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Dynamic Changes of Nitrogen Loads in Source–Sink Landscapes under Urbanization

Yanmin Li [1], Jianxiong Tang [2] and Shenghui Cui [3,4,5,*]

[1] School of Geomatics, Anhui University of Science and Technology, Huainan 232001, China
[2] Xiamen Municipal Natural Resources and Planning Bureau, Xiamen 361021, China
[3] Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[4] Xiamen Key Lab of Urban Metabolism, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[5] University of Chinese Academy of Sciences, Beijing 100000, China
* Correspondence: shcui@iue.ac.cn

Abstract: The dynamic changes of nitrogen (N) loads have been significantly impacted by the rapid expansion of many cities, potentially escalating the risk of N pollution in cities. However, the spatiotemporal changes of N loads in source and sink landscapes remain unclear in urbanization. In this research, we used source–sink landscape theory to identify the source–sink landscape in the process of N flow at the city scale and investigated the spatiotemporal changes of N loads in the source–sink landscape from 2005 to 2015 in Xiamen, a rapidly urbanizing city in southern China. The total N loads of source landscapes increased by 2 times between 2005 and 2015, with an average annual growth of 26%, while the total N loads of sink landscapes climbed gradually, with an average annual increase of 8%, according to our findings. Moreover, in terms of the spatial gradient, the N loads of the source landscape fluctuated downward and reached their peak in the urban center, whereas the N loads of the sink landscape tended to rise and reached their peak outside of the city. Our findings offered a fresh viewpoint on the source–sink landscape in N flows at the city scale and offered useful guidance for N spatial management to support sustainable city development.

Keywords: nitrogen loads; spatiotemporal change; source–sink landscape; urbanization; spatial gradient

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1. Introduction

Urbanization noticeably impacts the biochemical cycle of nitrogen (N) at a city scale [1–3]. Furthermore, the source and sink landscapes of cities also are greatly altered by urban expansion [4]. Due to the high concentration of people and socioeconomic activities that occurs in cities, cities have become hotspots of global N pollution [5]. The increasing N loads in the environment result in city ecosystem degradation (e.g., the greenhouse effect, ozone layer destruction, acid rain, eutrophication and biodiversity reduction) and damage to human health [6–9]. N management of cites is a critical part of Sustainable Development Goals and ecological environmental development [10]. Thus, clarifying the dynamic changes of N loads in source–sink landscapes are the key to reduce and manage N pollution in cities effectively.

Source–sink landscapes are defined as the origin and retention, respectively, of an object or substance [11–14]. Source and sink landscapes have different roles in ecological process [15]. The source promotes the progression of ecological processes, while the sink delays this progression [16]. Some researchers have defined and studied the source and sink landscapes in different processes and scales, including the carbon cycle [17], the urban heat island effect [18] and air pollution [19]. However, the source and sink have different significances in different research fields [20], and few researchers have clearly identified the source–sink landscape in the N flowing process. Furthermore, the spatial characteristics of N loads in source and sink landscapes are still unclear.

Cities, with higher population densities and fossil fuel consumption, are hot spots of N pollutants, resulting in environment pollution and public health impacts [5]. Previous studies on N flows and N loads at the city scale have achieved considerable achievements [21–23]. These studies have primarily clarified the human activity changes and the spatial distribution of N loads [24,25]. However, most of them selected the smallest administrative districts as their cases, while ignoring spatial gradient characteristics analysis at the city scale. In recent years, numerous cities throughout the world have proceeded with unprecedented rapid and large-scale urbanization and expansion [26], changing the source–sink landscapes of cities along the spatial gradient, thereby affecting the circulation of nutrients at the spatial gradient [27–29]. Furthermore, these changes have interfered with terrestrial ecosystems and changed the N biochemical cycle [30,31]. However, the linkage between urban expansion and the N loads in source–sink landscapes, along a spatial gradient, remains unclear. Therefore, exploring the dynamic characteristics of N loads along a spatial gradient at the city scale is more significant.

Based on the source–sink landscape theory and N loads analysis method, this study proposes a new perspective to identify the source and sink landscapes in the N flowing process and comprehensively analyze the dynamic characteristics of N loads along a spatial gradient, taking Xiamen as an example from 2005 to 2015. The main research objects are as follows: (1) identifying the source and sink landscapes in the N flowing process using a novel perspective; (2) revealing the spatiotemporal dynamics of source and sink landscapes; (3) investigating the spatiotemporal characteristics of N loads caused by the dynamic changes of source and sink landscapes.

2. Materials and Methods

2.1. Study Area

Xiamen (24°26′46″ N, 118°04′04″ E) is recognized as a typical coastal city, as well as a designated special economic zone, in southeastern China (Figure 1). Over the past forty years, Xiamen's booming economy and rapid urbanization have remarkably altered its land use distribution. Notably, from 2005 to 2015, the per capita annual income surged from 16402.75 to 42606.62 yuan, the urbanization rate of Xiamen increased from 62.7% to 81.3% and the construction area grew by 2.5 times [32]. Xiamen is surrounded by mountains on the north, decreasing in altitude to a loess plateau on the south. Xiamen Island is located in the southwestern part of Xiamen. It is a highly urbanized area and is the center of the local economy (e.g., manufacturing and high-tech industries), culture and education. The urban expansion triggered the loss of farmland and caused environmental deterioration [33,34]. The rapid urbanization has expanded from Xiamen Island to outward, southwesterly.

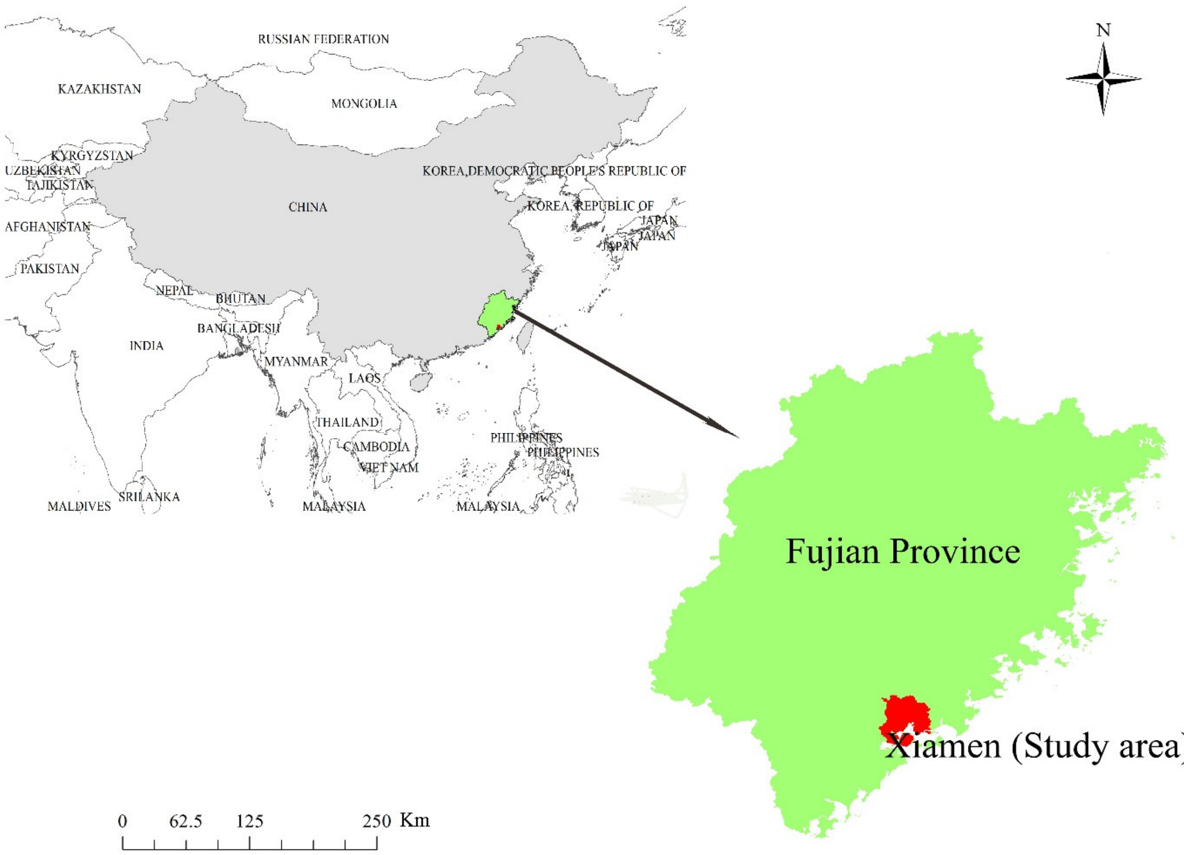

Figure 1. Study area.

2.2. Data Sources

The data required for this study can be divided into three categories: socioeconomic data, N flowing parameters and geospatial data. The data sources consisted mainly of government statistical yearbooks, published literature, survey data and the website of the Resource and Environmental Science and Data Center (https://www.resdc.cn/data.aspx?DATAID=335 (accessed on 6 August 2022)) The details are shown in Figure 2. Socioeconomic data can be obtained from the official statistical bureaus in Xiamen for 2005 to 2015. The land use data of Xiamen originated from Landsat-8 TM/ETM remote sensing images (30 × 30 m) in 2005, 2010 and 2015. The remote sensing land images were artificially interpreted and classified into 7 types of land use (cropland, forest, greenbelts and parks, urban residential areas, rural residential areas, traffic land and industrial land). Specific to the calculation of the N loads, the parameters of the N flowing came from our surveys and the existing literature.

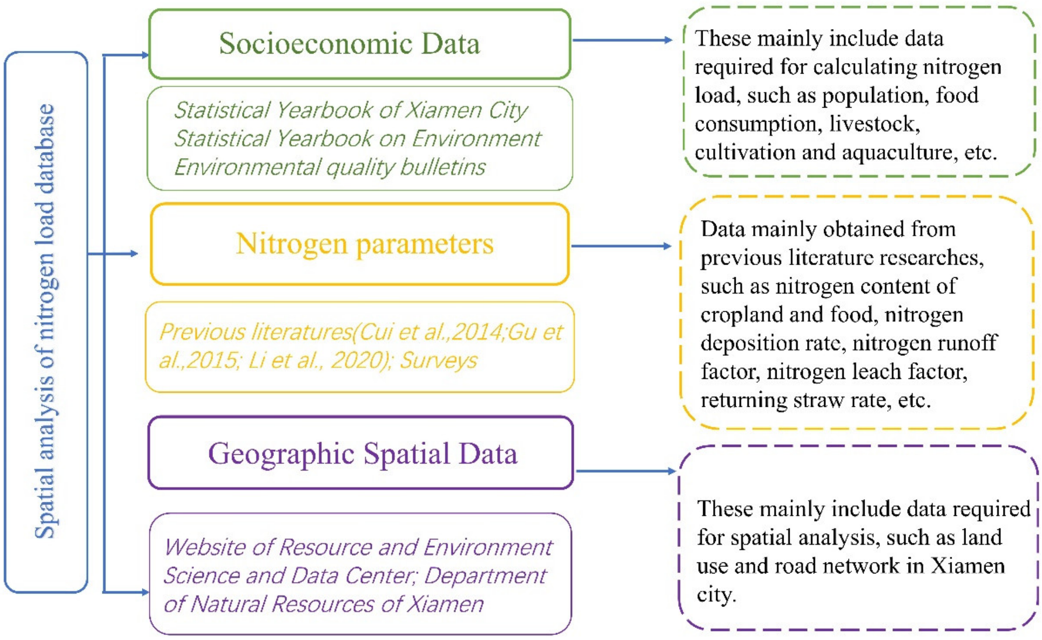

Figure 2. Construction of the spatial analysis of the nitrogen loads database.

3. Methodology

3.1. Source–Sink Landscape Identification in the N Flowing Process

In 2003, the source–sink theory was introduced into landscape ecology, and the source–sink landscape theory was constructed [16]. The source–sink landscape theory can better integrate landscape type, area and spatial location and the impact of the landscape on ecological processes. According to source–sink landscape theory, in the process of N flowing, the source landscape can promote the progression of N emissions, while a sink landscape is a type that prevents or delays the progression of N loss. As an acceleration of urbanization, landscape types turn out to be more complex, affecting the N flowing process and ecological functions in cities [27]. Source and sink landscapes play different roles in the functions of the N flow and either negatively or positively affect the environment at the city level.

Combining mechanisms of N flows with source–sink landscape theory, the source and sink landscapes are identified in this study. The source landscape refers to a landscape type that can promote the N flowing process, and seriously impacts the air, water and soil [35]. For instance, cropland landscape has high-intensity fertilizer inputs that result in considerable N runoff and leaching. Residential land, traffic land and industrial land are significantly positively related to human activities that can cause tremendous N pollution (e.g., air pollution, sewage and garbage). Therefore, cropland, residential land, industrial land and traffic land are identified as source landscapes in the N flowing process of a city. Conversely, sink landscape refers to a landscape type that inhibits the N flow process and delays N loss. For instance, existing reviews have examined the mechanism of N uptake, assimilation and transport, and the N utilization of plants growing in the soil, identifying areas with these functions as sinks [36–38]. Forests and greenbelts can retain N and delay N loss, and are therefore identified as sink landscapes in the N flowing process of a city.

3.2. Calculation of N Loads

This study calculated the N loads in 2005, 2010 and 2015, based on the material flow analysis (MFA) method, which is the widely accepted N budget accounting framework and methodology, N sources and sinks under the framework (Figure 3) are estimated [7,39,40]. It is worth noting that the N loads of the source landscape refers to parts of N emissions (including gases N and liquid N), while the N loads of sink landscape refers to parts of N retention. Therefore, in order to distinguish the different N loads between sources and sinks, when calculating N loads, the N loads value of sink landscapes was defined as a negative value, and its size was compared by absolute value rules, while the N loads value of source landscapes was defined as a positive value. The formula of estimating the number of N loads is given below, and the N parameters involved are shown in the Supplementary Information (**SI**).

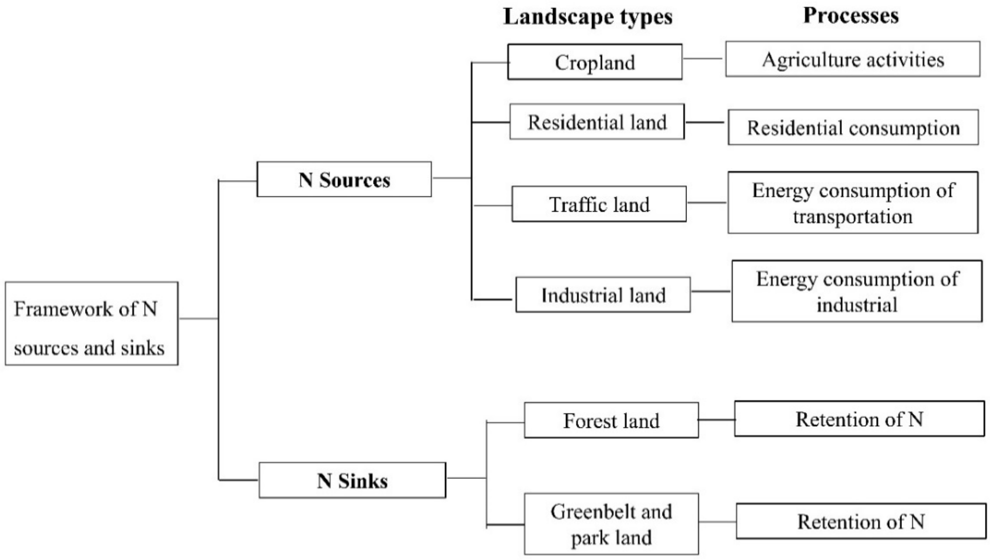

Figure 3. Accounting framework for N sources and sinks.

(1) Cropland

$$C_{input} = C_{fertilizer} + C_{BNF} + C_{deposition} + C_{straw} + C_{seed} + C_{irrigation} + C_{manure} \quad (1)$$

$$C_{output} = C_{harvest} + C_{denitrification} + C_{leach} + C_{runoff} + C_{NH_3} \quad (2)$$

In Equations (1) and (2), C_{input} and C_{output} respectively denote the total N input and output in the cropland landscape; $C_{fertilizer}$ denotes the N fertilizer input in agricultural production;C_{BNF} is the biological N fixation; $C_{deposition}$ is the N deposition in cropland; C_{straw} is the straw returned to the field; C_{seed} refers to the seeds in agricultural production; $C_{irrigation}$ is the irrigation water input to agricultural production; C_{manure} refers to the animal and human feces returned to the field; $C_{harvest}$ is a crop product; $C_{denitrification}$ refers to denitrification during cropland production, including N_2 and N_2O; C_{leach} and C_{runoff} denotes Nr leaching from cropland and N runoff from cropland; C_{NH3} is ammonia volatilization from fertilizer and manure in cropland production. The specific calculation formulas and parameters are presented in the **SI** (Tables S1 and S2).

(2) Forest

$$F_{input} = F_{BNF} + F_{deposition} + F_{litter} \quad (3)$$

$$F_{output} = F_{denitrification} + F_{run\ off} \quad (4)$$

$$F_{retention} = F_{input} - F_{output} \quad (5)$$

In Equations (3)–(5), F_{input}, F_{output} and $F_{retention}$ denote the total N input, output and N retention in the forest landscape, respectively; F_{BNF} denotes the biological N fixation in the forest; $F_{deposition}$ expresses the N deposition in the forest; F_{litter} denotes litter returned to the forest; $F_{denitrification}$ refer denitrification of the forest, including N_2 and N_2O; F_{runoff} is the N runoff from the forest. The specific calculation formulas and parameters are presented in the **SI**.

(3) Greenbelt and park

$$G_{input} = G_{BNF} + G_{deposition} + G_{pet\text{-}excreta} + G_{fertilizer} + G_{irrigation} \quad (6)$$

$$G_{output} = G_{runoff} + G_{N_2O} + G_{N_2} + G_{NH_3} \quad (7)$$

$$G_{retention} = G_{input} - G_{output} \quad (8)$$

In Equation (6)–(8), G_{input}, G_{output} and $G_{retention}$ denote the total N input, output and retention in the greenbelt and park landscape, respectively; $G_{fertilizer}$ represents the N fertilizer input to the greenbelts and parks; C_{BNF} expresses the biological N fixation; $G_{deposition}$ is the N deposition in greenbelts and parks; $G_{pet\text{-}excreta}$ denotes the excreta of domestic pets; G_{N2O} denotes the N_2O emitted during denitrification; G_{N2} denotes the N_2 emitted during denitrification; G_{NH3} is the NH_3 volatilities during the fertilization process; G_{runoff} represents the N runoff from the greenbelt and park lawns. The **SI** (Tables S1 and S2) presents the specific calculation formulas and parameters.

(4) Residential

$$R_{output} = R_{garbage} + R_{sewage} + R_{energy\text{-}consumption} \quad (9)$$

In Equation (9), R_{output} denotes the total N output from the residential landscape; $R_{garbage}$ denotes the waste generated by residents; R_{sewage} represents the sewage generated by residents; $R_{energy\text{-}consumption}$ expresses the energy consumption of households, which generates considerable NOx and N_2O in residential areas. Detailed calculation formulas and parameters are illustrated in the **SI** (Tables S1 and S2).

(5) Traffic

$$T_{output} = T_{N_2O} + T_{NO_X} + T_{NH_3} \quad (10)$$

In Equation (10), T_{output} expresses the total N output in the traffic land; T_{N2O} represents the N_2O emitted by the consumption of fossil energy; T_{NOX} expresses the NOx emitted by the consumption of fossil energy; and T_{NH3} is the NH_3 emissions. The **SI** (Tables S1–S6) illustrates the detailed calculation formulas and parameters.

(6) Industrial

$$I_{output} = I_{NO_X} + I_{N_2O} + I_{sewage} \quad (11)$$

In Equation (11), I_{output} denotes the total N output from the industrial landscape; I_{NOX} represents the NOx emitted by the consumption of fossil energy in industrial processes; I_{N2O} represents the N_2O emitted by the consumption of fossil energy in industrial processes; I_{sewage} expresses the industrial sewage. The data for industrial N emissions directly originate from the compilation of environmental statistics (2005, 2010 and 2015) of the Xiamen Environment Bureau.

3.3. Spatial Gradient Analysis

Existing studies have used spatial gradient analysis to quantify spatial patterns of urbanization [41]. The evolution of cities has often resulted in concentric morphologies in many Chinese cities [42,43]. To examine the spatial gradient characteristics exhibited by landscapes and N load values in cities with concentric development patterns from the urban center to the fringe, GIS-based concentric buffer zones were built from the city development core along a spatial gradient (Figure 4). The buffer zone was clipped into 50 concentric areas, covering the entire area of Xiamen. The outward radiation distance between any two contiguous buffer zones was 1 km to avoid spatial autocorrelation. The number of buffer zones differed for each area. Lastly, 50 buffer zones were taken to calculate the source–sink landscapes and their N loads. This method improved the calculation accuracy of the spatial gradient characteristics of source–sink landscapes and their N loads.

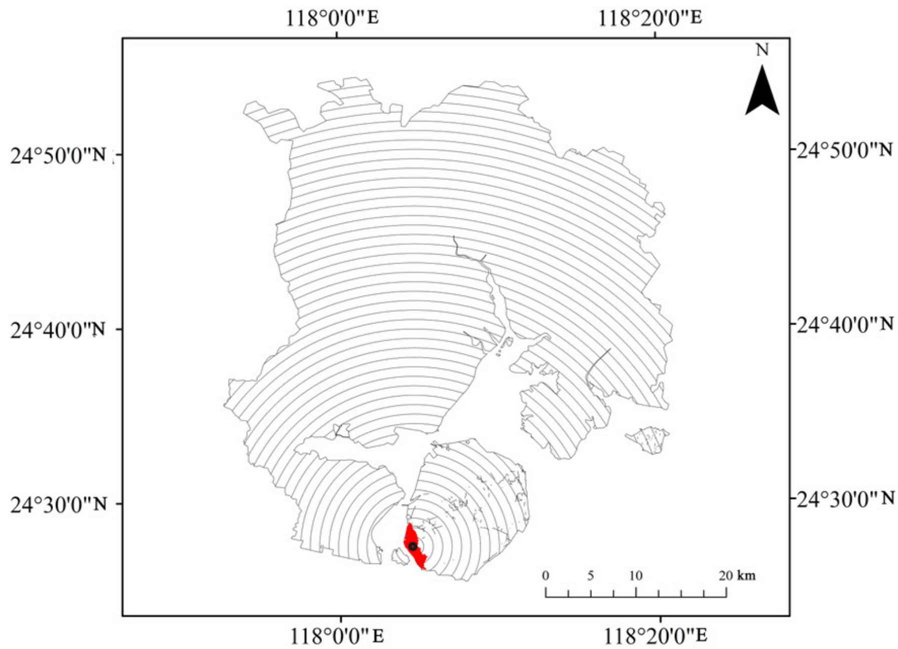

Figure 4. Study area and buffer zone construction.

4. Results

4.1. Changes in Landscape along the Spatial Gradient

From 2005 to 2015, urbanization was being expedited, and the total area of source landscapes (cropland, rural residential land, urban residential land, industrial land, traffic land) in 2015 exceeded that in 2005 (Figure 5). It is clear that cropland and forest land have been the dominant type of land change in the decades in Xiamen. By the spatial distribution of urban sprawl, the total area of the source landscape tended to fluctuate, although its peaks were concentrated at 20 km and 31 km away from the urban center. The total area of the sink landscape also fluctuated, reaching its peak at 43 km from the urban center.

Different landscape types present different characteristics along the spatial gradient; specifically, the built-up landscape covered the area in the inner 25 km of the urban core, while the forest and cropland landscapes progressively increased in the land 18 km and more away from the urban center. Moreover, the traffic land and residential landscapes continued to expand to the periphery of urban areas, and witnessed the most dramatic expansion of urban land. This may be largely due to well-developed infrastructure and a favorable economic foundation. Generally, the characteristics of landscape change in Xiamen can be summarized as follows: (1) cropland and residential land were the major source landscapes of urban expansion throughout the last several decades; (2) forest land is the major sink landscape which is concentrated at the edge of the urban areas.

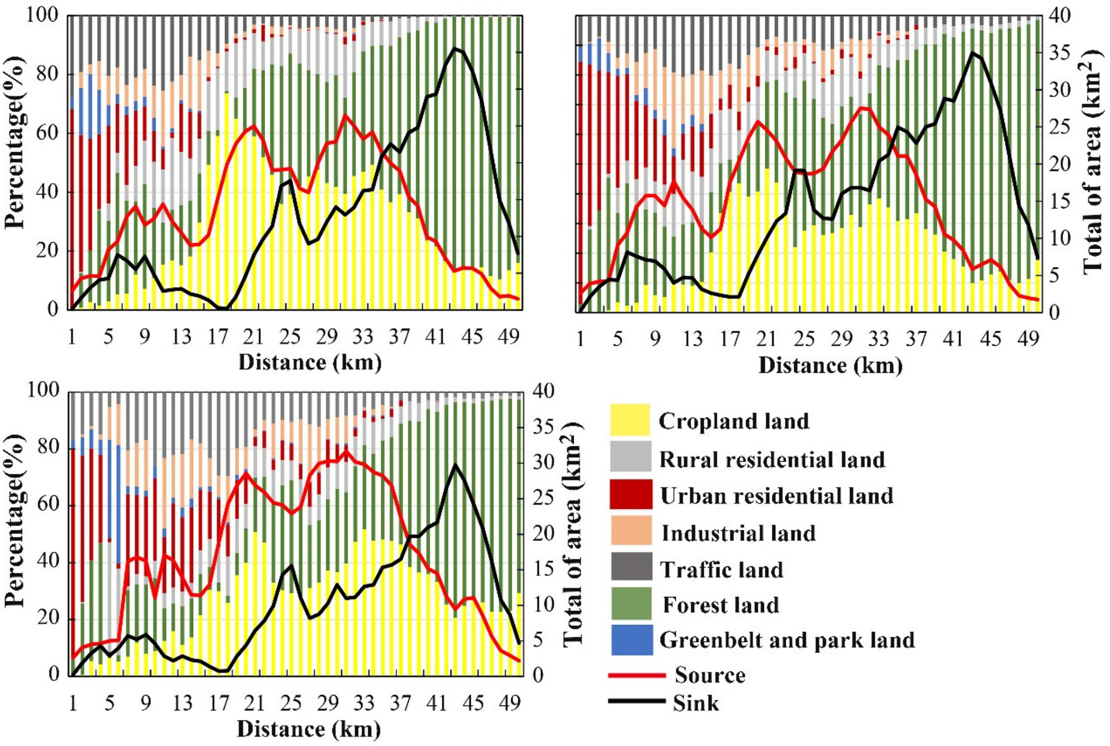

Figure 5. Spatio-temporal characteristics of landscape types.

4.2. N Source and Sink

4.2.1. Change in N Intensity

As illustrated in Table 1, the source and sink landscapes in Xiamen have different N intensities. With the urban development that occurred from 2005 to 2015, the N intensity of the source landscape reached levels higher than that of the sink landscape. Among all the source landscapes, urban residential land had the largest N intensity, with an average of 4832.84 kg/ha. The second and third intensities came from the industrial land and traffic land, with averages of 3651.27 kg/ha and 2484.41 kg/ha, respectively. These three types of source landscapes had significantly higher intensities than the other source landscapes, such as cropland and rural residential land. However, their N intensity trends were inconsistent. The urban residential land and traffic land kept increasing, while the industrial land had a decreasing trend from 2005 to 2015. As for the sink landscape types, the N intensity of the forest landscape remained stable at 70.0 kg/ha. The N intensity of the greenbelt and park landscape increased from 455.94 to 1612.41 kg/ha. In the wake of urbanization, the changes in the distribution of landscape types in Xiamen significantly affected the N intensities of various landscape types.

Table 1. Nitrogen intensities of source and sink landscapes (kg/ha).

Year	Forest	Cropland	Urban Residential Land	Rural Residential Land	Industrial Land	Greenbelts and Parks	Traffic Land
2005	−70.0	241.04	5656.8	1050.87	5985.19	−455.94	1627.92
2010	−69.9	284.51	4258.22	1189.95	3654.65	−1608.35	1865.26
2015	−69.2	216.28	4583.51	2769.79	1313.98	−1612.14	3960.05

4.2.2. Spatio-Temporal Characteristics of N Loads

The N loads of source and sink landscapes presented different changing trends. Figure 6 presents the spatio-temporal changes in the N loads of the source and sink landscapes. Over the period of 2005 to 2015, the total N loads of the source landscape peaked at 8–10 km, 19–22 km and 28–30 km from the urban center, respectively, and tended to decrease as it approached the edge of the city. The total N loads of the sink landscape peaked at 4–10 km and 40–46 km from the urban center.

The total N loads of the source landscape increased by two times between 2005 and 2015, with an average annual increase of 26%, and the peak of N loads in the source landscape increased from 4.32 Gg to 5.51 Gg over this same period. The N loads came from considerable urban residential land and transportation networks concentrated in urban centers. The N loads of the sink landscape, though, were significantly lower than that of the source landscape. The total N loads of the sink landscape increased slowly, with an average annual increase of 8%, and the peak of N loads in the sink landscape was higher in 2015. For these reasons, the faster growth of greenbelt and park land in the urban center may be attributed to it.

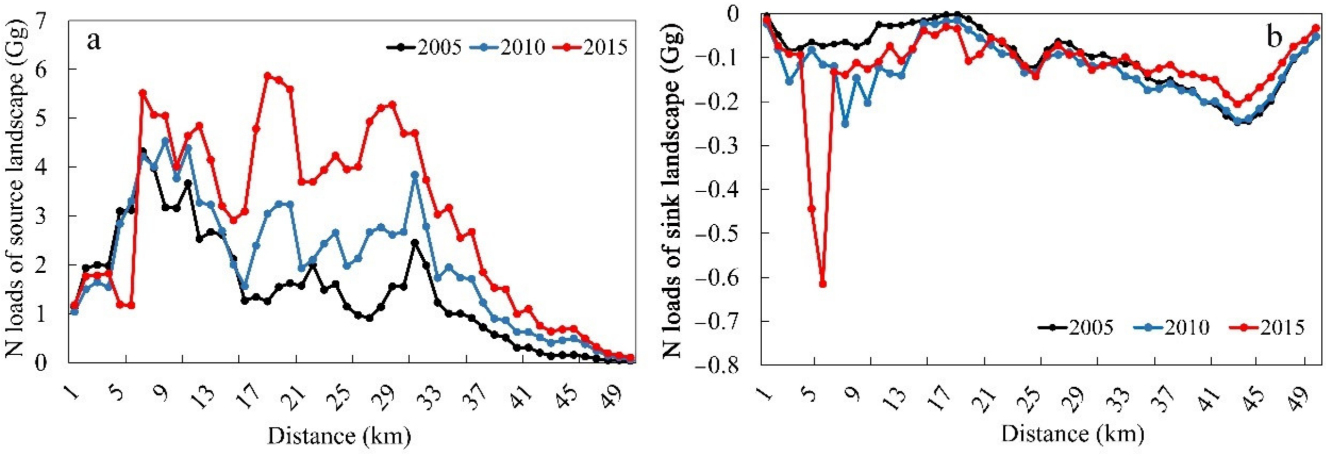

Figure 6. Nitrogen loads of source and sink landscapes along the spatial gradient ((**a**): source landscape; (**b**): sink landscape).

A range of landscape types achieved different N load values in the spatial gradient (Figure 7). Since the N loads were affected by the urban expansion and human activities at a spatial scale, concentric buffer zones were set to examine the spatial characteristics exhibited by the N loads. As indicated from the results, the changing trend of the N loads decreased as the zones moved from urban centers to rural areas. The source landscape types with high N loads consisted of residential areas and industrial land, as well as traffic land. The N loads of the residential and industrial land peaked between 1 km and 16 km from the urban core. From 2005 to 2015, among the source landscapes, the N loads of the urban residential areas and the traffic land increased most rapidly. Especially, the N loads of traffic land increased significantly, while the N loads contributions of the cropland, rural residential land and industrial land significantly declined.

Among the sink landscape types, the N loads of forest land gradually decreased from the edge region to urban core. While in the range of 4 km to 7 km from the urban core, the N load of greenbelt land and parks increased 24.8 times. As urbanization has forged ahead, the landscapes of sources and sinks have become seriously unbalanced. The area of source landscapes has expanded significantly, making the urban areas a hotspot for N pollution.

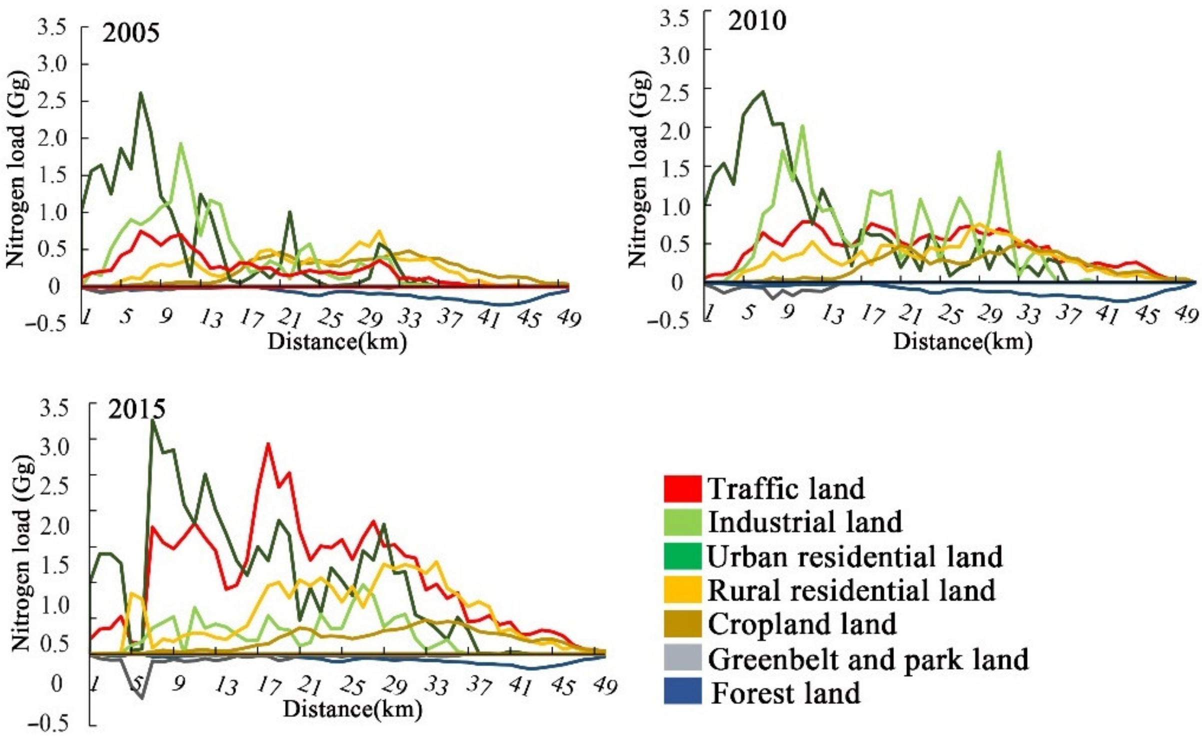

Figure 7. N loads of different landscape types along the spatial gradient.

5. Discussion

5.1. A Novel Approach to Identifying N Source–Sink Landscapes

In this study, the source–sink theory was innovatively introduced as an effective way to identify the source and sink landscape in the N flowing process. Many previous studies have applied source–sink theory to other research, such as on nonpoint pollution of watersheds, the urban heat island effect and carbon cycling [14,18,44–46]. The studies on nonpoint pollution of watersheds found that cropland and residential land were source landscapes, while grassland and forest land were sink landscapes [47,48]. However, it has until now remained unclear what the source–sink landscapes are for N flowing in a city ecosystem, although it has been shown that different types of landscapes have different roles in the N flowing process [37]. This study takes Xiamen as a case and can be helpful for understanding the characteristics of source–sink landscapes in N flows. Furthermore, this concept of the source–sink landscape in the N flowing process can be widely applied to other research areas.

5.2. Spatial Gradient Characteristics of Source–Sink Landscapes and N Loads

This study further analyzed the spatial characteristics exhibited by the source–sink landscapes and their N loads along the spatial gradient. This study found that source landscapes demonstrated a significant increase in the urban center of Xiamen and showed the higher N intensity. This is similar to previous results which found that industrial and traffic land showed the fastest increases in N intensity during urbanization [49]. This may be attributed to the faster growth of economic, energy consumption and urbanization in cities. However, the area surrounding Xiamen is taken up with a larger proportion of sink landscapes, whereas around the urban center, there was a peak in the sink landscape area in 2015, due mainly to the development of ecological infrastructure construction and significant increases in the greenbelt and parks in the urban center of Xiamen. According to the statistical data by the Xiamen statistics department, the area of greenbelt increased 2.7 times between 2005 and 2015 [32]. The above-mentioned results are similar to those for the coastal city of Shanghai [50], but different from most inland cities (e.g., Xi'an), primarily because the urbanization level of coastal cities is higher than that of inland cities [35].

Researchers have reached a consensus that due to rapid urban expansion and development, city N loads have been changed significantly along the spatial gradient. Based on field investigations and experimental analysis of the N concentration of the river which flows through Xiamen from the outside to the urban center, the N concentration increased along the river downward, and was significantly correlated with built/residence lands [51].

The most significant changes in source and sink landscapes have noticeable impacts on N flows, and these will lead to spatial heterogeneity of N loads in the city.

We find that the urban center is a high-N-load area, where a large number of source landscapes are concentrated. Moreover, source landscapes have a high intensity of human activity and N emissions. The previous study found that Xiamen may accumulate more N loads in human settlements during urbanization [23]. Such an increase in urbanization will continue to raise N emissions. Furthermore, with residential and energy consumption and the continued rapid development of urbanization, anthropogenic N emissions could become more serious in the future [7]. An increased population will lead to an increase in N loads at the city scale. Considerable N emissions come from the food and fossil fuel consumption of residents in the urban center. This result is quite close to the previous study of N loads in Xiamen, which found actual N contained in net imported foods rose almost double from 1993 to 2012 [52]. However, this result differs from those of several studies at the national scale, which found that cropland is the critical source in the N flow [40,53,54]. Therefore, given the premise of not adversely affecting economic development, the terminal system of N emissions can be controlled by ameliorating urban residents' food and energy consumption habits in the future [55–57].

As for sink landscapes, these are mainly distributed in areas surrounding the city and have low N loads. These sink landscapes mainly include forest and greenbelt lands, which cover and stabilize the soil surface, intercepting rainfall and delaying the timing of surface runoffs of N. At the same time, underneath the soil, the plant root system can absorb and intercept the N in the subsurface runoff and reduce the N loss from surface runoff [14,37]. To trap N pollution with sink landscapes, broadening the forest land and greenbelt can be most effective. In addition, forest land also can improve water quality [55,58]. For this reason, the results of this study suggest that the area of sink landscapes (e.g., greenbelts and parks) closest to the urban core should be appropriately increased to effectively reduce N loss in the environment.

5.3. Implications

Most researchers have found that rapid urbanization has led to an increase in N emissions in urbanized regions globally [2]. However, urban expansion changes the landscape significantly regarding the spatial gradient [59,60], and these changes have revealed the spatial trends of urbanization: increased human and economic development in urban area [61]. Furthermore, the spatial characteristics of N loads can be controlled by changes in source–sink landscapes along the urban–rural spatial gradient. Our case study found that the source–sink landscapes and N loads vary greatly along the spatial gradient from the urban center to the surrounding areas. City N spatial management strategies should be developed for a critical landscape type and N flowing process, in line with local conditions. However, the application of the ecological theory of source–sink landscapes to N flows at the city scale is still deficient, and no research on urbanization has yet proposed an accepted method of analyzing the source–sink landscapes and their N loads under urban spatial expansion.

Accordingly, the contributions of science and the results of this study can guide the spatial management of N loads in the future. Based on the Xiamen case study, we posit several policies for mitigating N pollution and promoting cities' sustainable development. First, more actions should be taken to control the acceleration of urban expansion since these areas have greater resource consumption and are hubs of N pollution [62,63]. In the future, the intensive use of build-up land instead of extensive urban expansion should be advocated in city N management [4]. Second, as an important strategy to offset the negative impacts of the source landscape in the N flowing process, policies for protecting forest and greenbelt lands, such as the "Ecological Garden", should be continually enforced.

6. Conclusions

In cities, the novel interactions between urban expansion and the N flow, generated by current rapid urbanization trends, are capable of generating novel ecological conditions and unprecedented effects, so that new ecological patterns, processes and functions may be created. This study provides a case that illustrates the interaction between the source–sink landscape and N loads changes under rapid urban expansion. The conclusions are: (1) the source and sink landscapes can be identified based on the landscape ecology theory and the mechanism of N flows; (2) considerable source landscapes tend to be concentrated close to the urban center, while sink landscapes tend to be located in the areas surrounding the city; (3) the N loads of source landscapes tend to fluctuate and decrease, with three peaks along the spatial gradient, while the N loads of sink landscapes tend to fluctuate and increase, with double peaks along the spatial gradient; (4) the N loads and their effects on the spatial gradient could be considered in formulating a city's urban growth boundary and coping with rapid urban expansion.

This study provides new viewpoints for the source–sink landscape in the N flowing process of city. Moreover, our findings help understand the mechanism by which urban expansion affects city N load dynamics, especially in terms of spatial heterogeneity. It is well documented that human activities affect the function of city ecosystems with spatial gradient heterogeneity. In addition to scientific contributions, this study also has also contributed to the formulation of city policies for N management. For example, N loads of source–sink landscape and their effects could be considered in formulating the urban expansion boundary. In the future, city planning should focus on the balance of source–sink landscape to reducing N pollution, and finally to achieve cities' sustainable development.

7. Limitation

While expanding our understanding of the source–sink landscape in the N flow and their N loads in the spatial gradient of a city, this study has several limitations and needs further improvement. (1) For further study, we could observe the dynamics of city N loads as the scale increases or decreases, aiming to articulate the homogenization hypothesis: that urbanization causes global homogenization or urbanization which might reduce the heterogeneity of city N loads at the scale of meters or below. (2) The dynamics of city N loads driven by social interactions are also worth studying. In our next study, we will further investigate the spatio heterogeneity of N intensity and reveal the effects of human activities on different landscape types along the spatial gradient at the city scale. Despite these limitations, however, this study has provided a novel perspective for identifying source–sink landscape in N flows and studying characteristics of their N loads along the spatial gradient at the city scale.

Supplementary Materials: The formula of estimating the number of N loads and the N parameters involved are shown in the Supplementary Information. The supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11081371/s1. Table S1: The parameters of N load calculation; Table S2: The activity data of N load calculation; Table S3: Factor of energy sector NOx emission(kg/t); Table S4. Factor of energy sector N_2O emission (kg/TJ); Table S5: Conversion of fuel calorific value (kJ/kg; kJ/m^3); Table S6. Factor of vehicle-miles of travel NH_3 emission. References [64–89] are cited in the Supplementary Materials.

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