotou being the city with the lowest SLI and Hulunbuir being the city with the highest. From east to west, the ecosystem types in Inner Mongolia are a forest-steppe transition zone, typical steppe zone, semi-arid steppe zone, and desert zone. Understandably, the land productivity in the eastern region is significantly higher than that in the west and the climate is relatively humid, meaning that the SLI is higher. In the westernmost city of Alashan, a typical arid area in the desert region, the SLI is also higher, mainly because of population and social factors. Despite the low productivity and large geographical area, the population base is low because the population is concentrated around the main towns. In addition, the national macro policy regulation and support reduce the overall livelihood vulnerability. Moreover, fewer consumer products are required per unit of population. On the other hand, the central leagues or cities are typical resource-based cities (e.g., coal mines). With the depletion of resource exploitation, the pressure of population growth, and the degradation of grassland ecosystems, a series of link-strip socio-ecological problems arise, inevitably presenting a more extreme level of livelihood sustainability.

4.2. Obstacle factors analysis

The analysis of the sustainable livelihood obstacle degree factors for regions with different levels of aridity found that the main overall obstacle factors were related to human resources and natural capital constraints. Then, obstacle factors were also analyzed for the different leagues or cities to help each region to address other local development constraints. The analysis of the obstacle factors of each specific league or city revealed the degree of obstacle in Inner Mongolia, which has a rich array of arid ecological types, a vast area, and similar urban development patterns. The obstacle factors showed some commonality in terms of the frequency of occurrence among different leagues or cities, with the size of the labor force, total grassland area, livestock population, education level, and disposable income per capita ranking in fifth place. The use of this model analysis would be very helpful in some other countries and regions around the world, especially for the development of aridity-constrained areas, and these areas could learn some lessons from the development patterns of Inner Mongolia.

4.3. Suggestions for future development and considerations in policy design

The above results and analysis show that, in the Inner Mongolia region, a typical dryland that straddles three aridity types from east to west, the improvement of human capital, and social information exchange between regions are key factors that need to be improved in order to achieve sustainable livelihood targets in the future. According to this analysis, the following priority development interventions should be considered:

1. Strengthening grassland management and optimizing grass–livestock balance. Grassland ecological protection work should continue strengthening and taking all possible actions to protect grassland resources, take all measures to curb the trend of continued grassland degradation, and allocate and regulate livestock resources according to the projected health status of grazing areas in the future.
2. Improving the education level in pastoral areas. Human capital is the first factor for achieving SD and a central part of the SLF, which plays a decisive role in acquiring other livelihood capital, such as ecological cognition and information collection and processing. The education level of farmers and herders directly determines the direction of rural development. The government should continue to increase the investment of basic education as well as education in specific skills, cultivate new types of herders, create herder community skills training organizations, raise the level of ecological cognition, and improve the cultural competence of the next generation of herders.
3. Strengthening inter-regional connectivity and enhancing social capital in pastoral areas. Social capital is an important element of livelihood capital and plays a key role in improving SLs. The low levels of social capital found in this study indicate that it is important to continue to strengthen the construction of facilities, electrification levels, and networking levels to improve the level and quantity of communication between herders and the outside world, internally strengthen the promotion of multiform grassroots governance models such as joint family grazing, encourage small- and medium-sized herders to participate in grass flow and joint family operations, strengthen mutual interconnection and interoperability, provide help and learning for areas with low and high external sustainable household livelihoods and livelihood indices, strengthen communication between regions, improve mutual learning, enable the efficient allocation of resources to enhance the production cycle, and help regions cope with external climate shocks.

5. Conclusions

This research developed an SLI across a geographical gradient of aridity, which can provide a useful tool for exploring the conditions necessary for SD in drylands. This study also identified the problems and potential solutions for the SD of Inner Mongolia, focusing on different types of dryland zones (arid zones, semi-arid zones, dry sub-humid zones).

The findings of this analysis revealed that SLs vary greatly across zones with different levels of aridity in Inner Mongolia. Regarding livelihood assets, the SLI in the dry sub-humid zone was 15% higher than that in the arid zone. Regarding the use of a livelihood strategy, the results indicated that the semi-arid zone provided the greatest contribution to the SLI, rather than the dry sub-humid zone. Moran’s I index revealed that the SLI’s overall performance had a positive spatial correlation, meaning that similar SLIs clustered together. Additionally, the local spatial correlation showed that the hot spots were Hinggan and Chifeng, while Hohhot was the cold spot. The lack of material capital and social capital in these areas is an important obstacle to sustainable livelihood development. Based on the SL analysis, the characteristics of the sustainable development of local residents were revealed and priority development options were formulated accordingly. These findings can act as an important disciplinary reference for future SLs research in drylands. They can also help us to accurately determine the future development priorities of dryland areas, providing important guidance and information allowing scientists, governments, and international organizations to eradicate poverty faster and more efficiently in drylands.

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CRediT authorship contribution statement

Tong Li: Conceptualization, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Yuantong Jia:** Data curation, Methodology. **Francesco Fava:** Investigation, Supervision. **Zhihong Xu:** Conceptualization, Investigation, Methodology. **Jiapei Zhu:** Investigation, Resources. **Yaqian Yang:** Investigation. **Li Tang:** Investigation, Writing - review & editing. **Yanfen Wang:** Conceptualization, Funding acquisition, Resources, Supervision, Writing - review & editing. **Yanbin Hao:** Investigation, Writing - review & editing. **Xiaoyong Cui:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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