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REVIEW

Source-sink landscape theory and its ecological significance

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Abstract Exploring the relationships between landscape pattern and ecological processes is the key topic of landscape ecology, for which, a large number of indices as well as landscape pattern analysis model were developed. However, one problem faced by landscape ecologists is that it is hard to link the landscape indices with a specific ecological process. Linking landscape pattern and ecological processes has become a challenge for landscape ecologists. ''Source'' and ''sink'' are common concepts used in air pollution research, by which the movement direction and pattern of different pollutants in air can be clearly identified. In fact, for any ecological process, the research can be considered as a balance between the source and the sink in space. Thus, the concepts of ''source'' and ''sink'' could be implemented to the research of landscape pattern and ecological processes. In this paper, a theory of source-sink landscape was proposed, which include: (1) In the research of landscape pattern and ecological process, all landscape types can be divided into two groups, ''source'' landscape and ''sink'' landscape. ''Source'' landscape contributes positively to the ecological process, while ''sink'' landscape is unhelpful to the ecological process. (2) Both landscapes are recognized with regard to the specific ecological process. ''Source'' landscape in a target ecological process may change into a ''sink'' landscape as in another ecological process. Therefore, the ecological process should be determined before ''source'' or ''sink'' landscape were defined. (3) The key point to distinguish ''source'' landscape from ''sink'' landscape is to quantify the effect of landscape on ecological process. The positive effect is made by ''source'' landscape, and the negative effect by ''sink'' landscape. (4) For the same ecological process, the contribution of ''source'' landscapes may vary, and it is the same to the ''sink'' landscapes. It is required to determine the weight of each landscape type on ecological processes. (5) The source-sink principle can be applied to non-point source pollution control, biologic diversity protection, urban heat island effect mitigation, etc. However, the landscape evaluation models need to be calibrated respectively, because different ecological processes correspond with different source-sink landscapes and evaluation models for the different study areas. This theory is helpful to further study landscape pattern and ecological process, and offers a basis for new landscape index design.

Keywords source-sink landscape theory, landscape pattern, ecological process, landscape ecology

1 Introduction

Landscape ecology is a new and practical interdisciplinary subject that is closely related to land use planning, urban ecological planning, biologic diversity protection and ecosystem management (Fu et a1., 2001; Xiao et a1., 2003; Wu, 2000; Ormml et a1., 2002; Haase and Halle, 2004). One of the trademarks of landscape ecology is emphasizing the importance of scale in landscape pattern and ecological process. It is significant for landscape ecologists to study the effect of human activity on regional ecosystems, and to explore the relationship between landscape pattern and ecological process (Li and Wu, 2004; Johnson et a1., 2004; Naaaauer and Corry, 2004; Zeng et a1., 2000; Domer et a1., 2002). Since the advent of landscape ecology, landscape pattern indices and quantitative analysis method developed rapidly (Stevens et a1., 2004; O'Neillr et a1., 1988; Turner and Garder, 1991; Haines-Young and Chopping, 1996; Cook, 2002). To promote the development of landscape ecology and quantitative research, various indices and landscape pattern models were introduced (Raines, 2002; Apart et a1., 2002; Baker and Cal, 1992; Pearson, 2002). However, most studies are just resting on the calculation and analysis of landscape pattern index, and few are done

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for the connotation of the landscape index value. Since landscape pattern indices are affected by the spatial distribution of different landscape types, it is sometimes unable to denote the ecological effect veritably from index value. The ecological process is an issue that is difficult to grasp, while landscape pattern indices are simple and easy to calculate, making it difficult to link them together. Following the incessant development of landscape ecology, it seems that the calculation and analysis of landscape indices have encountered a problem. Although more attention is paid to the relationships of landscape pattern and ecological process, further study on landscape pattern indices is quite limited. The key problem is that it is difficult for these landscape pattern indices to reflect the function of the ecological process preferably (With and Crist, 1995; Tisehendorf, 2001). ''Source'' and ''sink'' are common concepts used in air pollution research, by which the movement direction and pattern of different pollutants in air can be clearly identified. The source-sink principle could be used to link the landscape pattern with ecological processes when investigating the relationships between them. Based on the primary source-sink principle in air pollution, a theory of source-sink landscape was proposed, and it is expected to give a basis for quantitative analysis of landscape pattern and ecological process.

2 ''Source–Sink'' landscape concept

The concepts of ''source'' and ''sink'' are used in global change and air pollution. The exhaust emission derived from industrial production, residential living and traffic could be regarded as the source of air pollution. Compared with the source of air pollution, the ''sink'' is a region or an ecosystem that could assimilate the contaminants. The proposition of ''source-sink'' landscape provides a very useful means for investigating the cause and effect of air pollution. The research of landscape pattern and process becomes stagnant because of the difficulty in understanding the ecological process, and the introduction of ''source-sink'' landscape will be helpful to clarify relationships between landscape pattern and ecological process.

2.1 Concepts of ''source'' and ''sink'' landscape

''Source'' is the origin of a process, and ''sink'' refers to the process disappearance. Identification of the ''source'' or ''sink'' landscape in landscape ecology should be integrated with a specific ecological process. ''Source'' landscapes are ones that may promote the development of an ecological process, while the ''sink'' landscapes are those that may stop or retard the development of an ecological process. However, it is required to take a specific ecological process into consideration when distinguishing the ''source'' or ''sink'' landscape, because ''source'' and ''sink'' landscapes are connected to a certain ecological process. Defining the type of ecological process is the basis to ascertain the nature of landscape types. For instance, some landscape types may play a role as ''source'' in non-point source pollution, such as sloping cropland, fertilized cropland, urban area, etc., while some types may play a role as ''sink'' landscape, for example, grassland, wetland, woodland, and also some others may play a role as transmission.

With regard to soil and water (nutrient) loss, the ''source'' landscape is a place where runoff soil and nutrient loss occur. If no ''sink'' landscape were in the lower reaches of a ''source'' landscape, the soil, water and nutrient loss from the ''source'' landscape would enter the surface water or groundwater directly, and then non-point source pollution would be induced.

As for the greenhouse gas emission, landscape emits CO_2, CH_4 and other greenhouse gas. As an exmple, an urban landscape is the ''source'' landscape, while grassland and woodland absorbing CO_2, should be the ''sink'' landscape.

Concerning biologic diversity protection, the landscape that offers a habitat for target species and meet the fundamental requirement of one population would be a ''source'' landscape, and these resource patches are beneficial to species dispersal. Patches that are disadvantageous for survival and inhabitation, or having natural enemies of a target species, would be ''sink'' landscapes. ''Source'' landscape and ''sink'' landscape are relative, but they are concrete in a specific process.

2.2 Comparison between ''source'' and ''sink'' landscape

By comparing the ''source'' and ''sink'' landscape, the following characteristics are found.

(1) ''Source'' and ''sink'' landscapes are dependent on concept. Landscape pattern analysis would give no sense if it were not linked with a specific ecological process. The source-sink landscape theory aims to solve the problem that ecological processes were ignored in landscape ecology research, and give a connotation of each landscape by linking it with a specific ecological process. Therefore, it is vital to know the concerned ecological process before distinguishing a landscape either as ''source'' or as ''sink''. A landscape may be a source for one process, or a sink for another one. The key to distinguish a landscape as ''source'' or ''sink'' is based on the function of landscape playing as positive or negative during a specific ecological process. For example, farm is normally a ''source'' landscape for non-point source pollution because of a large amount of fertilizer and pesticide applied, whereas it is a ''sink'' landscape for

carbon cycle in terrestrial ecosystems since crop growth may absorb a large volume of CO_2 from air.

(2) Identification of ''source'' or ''sink'' landscape should be linked with a specific process. The essential difference between ''source'' and ''sink'' landscape is that ''source'' landscape can contribute positively to the development of the ecological process, while ''sink'' landscape plays an opposite effect. Definition of the ''source'' and ''sink'' landscape may be different in different processes. If the ecological process has not been clarified, it is hard to define the ''source'' or ''sink'' landscape in landscape pattern analysis.

(3) Different contributions may be produced for the ecological process by different ''source'' and ''sink'' landscapes. It is necessary to determine the weight of different landscape types on ecological processes. Even for the same ''source'' (or ''sink'') landscapes, it is also need to consider the different contribution. For example, cropland, vegetable field and orchard are all ''source'' landscapes, but they give different contributions on the non-point source pollution. Meanwhile, although grassland and forest are all ''sink'' landscapes, they have different effects on nutrient retention.

3 Ecological significance of ''source'' and ''sink'' landscape

The source-sink landscape theory was proposed based on the ecological balance theory, by which the general landscape was endowed with definite function connotation. The approaches and methodologies are explored for ecological process regulation by analyzing the balance of spatial distribution between source and sink landscapes. Source-sink landscape theory can be applied in the following fields.

3.1 Landscape pattern design and non-point pollution control

Upon the source-sink landscape theory, some landscape types play as the source and the other landscape types play as the sink in the transportation of material. As for water contamination, agricultural landscapes should be considered as different source or sink landscapes. If a reasonable landscape pattern in terms of ''source and sink'' landscapes was considered in a watershed eco-planning, the non-point source pollution process would be regulated in a heterogeneous landscape, and the non-point source pollution would be controlled finally.

The non-point source pollution, especially the water-body eutrophication, is virtually induced by the imbalanced temporal-spatial distribution of nutrients. The most reliable method to reduce the non-point source pollution is to mitigate the source of the contaminants (or nutrient), minimizing the emission source. Generally speaking, there are two approaches to prevent nutrients from enter the water body. One is to make the nutrient null emission in each landscape unit, thus there would be no contamination induced. The other one is to design a reasonable landscape pattern, and to let the contaminant die away in space (before entering the water body) by intercepting the nutrient. Chen's study showed that there was a close relationship between the spatial distribution of ''source'' and ''sink'' landscapes and the non-point source pollution (Chen et al., 2003a; 2003b). Thus, in order to reduce the risk of non-point source pollution, it is feasible to control nutrient loss from temporal-spatial scale by exploring the spatial combination of different landscapes (Turner and Gardner, 1991; Haines-Young and Chopping, 1996).

The objective of researching non-point source pollution is to protect water bodies, such as lakes, rivers, oceans, etc. The risk evaluation of pollution is to take the water body as the research object, to clarify the source and sink landscapes, and to reveal the effect of regional pattern of source and sink landscapes on the water quality by establishing the corresponding evaluation method.

3.2 ''Source'' and ''sink'' landscape pattern design and biologic diversity protection

The key to protecting biological diversity is to protect the habitat of the endangered species. None but habitat protection can protect a certain species effectively.

When we consider the habitat patches and the surrounding resource patches as the source landscape of a certain species, the patches become unsuitable for the survival of the species if they are occupied by human beings or native enemies. This could turn the habitat patches into a ''sink'' landscape in a sense.

Whether the landscape pattern is helpful for a certain species survival or not can be judged by evaluating the spatial relationships between the dwelled patches and surrounding patches. If more resource patches were available for the target species in the surrounding areas, this landscape pattern would be helpful for the survival of the species. However, if there were more sink landscapes in the surrounding areas, it would be adverse for species survival and protection. Therefore, the suitability of the landscape pattern for a species can be evaluated by using ''source'' and ''sink'' landscape evaluation models when the role of different landscape types is identified.

The theory of source-sink landscape was proposed based on the concept that was used in air pollution research. Therefore, bio-diversity protection evaluation should aim at a concrete ''source'', and consider the source patches as a point. Then, the landscape evaluation models are used to analyze the role of the surrounding landscape pattern on the ''source'' (a point), and to

clarify how the role of landscape pattern acts in target species conservation.

3.3 "Source" and "Sink" landscape pattern design and urban heat island effects

An urban ecosystem is disturbed intensively by human beings. As the urban area spreads, common issues related to urban outspread become increasingly serious, such as urban heat island effect and traffic jam. The essential reason for this is the irrational design of the urban landscape pattern.

To a certain extent, the appearance of the urban heat island effect and heavy traffic could be considered as the imbalance of the "source" and "sink" landscape in an urban area. Urban landscape includes "gray landscape" (i.e., buildings and road), "blue landscape" (i.e., river, lake), and "green landscape" (i.e., garden, turf, vegetation belt). Different landscape types play distinct roles in the urban heat island effect, and the over-centralized-distribution of gray landscape results in temperature increase. So the gray landscape can be considered as the source of the heat island effect, while the blue and green landscape may alleviate the urban heat island effect. However, because of land resource limitation, the areas used for the blue and green landscapes are few. In order to reduce the heat island effect, a potential way is to design a reasonable landscape pattern by using the limited land resource.

As for any city, it is better to have more blue and green landscapes on heat island effect mitigation. However, if the proportion of the blue and green landscapes is fixed, how to design a landscape pattern scientifically and arrive at the best efficacy is very important. We know that the blue landscape always has a lower temperature than the gray landscape, and the blue landscape can provide a comfortable environment for the residents. Therefore, when researching the heat island effect, it is necessary to regulate the gray, blue and green landscapes in a spatial extent based on the features of the "source" and "sink" landscape.

4 "Source" and "Sink" landscape evaluation models and their application

The source-sink landscape theory is to regulate the ecological process under the point view of the landscape pattern. The ecological process should be clarified before "source" or "sink" landscape are defined. "Source" landscape and "sink" landscape are recognized with regard to the special ecological process. If the ecological process were changed, the nature of the "source" or "sink" landscape will be changed too.

Based on the essential premises, the ecological process has been clarified. "Source" and "sink" landscape theory is to analyze the role of different landscapes, identify the "source" or "sink" landscape, and estimate the contribution of different landscapes in the ecological process. On the basis of "source-sink" landscape theory, the location-weighted landscape contrast index was presented by Chen Liding (Chen et a1., 2003). Through comparative study, different roles of landscape types for the non-point source pollution was identified. Based on the theory and method of the Lorenz curve, this index was proposed from 3 aspects including distance, slope and relative altitude. The index value is a reflection of the effect of landscape pattern on the ecological process (Cook E A, 2002). This model takes relationships between pattern and process into consideration, and establishes a new way for the research of landscape pattern and ecological process.

4.1 Conceptual evaluation model for "source" and "sink" landscape

The location-weighted landscape index proposed is devoted to study soil and water loss, as well as non-point source pollution. In principle, a general "source" and "sink" landscape evaluation model could be developed as follows.

$$LLI = \log\left\{\sum_{i=1}^{M}\int_{x=0}^{D} S_{xi}\omega_i dx \Big/ \sum_{j=1}^{N}\int_{x=0}^{D} H_{xj}\mu_j dx\right\}$$

Where LLI represents the location-weighted landscape contrast index; D is the maximal distance between the region and the target patches (or monitoring stations and watershed outlet); M and N are the number of "source" landscape and "sink" landscape, respectively; S_{xi} and H_{xj} are the areas accumulated curve of ith source, jth sink landscape, respectively (Cook E A, 2002); ω_i and μ_j are separately the weight of the ith source landscape and the jth sink landscape. In order to make the result value change around zero, the result is calibrated by logarithm. If the LLI is higher than zero, it means that the landscape pattern is helpful for the ecological process, otherwise it is negative.

4.2 Differences between the "source-sink" landscape evaluation and the traditional landscape pattern analysis

By taking 4 typical small watersheds in the Yuqiao reservoir basin as the research object, and non-point source pollution as the target process, Chen Liding et al. analyzed the relationship between the location-weighted landscape contrast index and non-point source pollution in the watershed scale. The results of the index and the concentration of the non-point source contaminants could be linked with each other well. It indicated that the effect of different landscape patterns on the surface

water quality can be evaluated by a source-sink landscape model at the watershed scale.

We can see from the above-discussion that the location-weighted landscape contrast index is scale-independent. It can be used to evaluate the effect of landscape pattern on ecological processes in a homogeneous watershed. In general, a larger *LLI* value corresponds with a larger nutrient concentration in surface water, otherwise the concentration (run-off or sediment) is smaller. However, if the environmental backgrounds are different, it is useless to compare the results between different watersheds. It is required to calibrate the model and the parameters before calculation.

In traditional landscape pattern analysis, the landscape indices, such as mean patch area, fractal index, isolation index, diversity index, contrast index, cohesion index, etc, are calculated only based on the proportion of landscape types, and little consideration was paid on the ecological significance.

There are three aspects in the research of landscape pattern and ecological process at present. First, the effects of patch shape and the spatial combination on ecological process at plot scale are focused. Second, the effects of different landscape types and its spatial distributions on soil and water loss at transect scale are involved. Third, simulations of the effects of landscape pattern change on ecological processes are made in larger scale by using mathematical models (earing et a1., 2005 N; Hessel et a1., 2003; Coper and Waiters, 2002; Coper and Waiters, 2002; Deckers et a1., 2004; Evans, 2005). The former two are mainly conducted by emphasizing the concrete observation; however, it is hard to apply the conclusion to a larger scale. The result of the third one often disagrees with the real world, because of the lack of quantitative observation of landscape pattern and ecological processes in different scales. Since source-sink principles are established with regard to the effects (weight) of different landscape patterns on the ecological process and the landscape pattern indices, which are based on the source-sink principle, already have a special ecological sense.

5 Conclusions

Exploring the relationships between landscape pattern and ecological processes is the key topic of landscape ecology. The theory and method about how to link landscape patterns with ecological processes have become the difficulties and hot spots of landscape ecology research. Based on the primary source-sink principle in air pollution and the related studies, a theory of source-sink landscape was proposed, and was expected to give a basis for analyzing the relationship between landscape patterns and ecological processes. The source-sink principle can be applied to non-point source pollution control, biologic diversity protection, urban heat island effect, and other fields. When the source-sink principle is used, a special ecological process should be clarified first. By using a source-sink landscape evaluation model, a scientific basis can be given for landscape pattern design and planning. The location-weighted landscape contrast index discussed in this paper aims at the non-point source pollution and soil erosion. When applying it to the other study areas, the feature of the ecological process should be taken into consideration to build the corresponding evaluation model. The source-sink theory can be improved by more researches and case studies.

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