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The Relationship between Hydrological Connectivity Changes Inside and Outside Biodiversity Hotspots and Its Implication for Sustainable Environmental Management

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Abstract: The conservation management of biodiversity hotspots is of vital significance for biological conservation. For wetlands, which are a special type of ecosystems that are based on water as their main medium, a decline in external hydrological connectivity often leads to wetland degradation inside biodiversity hotspots. In this context, the relationship between hydrological connectivity changes inside and outside hotspots is worth exploring. Based on the wetland biodiversity hotspots identified using systematic conservation planning, this study selected eight representative biodiversity hotspots with concentrated area. Integral index of connectivity, probability of connectivity (representing structural connectivity), and morphological spatial pattern analysis (representing functional connectivity) were used to analyze the hydrological connectivity changes inside various hotspots for 1995–2015. By taking the catchment area involved as the minimum basin perimeter, this study calculated the external hydrological connectivity changes of various hotspots during this period and analyzed the relationship between hydrological connectivity changes inside and outside of hotspots. The internal and external hydrological connectivity of wetland biodiversity hotspots were found to be significantly correlated. Moreover, the internal hydrological connectivity of hotspots not only declined with declining external structural connectivity, but also changed with the proportion of core wetlands, the proportion of edge wetlands, and the proportion of branch corridors. In addition, hotspots located at intersections of high-grade rivers were more significantly affected by climate change than by human activities and their hydrological connectivity increased with increasing rainfall. The internal hydrological connectivity of hotspots near low-grade rivers presented a declining trend, mainly because of human activities. This study clarified the relationship between internal and external hydrological connectivity of wetland biodiversity hotspots. Targeted internal and external control strategies are proposed, with the aim to offer references for the conservation of wetland biodiversity.

Keywords: integral index of connectivity (IIC); morphological spatial pattern analysis (MSPA); probability of connectivity (PC); wetland management

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1. Introduction

Wetlands are essential ecosystems for the maintenance of biodiversity. With the acceleration of agricultural reclamation and urbanization, a series of ecological problems related to wetlands (such as a sharp drop in area, serious fragmentation, biodiversity loss, and service function degradation) have emerged. These pose considerable threats to regional ecological security, grain security, and sustainable socioeconomic development [1–3]. Efforts have been made by many studies to identify biodiversity hotspots and construct priority conservation networks, expecting to conserve remaining wetland ecosystems. However, the fragmentation of wetland ecosystems caused by improper land use not only reduces regional integral landscape connectivity, but also induces gradual wetland degradation inside conservation areas and biodiversity hotspots because of changes in hydrological regimes. In this sense, the conservation management of wetland biodiversity should not only focus on the internal hydrological connectivity of hotspots, but also consider the relationship between hydrological connectivity changes inside and outside hotspots. Thus, the areas outside hotspots can be properly controlled and the decline in external hydrological connectivity causing internal wetland degradation can be prevented.

Hydrological connectivity refers to the transport of materials, energy, and organisms mediated by water within or between hydrological cycle elements [4]. Wetland ecosystem management in a certain range is an important application to understand hydrological connectivity, which has been interpreted and measured by researchers [5]. Structurally, hydrological connectivity of wetland can be defined as the connectivity of wetland patches and the habitat accessibility of wetland species [6]. Functionally, different landscape types have different ecological meanings in terms of hydrological connectivity. For example, the core wetland is a large habitat patch, which plays the role of ecological source in the wetland connectivity function. The edge wetland refers to the transition zone between the core wetland and non-water area, which often has the characteristics of rich material and energy exchange. Bridges, branches, and loops play a similar role as ecological corridors [7]. Currently, large-scale, high-intensity land use changes have already reduced hydrological structural connectivity in many wetland biodiversity hotspots or conservation areas [8]. This has resulted in declined wetland hydrological connectivity and a degradation of wetland ecological functions [9]. In particular, the decline in hydrological connectivity weakens the biodiversity maintenance function of wetlands, a function that is of great concern [10,11]. The declining wetland landscape connectivity also changes hydrological quality [12,13] and further deepens the trend of gradual wetland degradation of conservation areas and biodiversity hotspots. Existing studies have shown that surface hydrological connectivity has potential ecological effects, such as maintaining biodiversity and ecological integrity, providing ecological diffusion channels, offering nutrients through biological-geographical-chemical processes, and transporting substance and energy downstream [14–18]. Hydrological connectivity and pattern changes caused by climate change and human interferences also exert significant effects on avian diversity in wetlands [19,20]. Thus, it is necessary to adopt hydrological connectivity as an important index for wetland conservation and monitoring. In any region, water has its own source and path, and interfering with the path water in a region takes may affect the hydrological state of the entire region. In this sense, the relationship between the internal and external hydrological connectivity of wetland biodiversity hotspots or conservation areas should become the center of focus. This enables targeted control strategies both inside and outside hotspots with the goal to better maintain wetland hydrological connectivity and guarantee normal ecological functions.

The quantification of hydrological connectivity constitutes the basis for evaluating the hydrological patterns of wetland biodiversity hotspots. To that end, many methods are available, including in situ monitoring, hydrological models, connectivity functions, graph theory, and remote sensing [21–24]. Two indexes that have combined graph theory and habitat availability, i.e., integral index of connectivity (IIC) and probability of connectivity index (PC), can express both the structural quantification of connectivity and the quantification of habitat functions. They are ideal indexes for quantifying connectivity related to species habitats on regional scales. However, morphological spatial pattern analysis (MSPA) classifies the foreground pixels of raster binary images into seven mutex types, namely, core, islet, edge, perforation, bridge, loop, and branch. Based on the definitions and characteristics of different landscape classes, it is possible to judge their significance as wetland connectivity indexes [7,25], thus giving a satisfactory description of connectivity in terms of wetland functions. Structurally and functionally, both types of connectivity offer sound quantitative indexes for the measurement of wetland hydrological connectivity, enabling convenient description and analysis of the internal and external hydrological connectivity of wetland biodiversity hotspots.

Starting with the management of wetland biodiversity hotspots, this study analyzed the trends of hydrological connectivity changes in biodiversity hotspots, identified the effect of external hydrological connectivity on internal connectivity, and proposed targeted control strategies. By identifying the multi-year changing trend of the internal hydrological connectivity of multiple wetland biodiversity hotspots on the mesoscale, hydrological connectivity changes of biodiversity hotspots with different spatial characteristics were examined. Moreover, the relationship between hydrological connectivity changes inside and outside of wetland biodiversity hotspots (the minimum basin) were clarified. Based on this, targeted conservation and management strategies were proposed for areas both inside and outside wetland biodiversity hotspots.

2. Overview of the Study Area

Sanjiang Plain, located in the east of Heilongjiang Province, is the largest freshwater swamp distribution area in China. Its geographical coordinates are 43°49′55″–48°27′40″ N and 129°11′20″–135°05′26″ E (Figure 1). Sanjiang Plain is rich in wetland biodiversity resources. It is the biodiversity hotspot designated by the Ministry of Environmental Protection of China and is known as the "unique gene bank of wildlife". However, after more than half a century of development, Sanjiang Plain has also become the largest commercial grain base in China. Excessive agricultural reclamation and the destruction of the natural environment have led to many ecological and environmental problems.

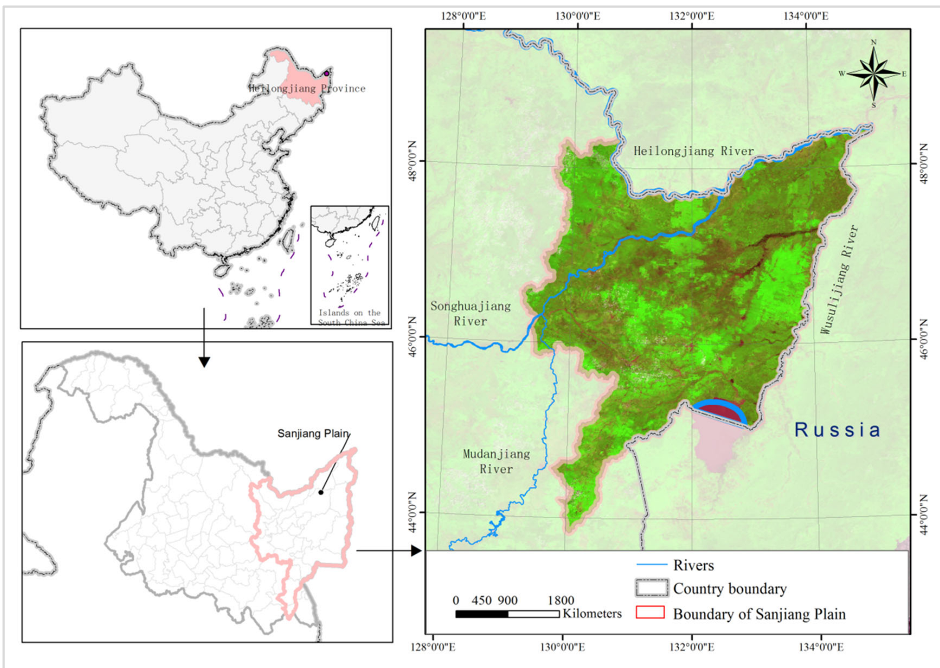

Figure 1. Location map of the study area.

3. Research Methods

In this study, we selected eight hotspots identified by systematic conservation planning (SCP) in the Sanjiang Plain wetlands in 1995. The normalized difference water index (NDWI) was used in combination to interpret remote sensing images and extract the distribution scope of wetlands inside and outside of hotspots. Connectivity indexes (IIC and PC) and MSPA models were employed to analyze the changing trend of the internal hydrological connectivity of hotspots for 1995–2015. The catchment area was taken as the minimum basin to calculate the external hydrological connectivity of hotspots, explore the effects of external structural and functional hydrological connectivity on the internal hydrological connectivity of hotspots, and clarify the relationship between hydrological connectivity changes inside and outside of hotspots.

3.1. Identification of Biodiversity Hotspots

We used our previous results of biodiversity hotspots as the study objects (Qu et al., 2019). These biodiversity hotspots were identified using SCP, a method widely adopted for biodiversity conservation [26,27]. This method consists of three steps: selection and spatial distribution prediction of representative biodiversity features, setting the conservation target of representative features, and determining biodiversity conservation values through calculating irreplaceability (IRR). First, a total of 93 representative biodiversity features were selected from the study area, including 78 representative species, 9 key ecosystems, and 6 key ecological processes. China Red Data Book of Endangered Animals, China Species Red List, and other literature about corresponding species [28–31] were referenced for the spatial description of species habitat preferences, ecosystems, and ecological processes. Then, the potential spatial distribution of each representative biodiversity feature was simulated (or extracted) based on wetland vegetation type distribution data, soil data, and digital elevation model (DEM). The conservation target of each representative biodiversity feature (difined as the percentage to be conserved in the potential spatial distribution) was set by exponential interpolation. Features with distribution areas larger than 10,000 km^2 were assigned a target of 15% based on the requirement of the Convention on Biological Diversity and features with distribution areas smaller than 7.8 km^2, the minimum variable area for a key species in the region to avoid habitat deficiency, were assigned a target of 100%. The other intermediate-range restoration features were assigned targets exponentially interpolated between the above two thresholds [32]. To make the targets practical, they were revised by a local expert based on his experince on endangerment category, conservation priority, and habitat rarity. Finally, rasters 1 km $\times$ 1 km in size were adopted as planning units, and C-Plan conservation planning software was employed to calculate the IRR of each planning unit using SCP. Thus, the importance of each planning unit for realizing the overall conservation target could be expressed. SCP values are continuous values within a range of 0–1. Larger SCP values mean that the planning unit concerned has a higher conservation value, and that the number of other planning units that can replace this planning unit for accomplishing the conservation target is smaller [33,34]. To analyze the hydrological connectivity changes of biodiversity hotspots in different locations, biodiversity hotspots with concentrated area and different spatial characteristics from the study area were selected. These were used as sampling sites for analyzing the internal/external hydrological connectivity changes of hotspots and their influencing factors.

3.2. Relationship between Hydrological Connectivity and Pattern Changes Inside and Outside of Biodiversity Hotspots

3.2.1. Extraction of Wetland Distribution Based on NDWI

Wetlands inside and outside of biodiversity hotspots were identified by remote sensing interpretation. Landsat5 TM data were used to provide remote sensing images. With the experiences of experts, the geometric shapes, color characteristics, texture characteristics, and spatial distribution of ground features were analysed to build the interpretation standards. Water content distribution was simulated using NDWI for wetland distribution verification. NDWI was calculated according to green and near-infrared (NIR) bands combining with field survey data on water content. Finally, raster data on land use were acquired through interpretation, and the quality of data products was assessed through combining field survey with repeated interpretation of randomly selected dynamic map spots.

3.2.2. Changing Trends of Hydrological Connectivity Inside Biodiversity Hotspots

Wetland structural connectivity was evaluated using IIC and PC, and wetland functional connectivity was evaluated using the MSPA indexes. IIC and PC are connectivity indexes created based on habitat availability (Pascual-Hortal and Saura 2006; Saura and Pascual-Hortal 2007a, Saura and Pascual-Hortal 2007b). They were used to represent the IIC and PC between various nodes of the study area within a certain threshold range. To ensure comparability between the calculation results of IIC and PC, the probability of connectivity was set to 0.5 (Saura and Pascual-Hortal 2007b). IIC and PC indexes were calculated using Conefor26 software according to the following formula:

$$\mathrm{IIC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}}{A_L^2} \quad \mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}^{*} \times a_i \times a_j}{A_L^2}$$

where n denotes the total number of core wetland patches in the study area; a_i and a_j denote the areas of core wetland patches i and j, respectively; nl_{ij} denotes the number of connections between core wetland patches i and j; A_L denotes the total area of core wetland patches in the study area; p^{*}_{ij} denotes the maximum product of all path probabilities between core wetland patches i and j. IIC and PC values have the same range of 0–1, where a larger value means better connectivity.

In the MSPA model, there are seven indexes for representing functional connectivity of wetlands: core, edge, branch, bridge, loop, islet, and perforation [7,25]. Core wetlands are large habitat patches in foreground wetlands, which play the role of ecological sources in terms of wetland connectivity functions. Shrinkage and fragmentation of core wetlands often lead to a decline in connectivity. Edge wetlands are transition zones between core wetlands and non-water areas, which are often characterized by frequent rich substance and energy exchange. Branches, bridges, and loops all play corridor-like roles in terms of wetland connectivity functions. Specifically, a bridge is the channel connecting two different core patches. A branch is the connection between a core wetland and another wetland type, and a channel for species diffusion and energy exchange between a core patch and its peripheral hydrological landscape. A loop is the shortcut for connection inside core wetlands that contributes to their internal connectivity. In general, branch, bridge, and loop wetlands can be ranked in descending order of their contribution to hydrological connectivity as follows: bridge wetlands > branch wetlands > loop wetlands. Islet wetlands are interconnected small patches that often exist in the form of separate small puddles or ponds in the wetland landscape. The possibility of substance and energy exchange between islet wetlands and the outside world is low. Perforation wetlands are the edge zones of core wetlands, which, to a certain extent, obstruct the internal connectivity of core wetlands.

3.2.3. Relationship between Hydrological Connectivity and Pattern Changes Inside and Outside of Biodiversity Hotspots

Analysis was performed to explore how the internal hydrological connectivity of wetland biodiversity hotspots was related to their external structural connectivity (IIC and PC) and functional connectivity (MSPA indexes). The connectivity indexes of eight biodiversity hotspots in 1995, 2000, 2005, 2010, and 2015 were calculated, including internal connectivity indexes (IIC, PC, CORE, ISLET, PERFORATION, EDGE, LOOP, BRIDGE, and BRANCH) and external connectivity indexes (IICe, PCe, COREe, ISLETe, PERFORATIONe, EDGEe, LOOPe, BRIDGeE, and BRANCHe).

Correlation coefficients between internal structural hydrological connectivity (IIC and PC) and external connectivity indexes (IICe, PCe, COREe, ISLETe, PERFORATIONe, EDGEe, LOOPe, BRIDGeE, and BRANCHe) were calculated. Thus, the relationships between internal structural connectivity and external structural connectivity and functional connectivity were determined. Furthermore, correlation coefficients between internal functional hydrological connectivity (CORE, ISLET, PERFORATION, EDGE, LOOP, BRIDGE, and BRANCH) and external connectivity indexes (IICe, PCe, COREe, ISLETe, PERFORATIONe, EDGEe, LOOPe, BRIDGeE, and BRANCHe) were calculated. Thus, the relationships between internal functional connectivity and external structural connectivity and functional connectivity were determined. IIC and PC were calculated using Conefor26 [35–37]. CORE, ISLET, PERFORATION, EDGE, LOOP, BRIDGE, and BRANCH were calculated using GuidosToolbox2.9 [25]. Correlation between indexes was analyzed in R [38]. Analysis was intended to identify whether the decline in the external hydrological connectivity of a biodiversity hotspot would affect its internal hydrological connectivity and further compromise its ecological functions.

4. Results

4.1. Identification of Biodiversity Hotspots

To analyze the internal hydrological connectivity changes of biodiversity hotspots in the study area, this study used the spatial pattern of biodiversity conservation values in 1995 as basis for identifying biodiversity hotspots. The spatial pattern of the biodiversity conservation values (IRR) of the Sanjiang Plain wetlands in 1995 was calculated using SCP, as shown in Figure 2. IRR values have a range of 0–1, where a larger IRR value means a higher biodiversity conservation value and vice versa. Biodiversity hotspots with concentrated area and different spatial characteristics were selected from the study area as sampling sites for analyzing the internal hydrological connectivity changes of hotspots and their influencing factors. Eight sampling sites were selected: two located at the intersection between a first-grade river and a second-grade river (bio3 and bio4), two distributed along a first-grade river at different distances from the source (bio1 and bio2), two distributed along a second-grade river at different distances from the source (bio7 and bio8), and two located at the end of a third or lower-grade river (bio5 and bio6). The external area of each sampling site was the catchment area involved, which served as the distribution scope of the basin where the hotspot is located.

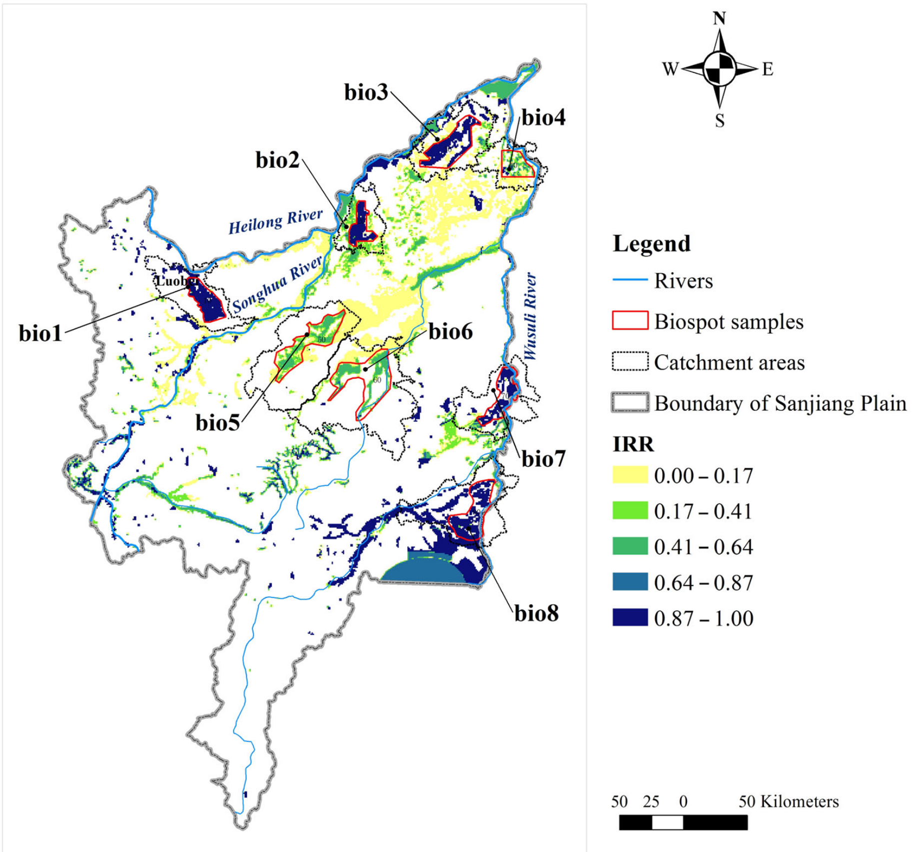

Figure 2. Spatial pattern of biodiversity conservation values and distribution of sample plots for analyzing the hydrological connectivity of biodiversity hotspots.

4.2. Changing Trends of Hydrological Connectivity Inside Biodiversity Hotspots

The distance threshold is the critical value for the distance between two patches with connection within the selected scope. If the distance between two patches exceeds the distance threshold, they are unconnected. If the distance threshold is greater, the connectivity indexes calculated will also be greater. IIC and PC express the structural connectivity of the wetland distribution. Studies have shown that in 1995–2015, the wetlands in the major biodiversity hotspots of the Sanjiang Plain had an IIC of above 0.5 (i.e., 0.5–0.7 in three hotspots and above 0.7 in all other hotspots), suggesting that most biodiversity hotspots have sound internal integral connectivity. Judging from temporal changes, biodiversity hotspots in different spatial locations presented different change laws (Figure 3). To be specific, the internal wetland hydrological connectivity of biodiversity hotspots located at the intersection between a first-grade river and a second-grade river presented a trend of declining first and rising afterwards, peaking in 2015. By contrast, the internal wetland hydrological connectivity of hotspots at other locations changed little in 1995–2010, but fluctuated abruptly in 2010–2015, showing declining trends of different amplitudes. The changing trend of PC was basically consistent with that of IIC.

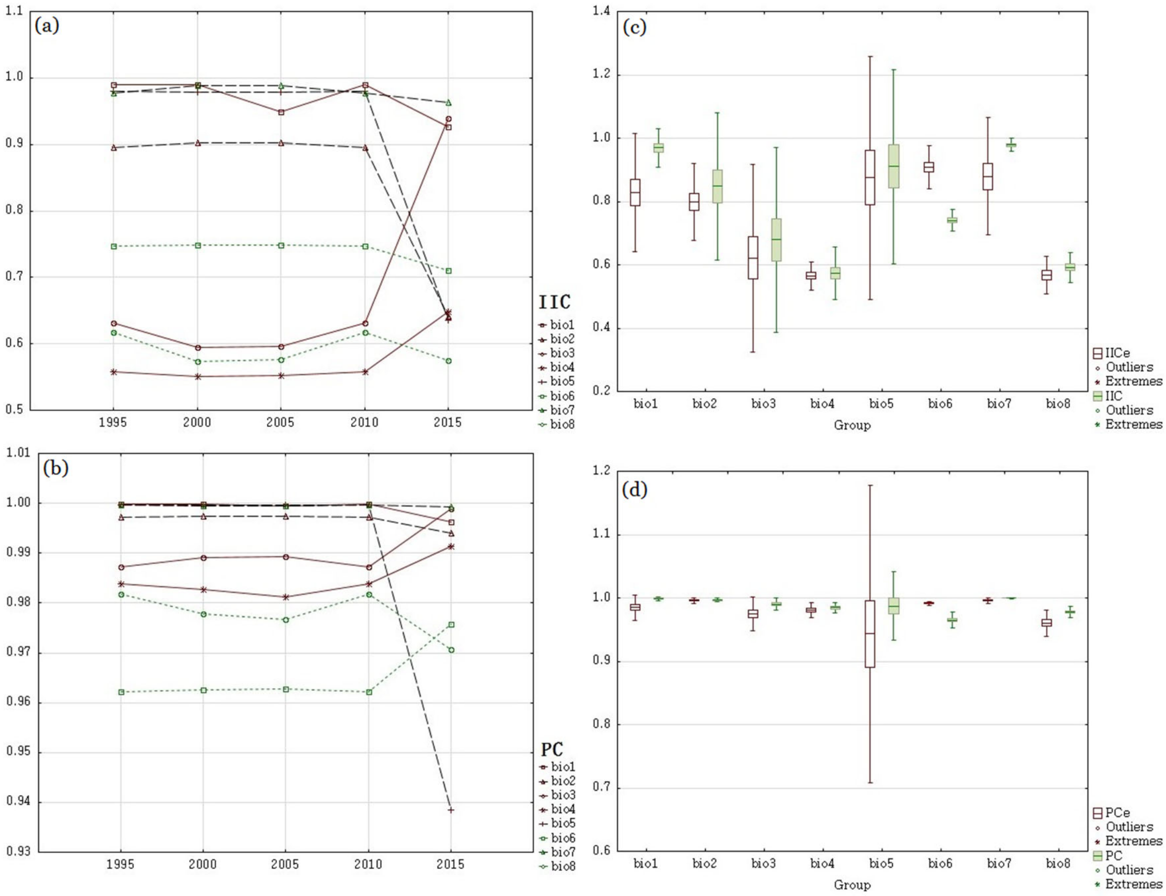

Figure 3. Wetland IIC and PC changes inside hotspots in 1995–2015 (IIC variation in each hotspot (**a**); comparison of IIC numerical values inside and outside each hotspot (**c**); PC variation in each hotspot (**b**); comparison of PC numerical values inside and outside each hotspot (**d**).

MSPA analysis identified the changes in the functional type of the internal wetland hydrological connectivity of various biodiversity hotspots in 1995–2015, as shown in Figure 4.

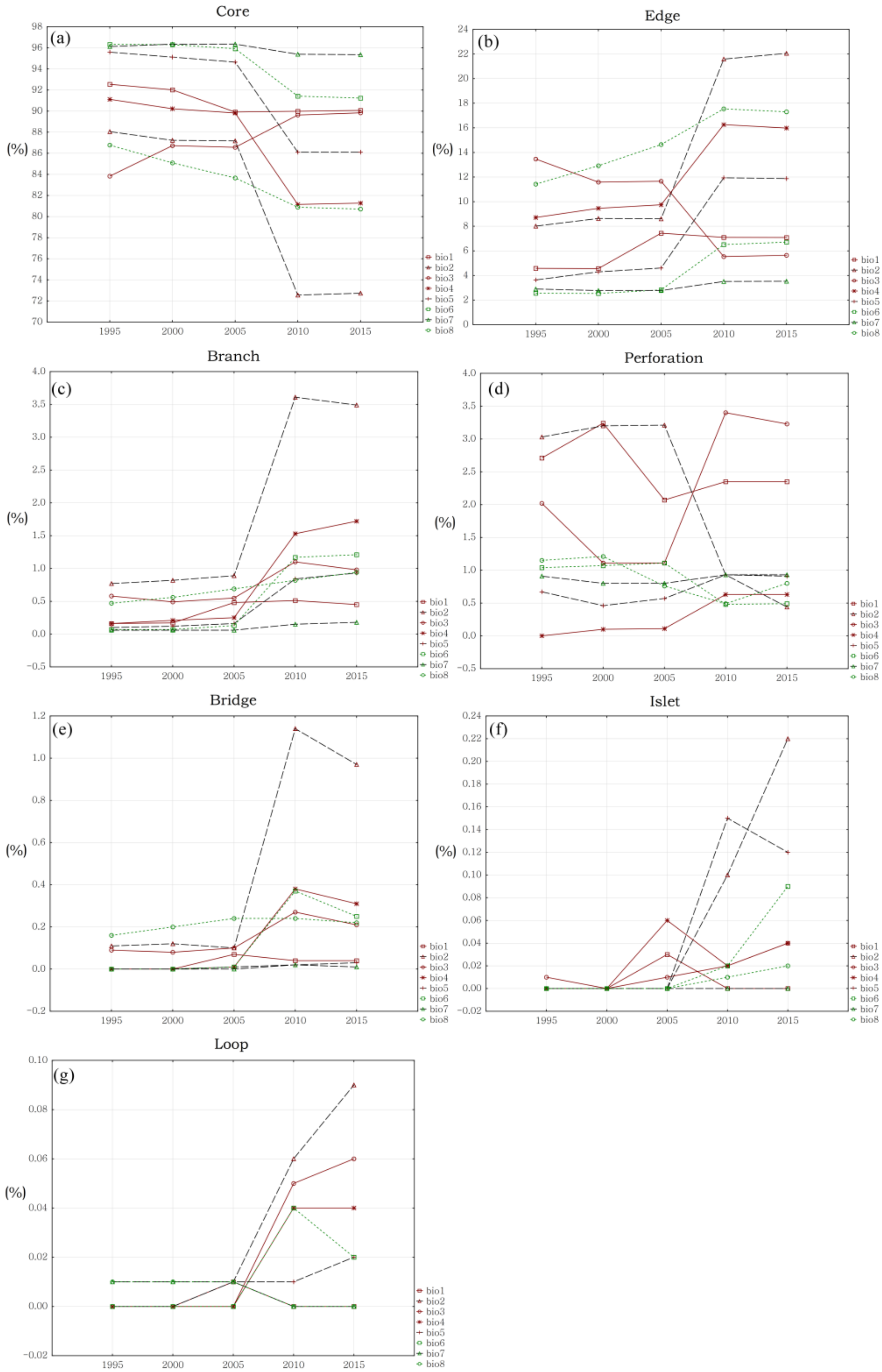

Figure 4. Wetland hydrological connectivity (morphological spatial pattern analysis (MSPA)) changes inside hotspots in 1995–2015. These functional hydrological connectivity indexes include Core (**a**), Edge (**b**), Branch (**c**), Perforation (**d**), Bridge (**e**), Islet (**f**), Loop (**g**).

The results (Figure 4a,b) indicated that, in 1990–2015, a declining trend was observed in the proportion of core wetlands in foreground wetlands in all hotspots except for hotspot bio3 (where a rising trend was observed); a rising trend was observed in the proportion of edge wetlands in foreground wetlands in all hotspots except for hotspot bio3 (where a declining trend was observed). Overall, the distribution of core wetlands and edge wetlands indicated that the core wetlands in most biodiversity hotspots of the Sanjiang Plain presented a trend of gradual fragmentation in 1990–2015. In combination with the changes in IIC and PC, core wetland changes had a dominant effect on hydrological connectivity.

Branch wetlands clearly accounted for a large proportion (0.00–3.60%) in all five stages under investigation, followed by bridge wetlands (0.00–1.15%) in the second place, while loop wetlands occupied the smallest proportion (0.00–0.09%). In 1995–2015, the proportions of the three types of wetland corridors in foreground wetlands presented basically the same changing trend, i.e., sharp increase in 2005 and increase at a reduced amplitude after 2010. In the background of a continuous decrease in core wetlands in these two decades, branch wetlands presented a rising trend in all hotspots except for bio3 and bio1. Bridge wetlands showed a trend of rising first and declining afterwards. Loop wetlands presented a rising trend in all hotspots except for bio6 (where they declined after 2010). This clarified that core wetlands basically degraded into edge wetlands and wetland corridors over the degradation process. The proportion of wetland corridors increased in most hotspots, but this increase failed to increase the internal connectivity of these hotspots, mainly because of the dominant effect of core wetlands (Figure 4c,e,g).

In 1995–2015, the proportion of islet wetlands increased in most hotspots but at an extremely small amplitude, except in bio2 and bio5, where it fluctuated considerably in 2005–2015. The largest amplitude of increase in the proportion of islet wetlands was 0.22%, and the effect of such increase on the internal wetland hydrological connectivity of hotspots was non-significant. In 1995–2015, the proportion of perforation wetlands increased in half of the biodiversity hotspots, and decreased in the other half. The amplitude of increase in the proportion of perforation wetlands was 1.35% at the maximum (bio3), and less than 1.00% in other hotspots (Figure 3f,g).

4.3. Relationship between Hydrological Connectivity Changes Inside and Outside of Biodiversity Hotspots

4.3.1. Effects of External Hydrological Connectivity on Internal Structural Hydrological Connectivity

(1) Effect of external structural hydrological connectivity on internal structural hydrological connectivity

The correlation coefficients between internal structural hydrological connectivity (IIC and PC) and external structural hydrological connectivity (IICe and PCe) (Figure 5) indicated that the internal integral connectivity (IIC) and external integral connectivity (IICe) of hotspots were significantly correlated ($R_{IIC,IICe} = 0.790$, $p < 0.01$); furthermore, the internal PC and external PC (PCe) of hotspots were significantly correlated ($R_{PC,PCe} = 0.670$, $p < 0.01$). The correlation between internal IIC and PC and external IICe and PCe of hotspots indicated that the internal wetland hydrological connectivity of a biodiversity hotspot was affected by the integral structural hydrological connectivity of the basin where the biodiversity hotspot is located; moreover, higher external structural connectivity meant higher internal hydrological connectivity and vice versa.

(2) Effect of external functional hydrological connectivity on internal structural hydrological connectivity

The correlation coefficients between internal structural hydrological connectivity (IIC and PC) and external functional hydrological connectivity (COREe, ISLETe, PERFORATIONe, EDGEe, LOOPe, BRIDGEe, and BRANCHe) (Figure 5) indicated that the internal integral connectivity (IIC) of hotspots was highly correlated with the proportion of external core wetlands (COREe), the proportion of edge wetlands (EDGEe), and the proportion of perforation wetlands (PERFORATIONe) ($R_{IIC,COREe} = 0.412$, $p < 0.01$; $R_{IIC,EDGEe} = -0.531$, $p < 0.01$; $R_{IIC,PERFORATIONe} = 0.487$, $p < 0.01$). None of the external functional hydrological connectivity index was significantly correlated with internal PC at the level of 0.01. The correlation between the internal IIC and PC and external functional hydrological connectivity indexes of hotspots indicated that the internal wetland hydrological connectivity of a biodiversity hotspot was affected by the integral functional hydrological connectivity of the basin where the biodiversity hotspot is located; a higher proportion of external core wetlands and a lower proportion of edge wetlands meant higher internal hydrological connectivity and vice versa.

Figure 5. Correlation between internal structural hydrological connectivity (IIC and PC) and external hydrological connectivity of hotspots.

4.3.2. Effects of External Hydrological Connectivity on Internal Functional Hydrological Connectivity

(1) Effect of external structural hydrological connectivity on internal functional hydrological connectivity

The correlation coefficients between internal functional hydrological connectivity (CORE, ISLET, PERFORATION, EDGE, LOOP, BRIDGE, and BRANCH) and external structural hydrological connectivity (IICe and PCe) (Figure 6) indicated that the proportion of core wetlands as ecological sources (CORE) and the proportion of edge wetlands with frequent rich substance and energy exchange were significantly correlated with integral connectivity (IICe) of the basin where the hotspot is located ($R_{CORE,IICe} = 0.615$, $p < 0.01$; $R_{EDGE,IICe} = -0.707$, $p < 0.01$). This indicated that the internal functional hydrological connectivity of biodiversity hotspots was affected by their external integral structural connectivity.

(2) Effect of external functional hydrological connectivity on internal functional hydrological connectivity

The correlation coefficients between internal functional hydrological connectivity (CORE, ISLET, PERFORATION, EDGE, LOOP, BRIDGE, and BRANCH) and external functional hydrological connectivity (COREe, ISLETe, PERFORATIONe, EDGEe, LOOPe, BRIDGEe, and BRANCHe) is shown in Figure 6. The results indicate that the internal functional hydrological connectivity indexes of biodiversity hotspots were all significantly correlated with external functional hydrological connectivity indexes. In particular, the proportion of external core wetlands (COREe) and the proportion of edge wetlands (EDGEe) significantly affected the proportion of internal core wetlands (CORE); moreover, the proportion of external branch corridors (BRANCHe) significantly affected the proportion of internal branch corridors (BRANCH) ($p < 0.01$). This indicated that the internal functional hydrological connectivity of biodiversity hotspots was also affected by their external functional connectivity.

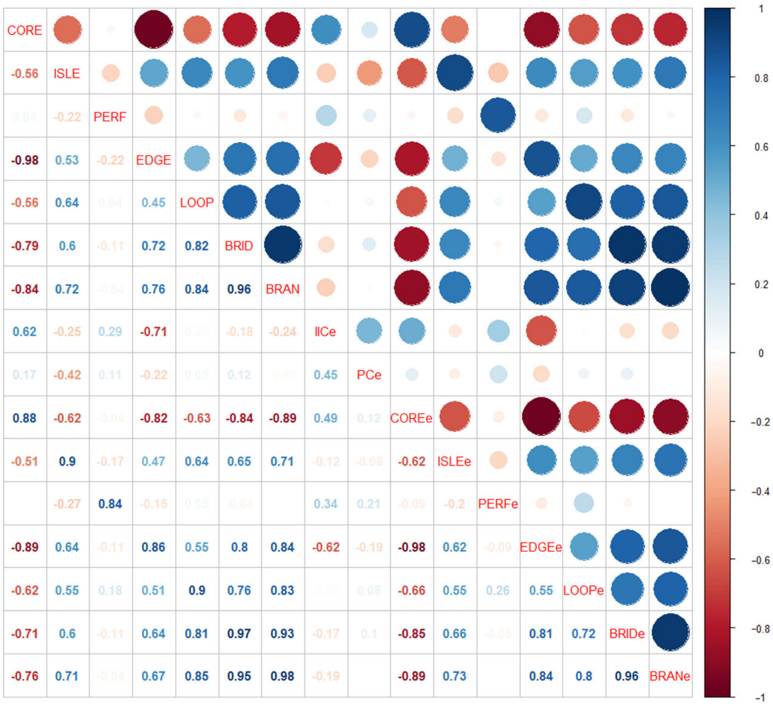

Figure 6. Correlation between internal functional hydrological connectivity (MSPA indexes) and external hydrological connectivity of hotspots.

5. Discussions

In this study, the internal hydrological connectivity changes of eight wetland biodiversity hotspots in 1995–2015 were explored using IIC and PC (structural connectivity) and MSPA (functional connectivity). Taking the catchment area involved as the minimum basin perimeter, this study analyzed the relationship between hydrological connectivity changes inside and outside hotspots. It was confirmed that the internal and external hydrological connectivity of wetland biodiversity hotspots were significantly correlated. Furthermore, the internal hydrological connectivity of hotspots not only declined with declining external structural connectivity, but also changed with the proportion of core wetlands, the proportion of edge wetlands, and the proportion of branch corridors. The wetlands in each biodiversity hotspot have undergone destruction of varying degrees. The loss ratio of core wetlands ranges from 1% to 14% in different hotspots. Most of the lost wetlands have been transferred to farmland, and a small amount have been converted to built-up areas. With the fragmentation of the core wetlands, the proportion of edge wetlands and branch corridors increases, and the ecological function of the wetlands degraded. If the situation is not controlled in time, with the continuous shrinking of area and the breaking of links, the core wetlands will lose their original function completely.

Judging from the internal hydrological connectivity changes of different hotspots, most hotspots in the study area presented a declining trend to varying extents in terms of both structural and functional connectivity. Further analysis indicated that the decline in hydrological connectivity was mainly attributable to climate change and human activities such as hydraulic engineering and land use [9,39,40].

Hotspots in different locations showed different patterns of hydrological connectivity changes. Hydrological connectivity gradually declined in most hotspots but began to rise in 2005 in several hotspots (bio3 and bio4, located at the intersection between a first-grade river and a second-grade river). An analysis of the rainfall and land use change of the area where bio3 and bio4 are located in 2005–2015 showed that rainfall increased and the connectivity of wetland decreased (caused by farmland occupation) year by year after 2005 [41,42]. The increase of structural hydrological connectivity index in bio3 and bio4 indicated that the internal hydrological connectivity changes of biodiversity hotspots located at the intersections of high-grade rivers or near the source were more significantly affected by climate change than by human activities. Comparing bio3 and bio4 in terms of the proportion of core wetlands showed that the proportion of core wetlands increased in bio3 but decreased in bio4. The changing trend of bio4 was contrary to that of structural hydrological connectivity index IIC, which is possibly because the wetland fragmentation process of bio4 was dispersed at small distances. The proportion of core wetlands decreased, but because of the effect of the threshold on IIC results [6], the connectivity between separated core wetlands would still present a rising trend if the distance between them did not exceed the threshold. Other hotspots were all greatly affected by human activities, because core wetlands changed into edge wetlands and branch corridors. Lastly, bio5 and bio6 were most significantly affected by human activities. Over the two investigated decades, the proportion of core wetlands in bio5 decreased by 10%. These core wetlands basically all degraded into edge wetlands, which played a connective role in the change into wetland corridors. Similarly, bio6 (located at the end of a fourth-grade river) experienced only a slight decline in structural and functional connectivity, mainly because of protection by conservation areas.

Judging from the relationship between the internal and external hydrological connectivity of hotspots, the external hydrological connectivity (the basin where the hotspot is located) of hotspots significantly affected their internal structural hydrological connectivity (IIC) and functional hydrological connectivity (COREe, EDGEe and, BRANCHe). IIC was significantly correlated with IICe, the proportion of external core wetlands, and the proportion of edge wetlands. Based on the descriptive statistics of the internal and external structural connectivity indexes of various hotspots (Figure 3c,d), external structural connectivity was lower than internal structural connectivity in most hotspots. This suggested that the decline in the structural connectivity of the basin where the hotspot is located likely causes a decline in the internal structural and functional connectivity of the hotspot. This conclusion is consistent with the conclusion of a prior study about the internal effect of land use changes on conservation areas on the basin scale [43].

Based on the internal hydrological connectivity changes of biodiversity hotspots in the study area and their relationship with external hydrological connectivity changes, different conservation management measures should be taken inside and outside of wetland biodiversity hotspots (the basin where the hotspot is located). First, depending on their current integral hydrological connectivity, hotspots should be classified into hotspots in need of urgent restoration (0–0.5), hotspots in need of general restoration (0.5–0.7), and hotspots in need of maintenance (0.7–1.00). Second, hotspots classified as hotspots in need of urgent or general restoration should be put under strict conservation without encroaching upon wetland resources in any form. Moreover, wetlands in basins where the hotspot is located should also be placed under restrictive control. For instance, the proportion of core wetlands in the basin should be no lower than 20% (this proportion is roughly the proportion of core wetlands in the external basin when the external integral connectivity of the hotspot is 0.7). Furthermore, restoration measures should be taken in cases where this requirement is not satisfied. For core wetlands outside the hotspot above the distance threshold, it is necessary to restore their hydrological state and vegetation state with core wetlands inside the hotspot, increase the area of core wetlands, and reduce the area of edge wetlands. For islets outside the hotspot above the distance threshold, the area of core wetlands and islets should be expanded through artificial interventions according to their distances away from adjacent core wetlands (with due consideration to restoration costs and islet values). Thus, their distances can be controlled within the threshold.

Wetland hydrological connectivity provides the basis for wetland ecosystems to function normally and constitutes the key to maintaining biodiversity. The efficient conservation of wetland biodiversity hotspots requires not only the internal hydrological connectivity of hotspots but also the external hydrological connectivity of hotspots, both structurally and functionally. The conservation management of wetland biodiversity hotspots located within basins of different grades, at different distances away from the source, or with different land use characteristics, should be customized with a focus on their specific characteristics. This study clarified the relationship between the internal and external hydrological connectivity of wetland biodiversity hotspots, offered scientific references for the effective conservation and management of wetland biodiversity hotspots in the future, and enables the prevention of the decline of external connectivity from causing the internal degradation of hotspots.

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