International Journal of *Geo-Information*

MDPI

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Spatiotemporal Change in Livestock Population and Its Correlation with Meteorological Disasters during 2000–2020 across Inner Mongolia

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Abstract: Inner Mongolia (IM) is one of the five major pastoral areas in China, and animal husbandry is its traditional industry. The population of livestock is an important factor affecting the sustainable development of livestock and grassland. Due to the special geographical location of IM, various meteorological disasters occur frequently, which have a significant impact on the local livestock population. In this study, principal component analysis (PCA) and geographically weighted principal component analysis (GWPCA) were used to explore the spatial and temporal patterns of small livestock and large livestock populations in county-level administrative units from 2000 to 2020, and the effects of meteorological disasters on livestock populations were also considered. We found that the cumulative proportion of total variance (CPTV) of the first two principal components of global PCA for small livestock and the first principal component for large livestock reached 94.54% and 91.98%, respectively, while the CPTV of GWPCA was in the range of 93.23–96.45% and 88.47–92.49%, respectively, which showed stronger spatial explanation; the small livestock population was significantly correlated with spring drought, summer drought, spring–summer drought and snow disaster. However, the correlation between large livestock and summer drought and spring–summer drought is greater. We conclude that GWPCA can better explain the spatial change of livestock populations; meteorological disasters have both advantages and disadvantages on the livestock population, and the drought types that have a greater impact on livestock are summer drought and spring–summer drought. There are geographical differences in the impact of meteorological disasters, with drought affecting most of IM and snow disaster mainly affecting the eastern region; large livestock were mainly affected by drought, while small livestock were affected by both drought and snow disaster.

Keywords: livestock population; GWPCA; PCA; meteorological disaster; grassland; IM

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Citation: Bai, H.; Wang, B.; Zhu, Y.; Kwon, S.; Yang, X.; Zhang, K. Spatiotemporal Change in Livestock Population and Its Correlation with Meteorological Disasters during 2000–2020 across Inner Mongolia. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 520. https://doi.org/10.3390/ijgi11100520

Academic Editors: Giuseppe Modica and Maurizio Pollino

Received: 23 August 2022
Accepted: 14 October 2022
Published: 16 October 2022

1. Introduction

Grassland, as the largest terrestrial ecosystem in China, covers an area of approximately 293 × 10^4 km^2 and plays an important role not only in the global carbon cycle but also in animal husbandry development, soil and water conservation, biodiversity maintenance and ecological balance [1–4]. Livestock, as one of the most important consumers of grassland ecosystems, has a significant impact on the sustainable management of grasslands [5]. At the same time, the quality and quantity of livestock are the result of the direct or indirect combined effects of air temperature, precipitation and extreme weather events, in which the impact of extreme weather events on livestock is more obvious and severe than that of long-term climate change [6–8]. In the context of global climate change, extreme weather events have increased, and corresponding meteorological disasters such as drought, floods, low temperature freezing, wind hail, and high temperature have occurred frequently, which not only cause economic losses but also critically endanger the lives of humans and livestock in grasslands [9,10].

Located at the edge of the East Asian monsoon climate and Central Asian continental climate, Inner Mongolia (IM) spans three climate zones, namely, the semihumid zone, semiarid zone and arid zone, and is often affected by various weather systems at the same time [11]. The instability of climate resources leads to frequent occurrence of meteorological disasters such as rainstorms, floods, strong winds, hail, drought, freezing damage and sandstorms in IM [12]. Meteorological disasters that have a greater impact on animal husbandry in IM mainly include droughts and snow disasters; in addition, low-temperature freezing damage, strong winds, sandstorms, torrential rain and floods, and hail will also have adverse impacts on livestock populations [13–16]. For example, from 1999 to 2001, Xilingol league experienced severe drought for three consecutive years. The affected grassland area reached 46 million hectares, 26.807 million livestock were affected, and 1.32 million died [17]. During the winter of 2006, there was a snow disaster in Tongliao city, which affected more than 3 million livestock and killed more than 200,000 livestock [16]. The severe sandstorm that occurred in the Alxa league from May 5 to 6, 1993, affected 1.33 million livestock and killed 98,000 livestock [18]. In 2004, more than 60,000 large livestock died due to rainstorms, floods and hail in the whole region [19,20]. Animal husbandry is the basic industry of IM, which plays an important role in guaranteeing the supply of green animal products and ecological security in China [21]. Therefore, it is of far-reaching significance to understand the spatiotemporal change pattern of livestock populations and consider the impact of meteorological disasters.

Principal components analysis (PCA) is a multivariate statistical analysis method, which can better explain different sources of variation and key trends in the data, and extract variables with relatively large information contributions [22,23]. However, this method ignores the spatial feature of the data, so geographically weighted principal components analysis (GWPCA) can be used as an alternative method to compensate for the lack of spatial effect analysis [22,24]. At present, this method is widely used in population, economy and soil characteristics [25–30]. In this paper, PCA and GWPCA were used for temporal and spatial analysis of the livestock population data in IM. PCA can reduce the dimension of time-based livestock population variables and observe the main trends, but PCA is based on global data analysis, while GWPCA can make up for the lack of ignoring the spatial structure of data in PCA. Then, local differences can be better understood.

The purpose of this research is to determine the spatiotemporal changes of livestock at the county level in IM and the effects of meteorological disasters on them. In addition, this paper proposes two hypotheses: First, whether the effects of meteorological disasters on the population of livestock in the county are both beneficial and harmful; second, whether there are regional differences in the impact of meteorological disasters. The final results will provide useful insight into the spatiotemporal changes in the livestock population and their relationship with meteorological disasters, and provide basis for sustainable management of livestock in IM.

In this study, based on county-level meteorological disasters index and yearly livestock statistical data between 2000 and 2020, we conducted analyses from three aspects: (1) annual livestock (small vs. large) dynamics and their correlations, (2) annual and county-level change patterns in livestock population change with PCA and the GWPCA methodology, and (3) spatial heterogeneity of the relationship between livestock population and meteorological disasters at the temporal scale.

2. Materials and Methods

2.1. Study Area

The study area of this paper is IM (37°24′–53°23′ N, 97°12′–126°04′ E), with a total area of 1.183 million km^2. The landform is mainly a plateau, and most areas are above 1000 m above sea level. IM is one of the five pastoral areas in China, with a grassland area of 8800 × 10^4 hm^2, which is an important livestock product supply base [31–33]. In IM, grassland animal husbandry is not only a traditional industry, but also a competitive industry, which plays an important role in promoting economic development [34]. More than 80% of the banners (counties, cities and districts) in the region have more than 100,000 livestock in their inventory, and by 2020, the gross value of animal husbandry production has reached 160,336 billion yuan [35]. There are 33 pastoral banners (counties, cities, districts) and 21 semipastoral banners (counties, cities, districts) in the entire region. These 54 banners include almost all the natural grasslands in IM (Figure 1) [36]. In pastoral areas, people mainly rely on grazing on natural grasslands to make a living, while in semipastoral areas, animal husbandry is more intensive [36,37].

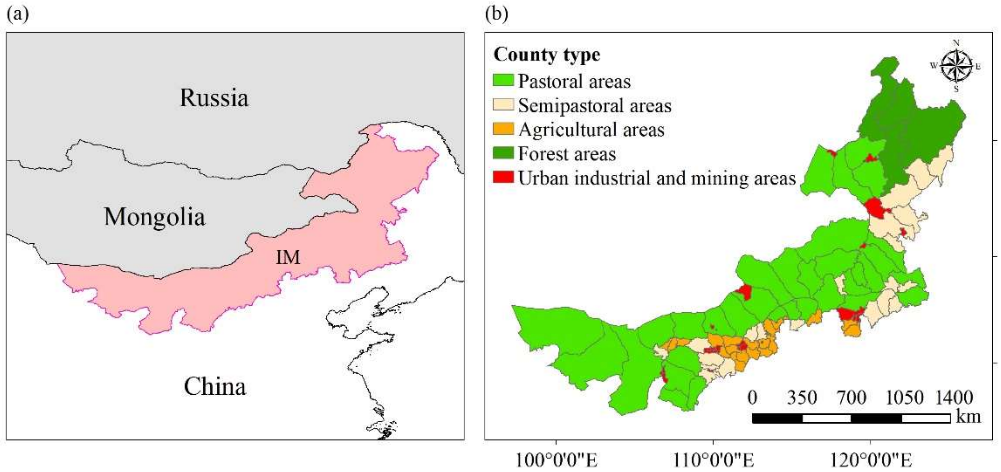

Figure 1. (**a**) Location of study area and (**b**) types of county-level administrative units in Inner Mongolia (IM).

2.2. Data

In this study, 102 county-level administrative regions (banners, counties, cities, districts; Zhalainuoer district is hosted by Manzhouli city) were used as the research unit, and the population of small and large livestock from 2000 to the end of 2020 was counted. The population of small livestock refers to the sum of goats and sheep, and the population of large livestock refers to the sum of cattle, horses, donkeys, mules, and camels (Figure 2). During the 21-year period, due to slight changes in the boundaries of some administrative regions or other reasons, the data were missing to a certain extent. The missing data of small livestock and large livestock accounted for 1.3% and 1.2% of the total data, respectively. Therefore, this study uses the latest administrative divisions, which are obtained from the National Geographic Information Resource Catalog Service System 1: 1 million public version of basic geographic information data (2021) (http://www.webmap.cn, accessed on 28 June 2022). The resulting missing data were filled by the *llsImpute* function in the R "pcaMethods" package [38].

Livestock data come from the *Inner Mongolia Statistical Yearbook* (2001–2018), *Inner Mongolia Survey Yearbook* (2019–2021) and relevant league and city statistical bureaus. According to the occurrence characteristics and damage degree of meteorological disasters, this study selects spring drought, summer drought and snow disaster in winter as the research objects [39]. The monthly scale data of the seasonal standardized precipitation-evapotranspiration index (SPEI-3) and standardized snow water equivalent index (SWEI) were extracted from the central points or nearby points of each county to quantify drought and disasters, respectively [40–43]. May, August and February represent spring, summer and winter, respectively. The SPEI comes from SPEI base v2.7 Dataset (http://hdl.handle.net/10261/268088 (accessed on 28 June 2022)), and SWEI from the Global Snow Drought Data Set (https://figshare.com/collections/Global_Snow_Drought_Data_Set/5055179 (accessed on 27 June 2022)). In addition, the occurrence of meteorological disasters comes from the *Yearbook of Meteorological Disasters in China* (2004–2020), the *China Meteorological Yearbook* (2001–2020) and other literature records [16,44–50].

Figure 2. Small livestock (**a**) sheep and large livestock (**b**) camels, (**c**) cattle, (**d**) horses.

2.3. Research Methods

First, we analyzed the correlation among the annual livestock population. Then, the GWPCA method was used to clarify the temporal and spatial change patterns of the livestock population. A standard PCA method cannot account for any spatial effects due to its nonspatial linear transform, so GWPCA could be used to replace PCA to compensate for the lack of spatial effect analysis [22,24]. GWPCA uses a moving window weighting method to find the localized principal components at the target location. For each target location, the adjacent observations are weighted according to the distance decay weighting function (bandwidth), and then these weighted data are subjected to standard PCA [23,51].

Before performing PCA, we applied the sample adequacy measure, Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity test. Such tests indicate the strength of relationships between test items. When KMO is greater than 0.5, it indicates that a component analysis is applicable to the test items dataset [52]. When the significance of Bartlett's sphericity test is less than 0.01, this indicates a strong relationship between the dataset of test items [53].

For PCA, given a $p \times q$ dimensional data matrix X, where p rows represent observations and q columns represent variables, a PCA of these data consists of conducting this transformation [22,23]:

$$LVL^T = S \tag{1}$$

where L is the matrix of eigenvectors with $p \times q$ dimensions, and each column of L represents the loadings corresponding to a principal component. V is the diagonal matrix of eigenvalues. S is the variance-covariance matrix with $q \times q$ dimensions. The proportion of variance of a component can be expressed by the eigenvalue by dividing by the trace of matrix V, $tr\,(V)$. In this study, p = 102, q = 21.

For GWPCA, the geographically weighted variance-covariance matrix for the livestock population dataset is calculated by the following formula [30,54]:

$$\sum(u, v) = X^T W(u, v) X \tag{2}$$

where X is the $p \times q$ matrix of livestock populations and $W(u, v)$ is the diagonal matrix of geographic weights generated by the chosen kernel weighting function W_{ij}. In this study, the spatial weighting matrix is obtained using a bisquare weighting function with adaptive bandwidth. The optimal bandwidth was determined by a cross-validation method [30,55].

The geographically weighted eigenvectors (local loading vectors) and eigenvalues are obtained by decomposing the geographically weighted variance-covariance matrix at a certain location in space [30,54]:

$$\sum(u_i, v_i) = LVL^T \mid (u_i, v_i) \tag{3}$$

where L and V are the diagonal matrix of geographically weighted eigenvectors and the geographically weighted eigenvalues, respectively. Dividing each local eigenvalue by $tr(V(u_i, v_i))$ finds a localized version of each component's proportion of the total variance in the original data. Thus, in each of the 102 counties of this study, GWPCA provides 21 components, 21 eigenvalues, and a component loading set of size 102 × 21 [23]. Before performing GWPCA, the number of retained components needs to be calculated a priori to determine the optimal bandwidth [51,56]. Therefore, for small and large livestock, PCA results can be used to determine the number of retained components, and the optimal bandwidth can be automatically found according to the cross-validation method. To further determine the regions with similar time dynamic changes in livestock populations, the loading data of GWPCA were analyzed using a distance-based hierarchical clustering method, and the optimal number of clusters was determined.

For meteorological disasters occurring in the 21 years from 2000 to 2020, this study classified according to IM's local standard *Standards for Meteorological Disasters for Animal Husbandry* (DB 15/T255-1997) on classification of disaster grades and the performance characteristics of pastures, livestock and grazing. It should be noted that this paper only counted the relatively serious drought and snow disaster with significant impact on livestock population, such as the following situations: pastures cannot turn green, grazing is generally affected, livestock feeding and drinking water are severely affected, and livestock lose weight significantly and livestock deaths. The meteorological disasters that occurred in the study period of this paper are all regional, and no meteorological disasters affecting the whole region have occurred. The classification of the SPEI and SWEI is shown in Tables S2 and S3 in the Supplementary Materials [42,57].

Finally, we explore the correlation between the livestock population and the statistical meteorological disaster index using the geographically weighted correlation indicator in the geographically weighted summary statistics. The formula is as follows [23,58]:

$$\rho(x_i, y_i) = \frac{c(x_i, y_i)}{(s(x_i)s(y_i))} \tag{4}$$

where $c(x_i, y_i)$ is the geographically weighted covariance:

$$c(x_i, y_i) = \frac{\sum_{j=1}^{n} W_{ij}\left\{\left(x_j - m(x_i)\left(y_j - m(y_i)\right)\right)\right\}}{\sum_{j=1}^{n} W_{ij}} \tag{5}$$

W_{ij} is the kernel weighting function, and $m(x_i)$ is the geographically weighted mean:

$$m(x_i) = \frac{\sum_{j=1}^{n} W_{ij} x_j}{\sum_{j=1}^{n} W_{ij}} \tag{6}$$

and a geographically weighted standard deviation is:

$$s(x_i) = \sqrt{\frac{\sum_{j=1}^{n} W_{ij}\left(x_j - m(x_i)\right)^2}{\sum_{j=1}^{n} W_{ij}}} \quad (7)$$

Since each county is not a region of the same size for spatial arrangement, it is reasonable to select an adaptive bandwidth. In this study, a bisquare kernel weighting function with an adaptive bandwidth N = 15 (approximately 15% of the total data) was selected to calculate the geographically weighted correlation [51,58].

In this study, the workflow was shown in Figure 3, and data analysis was performed using R 4.1.2 software [59]. The correlation among the annual livestock population was studied using the *cor* function; PCA was performed using the *princomp* function; GWPCA and geographically weighted correlation between livestock population and meteorological disaster index were implemented using the "GWmodel" package. The *hclust* function was used to hierarchical clustering, and "NbClust" package was used to determine the number of optimal clusters [60]. Finally, ArcGIS (10.6) was used for meteorological disaster information extraction and mapping.

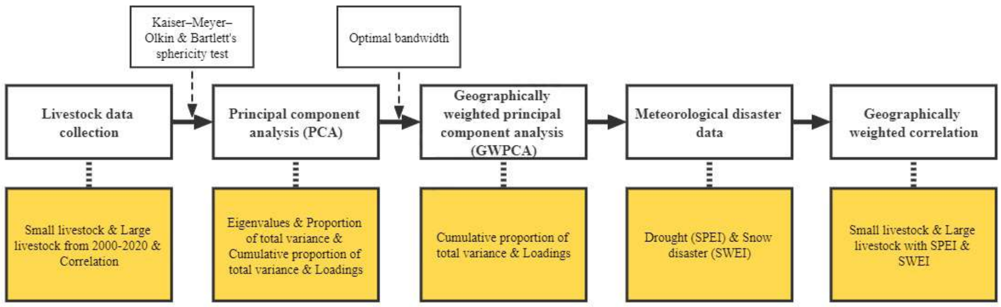

Figure 3. Data processing workflow.

3. Results

3.1. Annual Livestock (Small vs. Large) Dynamics and Their Correlations

The distribution of small livestock and large livestock in each county of IM from 2000 to 2020 is shown in Figure 4a,b. Small livestock are mainly distributed in parts of Xilingol league, Hinggan league, Tongliao city and Chifeng city in the central and eastern regions, and there are also large distributions in Ordos city, Bayannur city and Alxa Left banner of Alxa league in the west. Large livestock are mainly distributed in Chifeng city and Tongliao city in the eastern IM. During the study period, the trend of large livestock in IM was flat and almost unchanged, while the trend of small livestock was stable and rising and only decreased in 2006 (Figure 4e).

Regardless of whether small livestock or large livestock, the data show a strong correlation in general (Figure 4c,d). However, the correlation between small livestock from 2000 to 2002 and other years is weak, especially 2000. Large livestock in 2000 and 2005–2012, 2005–2010 and 2018–2020 have weak correlations, which indicates that the livestock population may have changed significantly in the above years, and it can also be seen that in different years, the effects of such changes in small and large livestock populations are different.

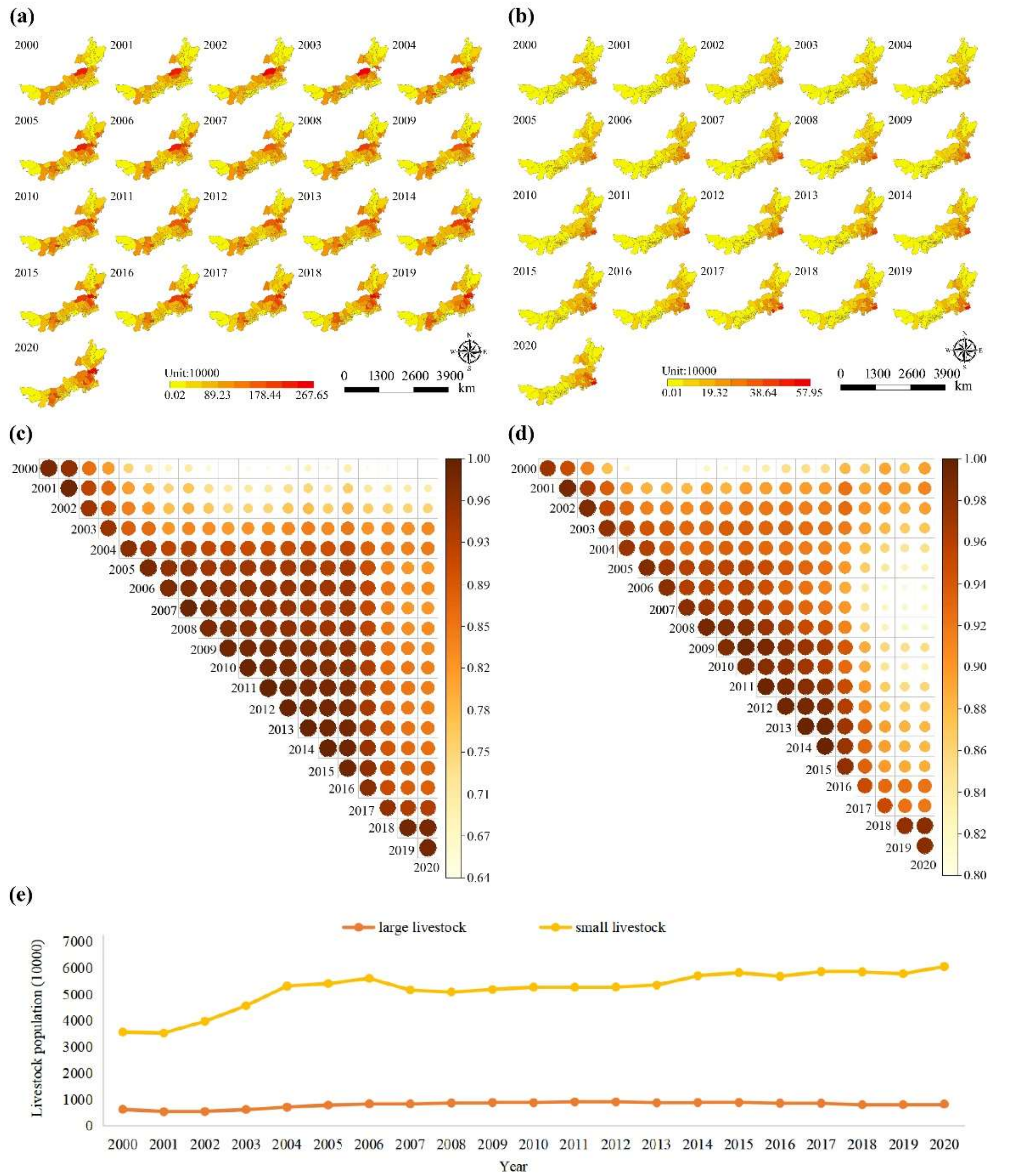

Figure 4. Dynamics of livestock in IM from 2000 to 2020. Distribution of (**a**) small livestock and (**b**) large livestock, (**c**) correlation matrix of small livestock and (**d**) large livestock, (**e**) trends of livestock change in IM.

3.2. Global Principal Component Analysis

Before better understanding the output of the geographically weighted model of livestock population, this study first performed a global PCA on 21 years of livestock population data from 102 county-level administrative units. The KMO results showed that the MSAsmall = 0.95 and MSAlarge = 0.94 for both small and large livestock were greater than 0.5, and the size of livestock Bartlett's sphericity test $p = 0.00$, less than the significance level of 0.01, so the research data are suitable for PCA.

It can be seen from the global PCA results of small livestock (Table 1) that the eigenvalues of the first two principal components are greater than unity, and the cumulative proportion of total variance (CPTV) reaches 94.54%, which explains most of the changes in the original data, indicating that there is a strong level of collinearity among the variables. The loading indicates the correlation between the principal component and the original variable. According to the results, the five years with the largest loadings on the first principal component are 2016, 2013, 2014, 2006, and 2011, while those on the second principal component are 2000–2003 and 2010.

Table 1. Eigenvalues, PTV, CPTV and Loadings for the global principal component analysis (PCA).

	$PC1_{(small)}$	$PC2_{(small)}$	$PC3_{(small)}$	$PC1_{(large)}$	$PC2_{(large)}$	$PC3_{(large)}$
Eigenvalues	18.37	1.29	0.63	19.13	0.77	0.39
PTV(%)	88.34	6.20	3.01	91.98	3.71	1.88
CPTV(%)	88.34	94.54	97.55	91.98	95.69	97.57
Loadings						
First	2016 (0.228)	2000 (0.527)	2020 (−0.507)	2013 (0.224)	2020 (0.377)	2000 (0.368)
Second	2013 (0.227)	2001 (0.479)	2019 (−0.504)	2011 (0.223)	2019 (0.365)	2001 (0.350)
Third	2014 (0.227)	2002 (0.434)	2018 (−0.448)	2012 (0.223)	2018 (0.364)	2002 (0.335)
Fourth	2006 (0.226)	2003 (0.284)	2007 (0.209)	2014 (0.223)	2000 (0.332)	2003 (0.322)
Fifth	2011 (0.226)	2010 (−0.165)	2008 (0.191)	2009 (0.222)	2008 (−0.251)	2004 (0.306)

Note: Only the first three principal components are displayed; PC—Principal component; PTV—Proportion of total variance; CPTV—Cumulative proportion of total variance.

The global PCA results of large livestock are also shown in Table 1. The eigenvalue of the first principal component is greater than unity, and the CPTV reaches 91.98%. At the same time, according to the results, the five years with the greatest influence on the first principal component are 2013, 2011, 2012, 2014 and 2009. According to the preliminary analysis results, in each principal component, the years affecting the large and small livestock populations are distinct. In addition, it should be pointed out that the livestock populations in different years represent a spatial variable, while the global PCA is a nonspatial analysis of the livestock populations. Therefore, the above results do not reflect the local structure of livestock populations in different years in each region, and further GWPCA is needed.

Because the eigenvalues of the first two principal components and the first principal component of the small and large livestock populations in the above global PCA are greater than unity, and CPTV were all greater than 90%, it is reasonable to keep the number of retained components as k = 2 and k = 1, respectively, in GWPCA. Then, the optimal bandwidth is bw = 72 and bw = 99. In the following calculations, all 21 components were retained for GWPCA; however, to correspond to the results of the PCA, only the first two component principal components of small livestock and the first principal component of large livestock were focused on the result output.

3.3. Geographically Weighted Principal Component Analysis

3.3.1. Proportion of Total Variance Data

The global CPTV of the first two principal components of the small livestock population is 94.54% (Table 1), which suggests that the changes in livestock populations in all regions are consistent, while the local CPTV range is between 93.23% and 96.45% (Figure 5), showing that the CPTV in different regions is different. It can be clearly seen that the local CPTV value in the central and western regions of IM is higher than the global CPTV value, while the local CPTV value in some central and eastern regions is lower than the global CPTV value. The global principal component variance of the first principal component for the large livestock population was 91.98%, and the local CPTV produced by GWPCA ranged from 88.47% to 92.49% (Figure 5). It is not difficult to see that in the entire IM, except for the central and eastern-south regions, the CPTV values are lower than the global CPTV. This further confirms the spatial non-stationarity of livestock population data.

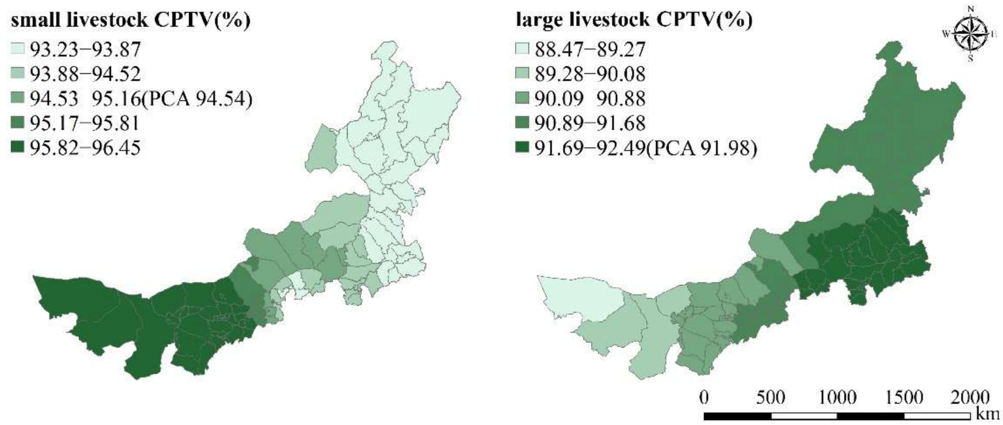

Figure 5. Cumulative proportion of total variance (CPTV) of geographically weighted principal component analysis (GWPCA) for small and large livestock population.

3.3.2. Loading Data

By visualizing the GWPCA loading data of the livestock population, the variable with the greatest local effect on the principal components, the winning variable can be found (Figure 6). For small livestock populations, the winning variables of GWPC1 are 2000–2004, 2007, 2008 and 2018, and those of GWPC2 are only 2000 and 2001. The winning variables for the GWPC1 of large livestock are 2002–2005, 2010, 2013, and 2016. It is not hard to see that the winning variables vary by region over this 21-year period.

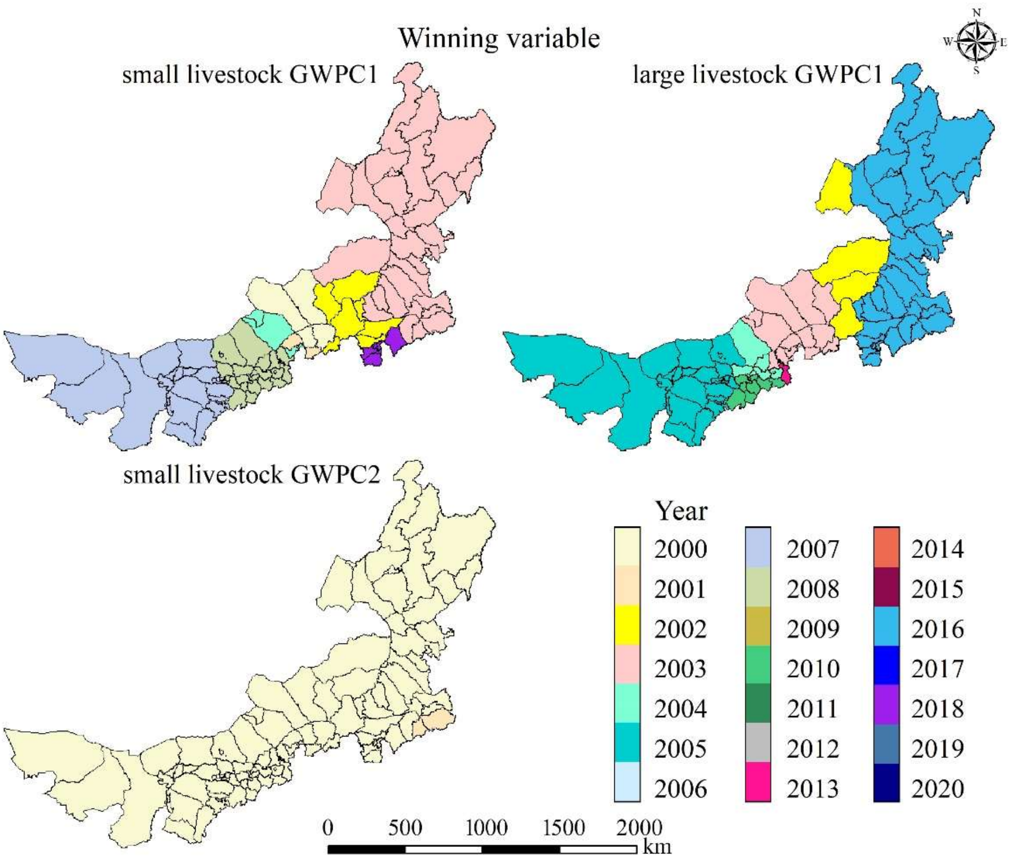

Figure 6. The winning variables of the GWPC1−2 of small livestock population (**left**) and GWPC1 of large livestock population (**right**).

Traditional winning variables cannot fully reveal the nature of spatial dependence between PCA indicators [61]. Therefore, using a distance-based hierarchical clustering method to analyze the loading data of GWPCA. As seen from Figure 7, clusters have strong continuity and present obvious east–west division. For small livestock GWPC1, IM is divided into three parts. Cluster 3 is in the central and western part of IM, and its mean loadings data the lowest point in 2007 and 2008 (Figure 8). Combined with the winning variables, it can also be seen that the corresponding region is mainly determined by these two years (Figure 6); the same is true for Cluster 2 and Cluster 1. Cluster 2 is mainly in the central and eastern IM, and its winning variable is 2003. Cluster 1 is dominated by 2000 in the central part of the IM, and it can be seen that the mean loading values of the corresponding clusters have reached the lowest point in both years. For small livestock GWPC2, the IM is mainly divided into two categories. Cluster 2 is mainly distributed in central IM, and Cluster 1 includes all other regions. The main dominant year and the minimum and maximum points of the mean loading value both occurred in 2000. For the large livestock GWPC1, the IM is divided into two parts with the Sonid Left banner and the Zhenglan banner as the boundary; Cluster 1 in the east and Cluster 2 in the west reach the lowest point in 2016 and 2005, respectively, and the winning variables of the corresponding regions are also dominated by these two years.

3.4. Relationship between Livestock Populations and Meteorological Disasters

Meteorological disasters occur frequently in IM, and different types and degrees of meteorological disasters occurred almost yearly during the study period (Supplementary Materials Table S1). Combining with the clustering results (Figure 7), we can know the occurrence of meteorological disasters in different clusters for the principal components of different livestock (Table 2). In addition, since there was no meteorological disaster in Cluster 3 in 2008, subsequent analysis was not performed.

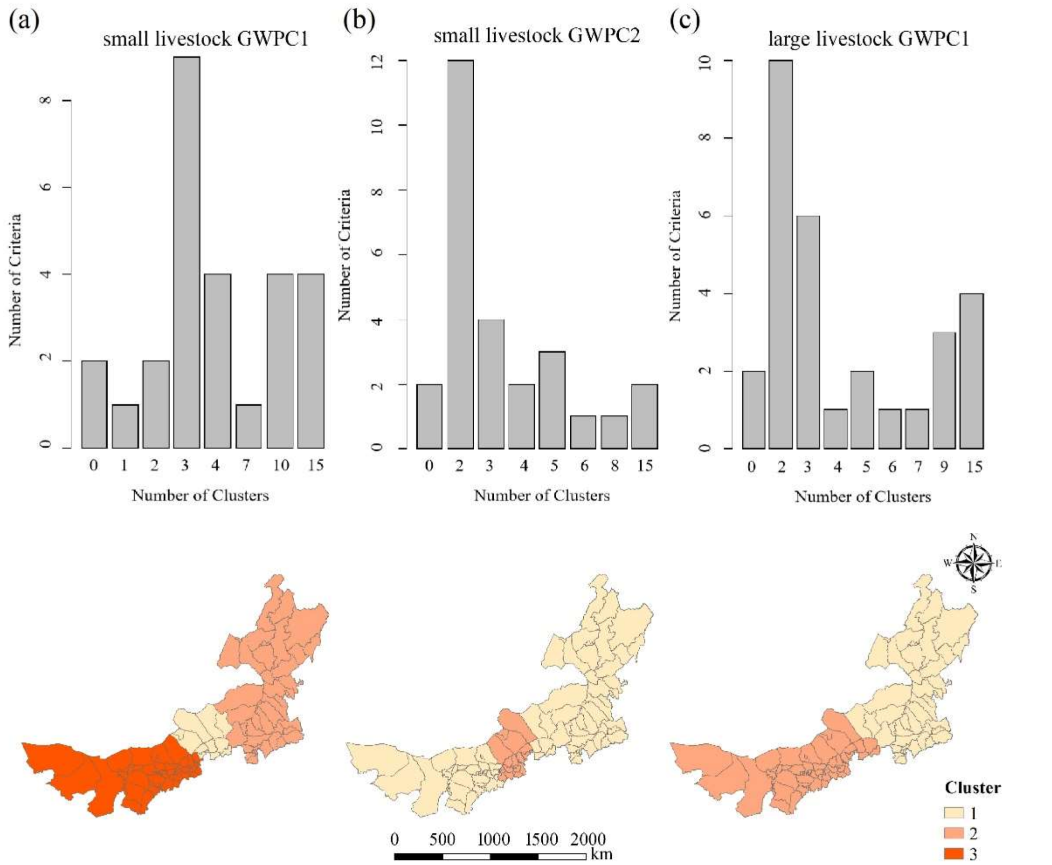

Figure 7. Optimal number of clusters and the distribution of clusters based on GWPCA loading. (**a**) small livestock GWPC1; (**b**) small livestock GWPC2 and (**c**) large livestock GWPC1.

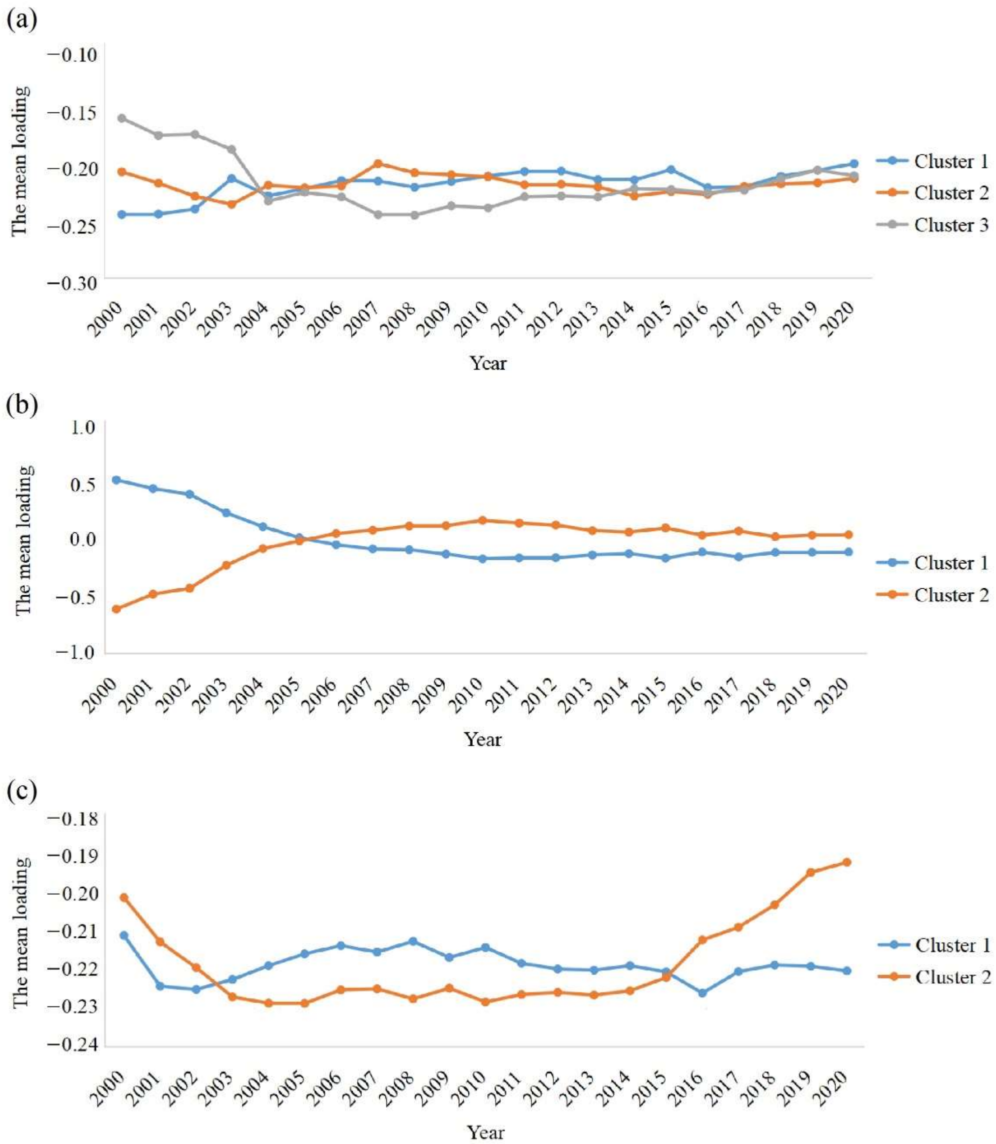

Figure 8. The mean values of GWPCA loading of clusters. (**a**) small livestock GWPC1; (**b**) small livestock GWPC2; (**c**) large livestock GWPC1.

Table 2. Occurrence of meteorological disasters for each cluster of small and large livestock.

	Small Livestock GWPC1				Small Livestock GWPC2		Large Livestock GWPC1	
Cluster	1	2	3		1	2	1	2
DY	2000	2003	2007	2008	2000	2000	2016	2005
D	√	√	√	×	√	√	√	√
SD	√	√	×	×	×	√	×	×

Note: DY—Dominant year; D—Drought; SD—Snow disaster; √—Indicating the occurrence of such meteorological disaster; ×—Indicating that no such meteorological disaster occurred.

For small livestock GWPC1, in the spring of 2000, light and moderate drought occurred in Cluster 1, and developed to moderate and severe drought in summer (Figure 9a,d), and SPEI was moderately negatively correlated with the population of small livestock in spring and summer (Figure 9g,j), indicating that the population of small livestock increased despite drought. At the same time, SWEI was in an abnormal wet and moderately wet period (Figure 10a), but there was almost no correlation between SWEI and the population of small livestock (Figure 10c), indicating that the impact of snow disaster was negligible compared with drought. In 2003, Cluster 2 suffered from light drought, even severe and extreme drought only in spring (Figure 9b), in which the SPEI in the western and northwestern Hulun Buir city was moderately positively correlated with the population of small livestock (Figure 9h), indicating that spring drought reduced the population of small livestock. In addition, most areas in winter are in abnormally dry to extreme drought periods (Figure 10b), and SWEI is less associated with small livestock population (Figure 10d), indicating that snow drought have no significant impact on the population of small livestock. In 2007, Cluster 3 had light drought and moderate drought in spring, and in summer the drought area expanded and severe drought appeared (Figure 9c,d). In the west of Ordos city, most of Bayannur city and Wuhai city, summer SPEI was moderately negatively correlated with the population of small livestock (Figure 9l), indicating that summer drought increased the population of small livestock in the above areas. However, there was a moderate positive correlation between summer SPEI and the population of small livestock in northwestern Hohhot city and southeastern Baotou city (Figure 9l), indicating that the population of small livestock in these areas decreased due to summer drought.

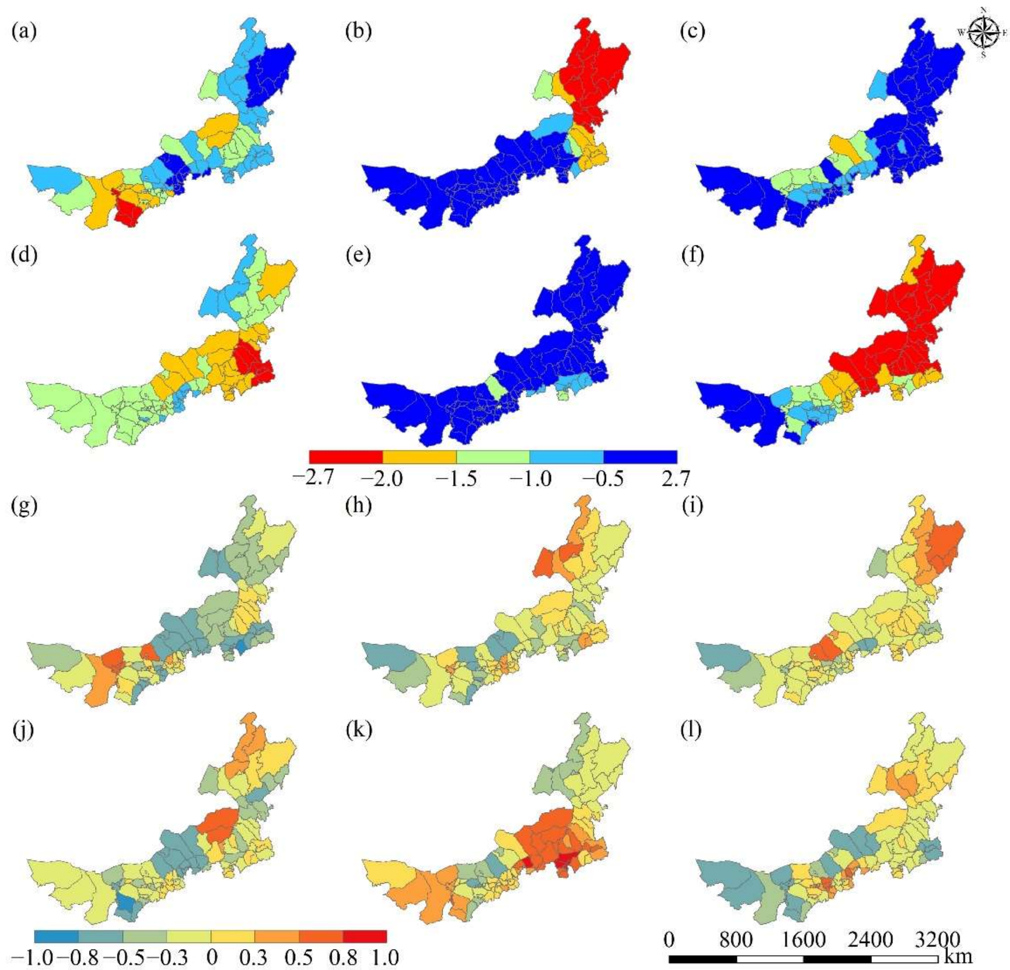

Figure 9. The distribution of SPEI in spring and summer of 2000, 2003, 2007 and the correlation between SPEI and small livestock population. (**a**–**c**) SPEI in spring of 2000, 2003 and 2007; (**d**–**f**) SPEI in summer of 2000, 2003 and 2007; (**g**–**i**) Correlation between SPEI and small livestock population in spring of 2000, 2003 and 2007; (**j**–**l**) Correlation between SPEI and small livestock population in summer of 2000, 2003 and 2007.

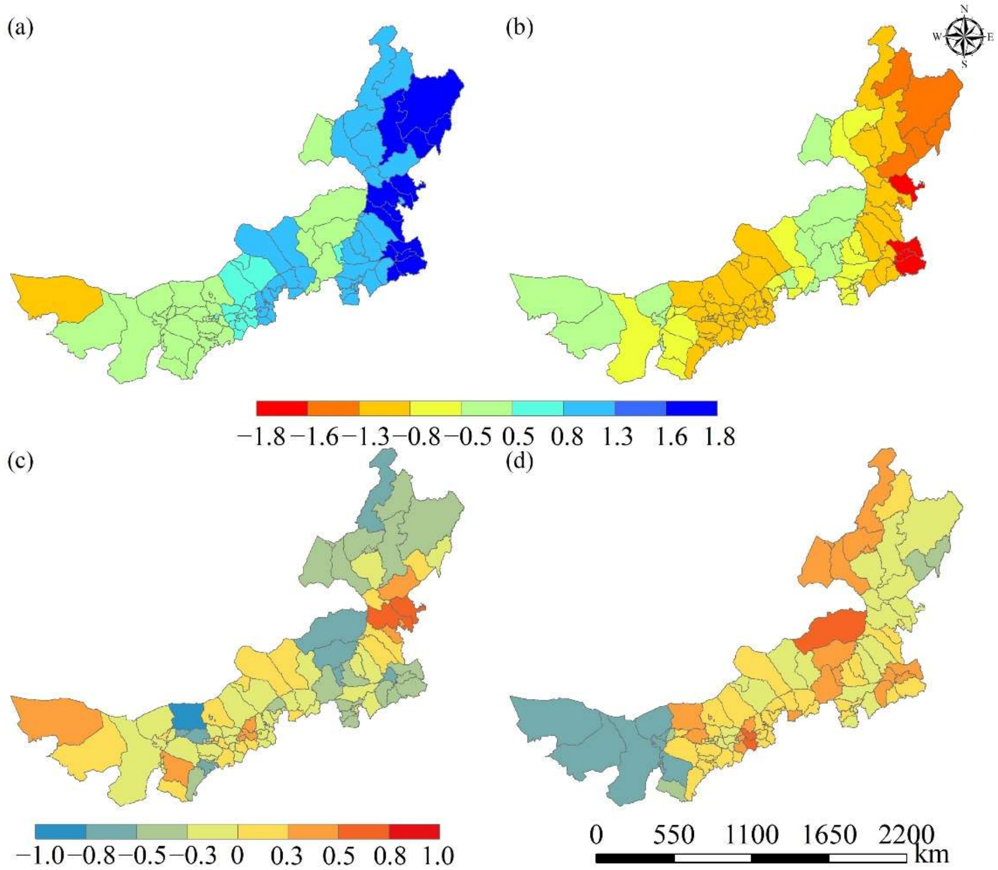

Figure 10. The distribution of SWEI in winter of 2000, 2003 and correlation between SWEI and small livestock population. (**a**,**b**) SWEI in winter of 2000 and 2003; (**c**,**d**) Correlation between SWEI and small livestock population in winter of 2000 and 2003.

For small livestock GWPC2, the leading year of Clusters 1 and 2 is 2000. In spring, severe drought and extreme drought occurred in the east of Alxa league, most of Bayannur city, Ordos city and Wuhai city (Figure 9a), among them, spring SPEI in the west of Bayannur city was moderately positively correlated with the population of small livestock (Figure 9g), indicating that drought promoted the decline of livestock in the above areas. Severe drought occurred in the east of Xilingol league. In summer, the drought area gradually expanded to Tongliao city, Chifeng city, Hinggan league and some areas of Hulun Buir city, and even developed into extreme drought (Figure 9d). Among them, the SPEI in the east of Xilingol league is moderately positively correlated with the population of small livestock in summer (Figure 9j), indicating that the drought in summer has led to a decline in the population of small livestock in the region. In addition, the SWEI in the middle and eastern IM is in a moderate or above wet spell except for some areas of Xilingol league, which is close to the normal level (Figure 10a). Among them, the SWEI in the middle and western and northeast of Hinggan league in winter is moderately positively correlated with the population of small livestock (Figure 10c), indicating that the snow disaster has promoted the increase in the population of small livestock. The SWEI in northern Hulun Buir city, eastern Xilingol league, northern Chifeng city and northwestern Tongliao city is moderately negatively correlated with the population of small livestock (Figure 10c), indicating that the snow disaster in this area has reduced the population of small livestock.

For GWPC1 of large livestock, Cluster 1 in spring of 2016, moderate and severe droughts occurred in Xilingol league, Tongliao city, Chifeng city and Hinggan league. In summer, the drought gradually moved northward to Hulun Buir city and developed into severe and extreme droughts (Figure 11c,d). Only in summer, the SPEI in the east of Xilingol league, the northwest of Tongliao city, and the central and southern parts of Hinggan league are moderately positively correlated with the population of large livestock (Figure 11h), indicating that the summer drought in the relevant areas reduces the population of large livestock. In addition, in the east and northeast of Hulun Buir city, the summer SPEI showed a moderate negative correlation with the population of large livestock, indicating that the summer drought increased the population of large livestock. In 2005, Cluster 2 had light and moderate drought in spring, and developed to moderate and above drought in summer (Figure 11a,b). There was a moderate and high negative correlation between SPEI and the population of large livestock in summer only in the south of Wuhai city and the west and south of Ordos city, which were the areas with severe and extreme drought in summer (Figure 11f). Indicating that drought increased the population of large livestock. Moderate and high positive correlations are found in most of Ulanqab city and the eastern part of Hohhot city (Figure 11e,f), which indicates that drought in spring and summer reduce the population of large livestock.

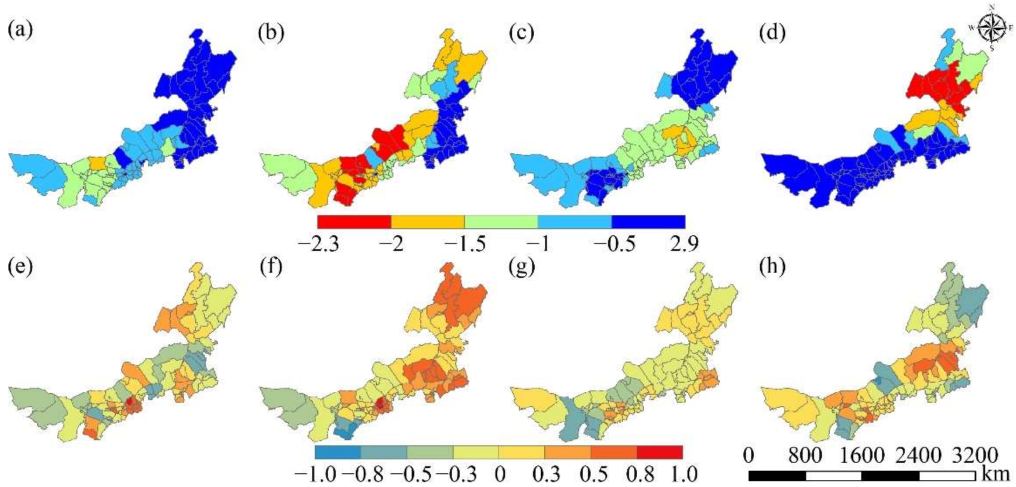

Figure 11. The distribution of SPEI in spring and summer of 2005, 2016 and the correlation between SPEI and large livestock population. (**a**,**b**) SPEI in spring and summer of 2005; (**c**,**d**) SPEI in spring and summer of 2016; (**e**,**f**) Correlation between SPEI and large livestock population in spring and summer of 2005; (**g**,**h**) Correlation between SPEI and large livestock population in spring and summer of 2016.

4. Discussion

The selection of bandwidth is very important for the application of GWPCA, and its size controls the influence of spatial scale on the analysis, so the results produced by different bandwidths may be different to some extent [23,62,63]. In this study, the number of retained components was determined a priori based on numerous current studies and then use the cross-validation method to determine the optimal adaptive bandwidth [30,51,56,61,64–67]. However, some studies have shown that this may not be the most ideal method and proposed a method to determine the bandwidth and retained components at the same time and applied different bandwidths to analyze the data, and the study shows that there are certain differences in the distribution of both PTV and winning variables [23].

Among the many meteorological disasters, droughts and snow disasters are considered to be the main threats to livestock production and the most important factors affecting livestock populations; even if this situation began to change after the pastoral reform, it still poses a significant threat to livestock populations [48,68–71]. We conclude that the effects of meteorological disasters on livestock populations are both positive and negative, which shows similarities with other studies. In general, the loss of livestock populations caused by disasters is a common phenomenon. Studies have shown that, due to the impact of meteorological disasters, the average annual mortality rate of livestock in the pastoral areas of IM is more than 5%, and the highest mortality rate is approximately 24% [72]. However, this is not completely the case. When drought occurs, the yield of forage decreases, and herdsmen will first choose to buy feed, which undoubtedly increases the cost of raising; therefore, herdsmen will retain their livestock and sell them after the market is stable, so the population of livestock on hand will increase after the drought [71]. When a snow disaster occurs, livestock graze less on plants, thus promoting the productivity of grassland and further increasing the population of livestock raised [73,74]. Thus, meteorological disasters not only directly cause livestock losses, but also indirectly affect livestock populations by affecting forage grass and so on. In addition, the impact of meteorological disasters has certain geographical differences, mainly due to the prevalence of drought in IM, the intensity of drought gradually increased from the east to the west, the western region is the main type of drought, while the main type of snow disaster in the east [75].

In addition to climate impacts, livestock populations are also affected by socioeconomic and policy impacts [76,77]. In general, the population of livestock in IM is generally more sensitive to weather conditions than economic conditions [76]. However, for Hohhot city, this study believes that socioeconomic factors have a greater impact on the characteristics of livestock population changes than climatic factors [78]. This may be due to the significant differences in the factors affecting animal husbandry at different spatial and temporal scales [79]. For cities with better economic development, such as Hohhot city, which are mainly urban industrial and mining areas and agricultural areas, they are highly intensive animal husbandry locations, and the response measures to meteorological disasters are relatively complete. Since 2000, several major national grassland protection programs have been implemented in IM, including the Beijing-Tianjin Wind/Sand Source Control Program since 2001 and the Grazing Withdrawal Program since 2003 [80]. More importantly, in 2011, a subsidy and reward mechanism for grassland ecological protection was promulgated; that is, subsidies were used to encourage people to control the population of livestock and reduce grazing intensity [81]. This subsidy and reward mechanism has different effects on the population of livestock in different regions, and in Xilingol league and Hulun Buir city, this effect is negative, but in Ulanqab and Ordos city, it is positive [82]. Meanwhile, the subsidy and reward mechanisms have no significant impact on large livestock but significantly reduce the total population of sheep and all livestock [37]. However, due to weak supervision or low subsidy amounts [69,83], the success of these policies is limited [71].

When severe climate changes such as droughts and snowstorms occur, there will be large fluctuations in the population of livestock [84]. Therefore, understanding the spatial and temporal characteristics of changes in livestock populations is critical for disaster response, sustainable management of grassland environments, and the impact of disasters [23]. In summary, this study has certain limitations and only considers the meteorological disaster factors that have a greater impact on the loss of livestock populations, while other factors also have certain effects. In addition, it only analyzes the data of large livestock and small livestock at the county level and does not subdivide it into datasets of horses, cattle, camels, donkeys, mules, goats and sheep. Next, we will explore more detailed datasets, and there may be some different findings.

5. Conclusions

In this paper, we use GWPCA to analyze the geographic data with a temporal index (year-end livestock population) and consider the impact of meteorological disasters. The results showed that, for small livestock GWPC1, spring–summer drought was the main disaster in Cluster 1 (Central IM), while Cluster 2s (Central and eastern IM) and 3 (Central and western IM) were spring and summer drought, respectively, and snow disaster can be ignored. For small livestock GWPC2, in Cluster 1 (except for a part of Central IM), mainly disasters were spring drought, summer drought and snow disaster, while Cluster 2 (Central IM) is spring–summer drought. However, for large livestock, in Cluster 1 (Central and eastern IM) and Cluster 2 (Central and western IM) were summer and spring–summer drought, respectively. Meanwhile, no matter whether for large livestock or small livestock, meteorological disasters have both advantages and disadvantages on the livestock population, and the drought types that have a greater impact on livestock are summer drought and spring–summer drought. Moreover, there are geographical differences in the impact of meteorological disasters, with drought affecting most of IM and snow disaster mainly affecting the eastern region. In addition, large livestock were mainly affected by drought, while small livestock were affected by both drought and snow disaster. In conclusion, GW-PCA can better explain the spatial variation of livestock populations. The study reiterated that different coping measures should be taken for different livestock types and regional differences should be taken into account when formulating disaster prevention strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi11100520/s1, Table S1: The occurrence of meteorological disasters in IM; Table S2: Drought classification of SPEI; Table S3: Classification of drought and wet spell based on SWEI.

Author Contributions: Conceptualization, Xiaohui Yang and Kebin Zhang; methodology, Xiaohui Yang, Yuanjun Zhu and Hui Bai; software, Hui Bai, Baizhu Wang and Semyung Kwon; validation, Xiaohui Yang, Baizhu Wang and Yuanjun Zhu; data curation, Hui Bai and Baizhu Wang; writing—original draft preparation, Hui Bai; writing—review and editing, Xiaohui Yang, Baizhu Wang and Yuanjun Zhu; visualization, Hui Bai, Baizhu Wang and Yuanjun Zhu; supervision, Xiaohui Yang and Kebin Zhang; funding acquisition, Xiaohui Yang. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by International (Regional) Cooperation and Exchange Program of The National Natural Science Foundation of China, grant number 32061123005 and National Natural Science Foundation of China, grant number 41971061.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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