Development of a New Index for Integrating Landscape Patterns with Ecological Processes at Watershed Scale

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Abstract: Understanding the relationship between landscape patterns and ecological processes has been a central yet challenging research theme in landscape ecology. Over the past decades, many landscape metrics have been proposed but few directly incorporated ecological processes. In this paper, we developed a landscape index, namely, location-weighted landscape index (LWLI) to highlight the role of landscape type in ecological processes, such as nutrient losses and soil erosion. Within the framework of the Lorenz curve theory, we develop this index by integrating landscape pattern and point-based measurements at a watershed scale. The index can be used to characterize the contribution of landscape pattern to ecological processes (e.g. nutrient losses) with respect to a specific monitoring point in a watershed. Through a case study on nutrient losses in an agricultural area in northeastern China, we found that nutrient losses tended to be higher for a watershed with a higher LWLI value, and vice versa. It implied that LWLI can be used to evaluate the potential risk of nutrient losses or soil erosion by comparing their values across watersheds. In addition, this index can be extended to characterize ecological processes, such as the effect of landscape pattern on wildlife inhabitation and urban heat island effect. Finally, we discuss several problems that should be paid attention to when applying this index to a heterogeneous landscape site.

Keywords: landscape pattern; location-weighted landscape index (LWLI); Lorenz curve theory; nutrient loss; surface water quality

1 Introduction

A primary goal of landscape ecology is to understand the reciprocal relationship between spatial pattern and ecological processes (Turner, 2005; Wiens and Moss, 2005; Wu and Hobbs, 2007), which is critical for any in-depth research in landscape ecology. Since the advent of landscape ecology, one of the salient features was the extensive use of landscape metrics (Gardner and Urban, 2007; Gustafson, 1998; O'Neil et al., 1998). Among those landscape metrics, most were introduced to characterize landscape patterns, while the ecological processes associated with landscape pattern analysis has been seldom examined (Corry and Nassauer, 2005; Li and Wu, 2004; Wiens and Moss, 2005; Wu and Hobbs, 2007).

Landscape-change studies have so far mainly focused on the documentation and spatial patterns analysis, and less attention was paid to landscape function and related processes (Pan et al., 2005). Understanding landscape pattern changes, however, requires a scientific understanding of the underlying ecological processes (Chen et al., 2006; Gergel, 2005; Lewis et al., 2007). Theoretically, ecological processes are related to a landscape pattern. However, how to characterize a landscape pattern within an ecological context is somewhat difficult. As one of the most important ecological processes, nutrient losses (or soil erosion) have been extensively examined in researches (Kloiber, 2006; León et al., 2001). Typically, a point measurement was made at the outlet of a watershed to characterize nutrient losses (or soil erosion). The metric characterizing landscape pattern at

Received date: 2008-08-28; accepted date: 2008-12-05

Foundation item: Under the auspices of Chinese Academy of Sciences (No. KZCX2-YW-421), National Natural Science Foundation of China (No. 40621061, 30570319)

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a watershed scale, such as landscape diversity, was difficult to be linked to a point-based measurement. How to relate the landscape pattern and the point-based measurement is fundamental to assess the impact of landscape pattern on ecological process in a watershed. Different land use types may play different roles in ecological processes, such as nutrient losses (Basnyat et al. 1999; Chen et al., 2002; Parsons et al., 2006). Some land use types may have a positive contribution, such as farmland, vegetable land, and residential area, some others may have a negative contribution, and the rest may serve as a pathway during nutrient losses. If a land use type displaying a positive role during nutrient losses is defined as a source landscape, and one playing a negative role is denoted as a sink landscape, the role of a watershed landscape pattern in nutrient losses could be identified based on the spatial arrangement of the source landscapes and the sink landscapes. If the function of the source landscapes is stronger than that of sink landscapes in a watershed, this watershed may produce more nutrient losses compared with a watershed having more sink landscape (Gergel, 2005). For quantitatively assessing the role of a watershed landscape pattern in ecological processes, a model based on Lorenz-curve theory was proposed. The objectives of this study are to elaborate how the model is developed and to validate if the model works by using field measurements.

2 Methodology

2.1 Case study area

A case study was conducted in Hailun County, Heilongjiang Province, a traditional agricultural area in Northeast China. Hailun is located in 46°58'–47°52'N, and 126°14'–127°45'E, with a coverage of 4667km². It is characterized by a semi-arid continental climate with an mean annual temperature of 1.0–2.0°C, an annual precipitation of 500–600mm. More than 80% of the precipitation occurs in the summer months (from June to September). The study area features rolling hills and wide valleys. Soils include black soil (63.4%), meadow soil (10.34%) and carbonate meadow soil (14.41%). Most areas are used for agricultural production, such as corn, rice, soybean and potato. In order to study the effect of landscape pattern on nutrient losses, two closely-located small watersheds (Jiangjiagang and

Wangmingtun) with homogeneous characteristics were chosen, which are 5km from Hailun Downtown in the southeastern direction. Land use types were delineated from remotely sensed TM image based on field survey. Those two watersheds are mainly covered by agricultural land use (Table 1).

Table 1 Land use types in studied watersheds

Land use type	Watershed 1 (Jiangjiagang)		Watershed 2 (Wangmingtun)	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Soybean field	488.39	48.36	2194.84	66.21
Corn field	383.91	38.02	475.38	14.34
Residential area	100.09	9.91	331.85	10.01
Paddy field	0.00	0.00	6.89	0.21
Woodland	23.15	2.29	38.37	1.16
Grassland	14.35	1.42	247.49	7.47
Water body	0.00	0.00	19.95	0.60
Total area	1009.89	100.00	3314.77	100.00

2.2 Effect of spatial pattern of source and sink landscapes on ecological processes

In a watershed, the contribution of a source landscape type to the nutrient concentration at the outlet can be defined by three measurements: the distance of a landscape type to the outlet of a watershed, the slope gradient of a landscape type location, and the relative elevation of a landscape type with regard to the outlet (monitoring point). Assuming a source landscape is close to the outlet of a watershed, it would therefore contribute more to the nutrient losses, comparing to the same landscape at a farther place. Similarly, a source landscape with a steep slope may contribute more to nutrient losses than that of the same landscape with a gentle slope. If a source landscape located at a relative low position, it may contribute more to the measurement at the outlet of a watershed.

Lorenz curve is often used to show the distribution of assets. In such cases, many economists consider it to be a measure of social inequality (Chakravarty, 1990). It can be introduced to describe the landscape pattern in a watershed to define the configuration of source and sink landscapes. In a watershed, if the outlet is used as the reference point, the spatial pattern of source and sink landscapes can be identified by comparing it to the landscape factors, such as distance, relative elevation and slope gradient (Fig. 1).

Fig. 1 Sketch of spatial distribution of “source” and “sink” landscape in a watershed

In Fig. 1, O(0,0) represents the outlet of a watershed (or monitoring point), Y-axis (OA) represents the area-accumulated percentage of a landscape (0, 100%) with increasing distance (relative elevation, slope gradient); X-axis (OC) represents landscape parameter (0,1), such as distance, relative elevation, slope gradient of a landscape location to the outlet in a watershed. The range is from 0 to 1 after standardization by dividing with the maximum value (1 means the maximum distance, the maximum relative elevation, and the maximum slope gradient). ODB, and OFB are, respectively, the curves of accumulated-area percentages of different landscapes.

In Fig. 1, OEB is an absolutely even-distributed curve of a landscape in a watershed. Suppose the area percentages of source and sink landscapes, as well as their weights to such processes as nutrient losses are the same, the ultimate contribution of the landscape pattern to the ecological processes shown as OEB would be at the best state. This means that almost all nutrient losses produced by the “source” landscapes would be retained by the “sink” landscapes.

However, if the spatial distribution of the “source” and the “sink” landscapes are not balanced, such as the curve ODB, or OFB, their contribution to the ecological process would vary. The contribution of each landscape to the ecological processes can be determined by the size of polygon ODBC and OFBC. If the curve ODB is closer to the point A, it means that the landscape is close to the outlet of a watershed on distance, or at a lower place, and its contribution to the measurement at the outlet would be higher. In this case, we may find the

area of the polygon ODBC is large. However, for a curve like OFB, the area of polygon OFBC would be small, which means the landscape is far from the outlet, and its contribution to the measurement at the outlet would be small. The spatial pattern corresponding to slope gradient has a reverse effect. If the curves of ODB and OFB are respectively represented as “source” and “sink” landscapes in a watershed, then a location-weighted landscape index (LWLI) can be used to depict the linkage between landscape pattern and the measurements of nutrient losses (or soil erosion) at the outlet of a watershed.

$$LWLI = A_{\text{source}} / [A_{\text{source}} + A_{\text{sink}}] \quad (1)$$

where, *LWLI* is location-weighted landscape index with regard to landscape parameters in a watershed (distance, relative elevation and slope gradient); A_{source} and A_{sink} represent the area of polygon ODBC (suppose it is a source landscape) and polygon OFBC (suppose it is a sink landscape), respectively.

From Equation (1), we can see that the value of *LWLI* changes between 0.5 and 1. The larger the *LWLI*, the higher the nutrient loss (or soil erosion) measurements at the outlet of a watershed. It means that this landscape pattern is prone to nutrient losses, or soil erosion. However, when *LWLI* value relative to slope gradient is larger, it implies that less nutrient losses, soil erosion would be induced.

2.3 Effect of different land use types on ecological process

In many cases, more than one land use types are distributed in a watershed, and the contribution of land use types to the nutrient losses is different. For example, cropland, vegetable land, orchard, and residential area, as source land use types, play different roles in nutrient losses. To account for the effects of land use types on the ecological processes, standardization to each land use type is required by assigning a weight, and *LWLI* can be calculated by Equation (2).

$$LWLI = \sum_{i=1}^m A_{\text{source}i} * W_i / [\sum_{i=1}^m A_{\text{source}i} * W_i + \sum_{j=1}^n A_{\text{sink}j} * W_j] \quad (2)$$

Further, if the area-percentage of each land use type in a watershed is considered, Equation (2) is changed into Equation (3).

$$LWLI = \frac{\sum_{i=1}^m A_{sourcei} * W_i * AP_i}{\left[\sum_{i=1}^m A_{sourcei} * W_i * AP_i + \sum_{j=1}^n A_{sinkj} * W_j * AP_j \right]} \quad (3)$$

where, $A_{sourcei}$ is the area of the i th source land use type vs the distance, the relative elevation, or the slope gradient; and A_{sinkj} represents the area of the j th sink land use type vs the distance, the relative elevation, or the slope gradient. W_i and W_j is the weight of the i th source and the j th sink land use type, respectively; m is the number of source landscapes, while n the number of sink landscapes; AP_i and AP_j are the area percentage of the i th source landscape and the j th sink landscape in a watershed, respectively. In Equation (3), when functions of source and sink landscapes are in balance, the value of $LWLI$ would be 0.5. This landscape pattern in a watershed would produce little nutrient losses or soil erosion.

If the effects of distance, relative elevation and slope gradient on the ecological processes are combined together, the index can be described as follows:

$$LWLI = LWLI_{distance} * LWLI_{elevation} / LWLI_{slope} \quad (4)$$

where, $LWLI_{distance}$, $LWLI_{elevation}$, and $LWLI_{slope}$ are the values of $LWLI$ with respect to the distance, relative elevation and slope gradient, respectively.

2.4 Surface water quality monitoring

Monitoring of surface water quality was conducted in July and August in 2006–2008. Water samples were collected at the mouth of each watershed after rainfall every two days until the runoff vanished. In total, 13, 13 and 15 samples were collected in each watershed in 2006, 2007 and 2008 respectively. The concentrations of TN, NO_3 -N, NH_4 -N and TP were analyzed immediately in the laboratory. The ammonium-N was determined with Nessler's reagent colorimetry; Nitrate-N with phenol disulfonic acid photometry; and phosphates with ammonium molybdate spectrophotometer.

3 Results and Analyses

3.1 Weight of land use types to nutrient losses

In principle, the weight of each land use type can be determined by comparing its contribution to the processes. In our study, as for nutrient losses, cropland and residential area are “source” landscapes, and the woodland and grassland are “sink” landscapes since they can retain

some nutrients from agricultural land. Water body was considered a pathway. The weight of “source” landscape is determined by comparing its importance to the nutrient loss. The residential area was assigned 1 as a key non-point pollution source, and the other land use types were assigned different weights according to their potential contribution on nutrient loss. Generally, a higher weight is given as the applied fertilizer increases. The weights of “sink” landscapes are determined by comparing their role in nutrient retention according to the field measurements and expert's knowledge (Table 2).

Table 2 Source and sink landscapes and their weights

	Landscape type	Weight
Source landscape	Soybean field	0.5
	Corn field	0.8
	Paddy field	0.8
	Residential area	1.0
Sink landscape	Woodland	0.8
	Grassland	0.5

Note: Water body was not considered when calculating LWLI since it does not produce nutrient loss directly

3.2 Landscape patterns and LWLI values

Although soil texture may affect the denitrification capacity, soil was not considered when exploring the relationship between LWLI and surface water quality since little differences were found on soil types in the two watersheds. It was found that some differences on the spatial distribution of land use types existed in these two watersheds (Table 1, Fig. 2, Fig. 3). Based on Equation (4), LWLI value of the landscape pattern can be examined (Table 3). Watershed 1 has a higher LWLI value than watershed 2.

3.3 Surface water quality during rainy season

Table 3 shows the surface water quality in the rainy season from 2006 to 2008. Watershed 1 has higher concentrations of TN, NO_3 -N, NH_4 -N and TP, than those in watershed 2. Only TP in the rainy season of 2008 was found higher in watershed 2 than that in watershed 1. This coincided with the LWLI value in the two watersheds, which implied that watershed 1 was more sensitive to nutrient losses as the LLWI index indicated.

4 Discussion

4.1 Relationship between LWLI and surface water quality

One of the biggest problems in rural area is over-fertiliz-

Fig. 2 Spatial distribution of different land use types in studied watersheds

Fig. 3 Distribution curves of different land use types by area-accumulated percentage in studied watersheds

ation, which results in nitrogen excess that contributes to aquatic eutrophication in water body (Kull et al., 2005). There are generally two ways to reduce nutrient loading

in the surface water, i.e. the source mitigation on the spot and the spatial filtering at the landscape scale. Best management practices were considered by many coun-

Table 3 Comparison of LWLI values and surface water quality in studied watersheds

Year	Item	Watershed 1*	Watershed 2*
2006	TN	14.94	12.87
	NO ₃ ⁻	3.16	2.07
	NH ₄	1.16	1.00
	TP	0.25	0.19
2007	TN	3.59	2.66
	NO ₃ ⁻	2.11	1.36
	NH ₄	0.87	0.81
	TP	0.87	0.64
2008	TN	5.51	4.88
	NO ₃ ⁻	3.24	2.44
	NH ₄	0.79	0.72
	TP	0.85	0.94
LWLI		1.42	1.31

Note: * Mean value of all measurements in rainy seasons

ies, particularly in fertilizer application reduction, and riparian buffer construction (Sliva and Williams, 2001; Young and Briggs, 2005). However, it is impracticable to reduce fertilizer use in many countries because of huge demand on grain production. A potential way to reduce nutrient losses from the farm plot and further into the water body, is landscape pattern design and planning. Thus N-use balance in a watershed relating to and sink areas has a high importance. Identification of the source and high-risk watershed will provide a basis for mitigating nutrient loads.

Landscape indicators are particularly useful for monitoring changes in water chemistry as water quality is often closely linked to nutrient sources in a watershed. For example, the percentage of human-altered land cover types in a watershed (e.g., agriculture, urban and non-forested cover types) is positively related to N, P, NO₃-N, NO₂-N, alkalinity, and total dissolved solids in surface waters (Johnson et al., 1997). Total N inputs to a basin are correlated positively with the percentage of agriculture and urban land use types and negatively with percentage of forest. Improved land use practices can reduce groundwater and surface water nutrient loads (Honisch et al., 2002). In this study, we found that landscape pattern with higher ILWI value in watershed 1 caused a higher nutrient loads in the surface water, while the landscape pattern with a lower ILWI value in watershed 2 resulted in a lower nutrient concentration. These

results highlight the importance of spatial arrangement of land use types in a watershed when estimating the non-point source pollutant loads. It also implies that landscape pattern modification is a potential way to control nutrient losses giving that the same proportion of land use types in a watershed is fixed. The nutrient loading in surface water body can be mitigated by landscape design and planning.

With an improved land-use planning, or landscape pattern design, we may be able to reduce some water pollution. Using the non-point source pollution model such as BASINS would help us to predict the plausible hydrological consequences of such changes in land use types. However, by calculating ILWI value, the effect of landscape pattern in different watersheds can be differentiated. Watershed, as a complex landscape with multiple potential sources or sinks of N and P, may contribute more to the nutrient loading when they have a higher LWLI value. The nutrient loads correspond to the increasing interest in providing various traps or sink structures (wetlands, buffer zones, etc.) on water pathways to slow down transportation and cycling of nutrients within agricultural watersheds (Kuusemets and Mander, 2002; Wang et al., 2005). Using landscape pattern design and planning would be a very valuable approach to reduce nutrient losses.

4.2 Effects of source, sink, pathway on ecological processes and their spatial arrangement

Source landscapes in a watershed play a critical role in nutrient loads to surface water. The percentage of a watershed occupied by agricultural areas is widely used to predict nutrient loads and in-stream water chemistry because water quality is often linked to non-point sources in a watershed. The higher NO₃-N concentration is typically found beneath well-drained agricultural fields that received manure and fertilizer N, while lower NO₃-N in ground water is found in grassland and riparian buffers, particularly for poorly drained soils (Young and Briggs, 2005). However, the spatial location of source landscapes have not been incorporated into most landscape indicators although many studies and watershed loading models suggest that spatially explicit information is useful for predicting nutrient loadings.

Sink landscapes, as the trapping place of nutrient loads in a watershed, also play a significant role. Research over the last two decades has focused on land-

scape influences such as riparian buffers on $\text{NO}_3\text{-N}$ transport after it has entered ground water (Gergel, 2005; Vidon and Hill, 2004; Young and Briggs, 2005). It was found that the predominant $\text{NO}_3\text{-N}$ attenuation processes in buffers include denitrification, dilution, and plant and/or microbial uptake (Altman and Parizek, 1995), with the relative importance of each mechanism being site- and time-specific. It was also found that the fate and transport of $\text{NO}_3\text{-N}$ in shallow ground water is strongly tied to soil type, hydrology, vegetation, and landscape management factors (Hill et al., 2000). Gilliam (1994) found that forested and grass riparian buffers in agricultural areas play critical roles in maintaining stream water quality.

It is important to understand both the total area of sources and sinks in a landscape, and also their spatial arrangement relative to flow paths (Gergel, 2005). Despite the widespread appreciation of the role of riparian buffer strips in trapping and processing non-point source pollution (Young and Briggs, 2005), Band et al. (2001) indicated that flow paths containing nitrate-rich water can consistently bypass riparian buffers, particularly during high flows. Clearly, the extent to which the spatial dynamics of flow paths are explicitly or implicitly modeled will impact the simulation results, and some watershed models are inherently designed to be insensitive to arrangement of patches and cover types (Gergel, 2005).

A variety of methods have been used to estimate non-point source loads for ungauged watersheds (Kloiber, 2006). However, most landscape indicators have focused on simple measures of percentages of land cover (Gergel et al., 2002), which do not indicate where in the watershed particular land use types or land use occur. Some simulations suggest that the spatial location of patches composing of different land use types is a fundamental driving force in governing watershed nutrient loads. Spatial arrangement of different land use types might be most important when linking landscape to watershed loads.

4.3 Ecological significance of LWLI

Landscape indicators and spatial watershed models are important tools for understanding watershed processes (Gergel et al., 2002; Griffith, 2002). In some cases, a simple model, or landscape indicators are much useful to characterize landscape sources, sinks and flows, as

well as their spatial configuration. Jetten et al. (2003) found that simple lumped models performed as well as the more complex distributed models because input errors increase with model complexity. Gergel (2005) developed a simple heuristic model based on percolation theory, which can be used to understand watershed loading.

There is currently much debate over the utility of spatially distributed watershed models vs non-spatial and often less mechanistic models of N export (Alexander et al., 2002), runoff and erosion (Jetten et al., 2003). The landscape index developed in this paper can help in examining the sensitivity of water-quality variables to alterations in land use types at varying distances from the watershed outlet. The index addresses the spatial arrangement of source and sink landscapes in a watershed, which is key to maintenance of stream water quality. It can be used by land managers in developing watershed management plans.

Firstly, LWLI is process oriented. When calculating the LWLI value, the contribution of land use types to the processes such as nutrient losses is addressed. Thus, LWLI can be directly linked to the measurement at the outlet of a watershed. However, LWLI value may vary with regards to different processes in the same watershed, since it is affected by the weights of land use types to the defined ecological processes.

Secondly, it is scale-independent. More effort should be allocated to develop a framework governing the use (and identifying the mis-use) of spatial data and spatial models. Ideally, this should be addressed using a variety of techniques and approaches including empirical, simple heuristic models, as well as complex, mechanistic simulation models. LWLI can be used to assess the effects of landscape pattern on ecological processes at a watershed scale, and can be extended to different sizes of watersheds.

Thirdly, it is important to emphasize that those hypotheses are all related to specific landscape patterns and ecological processes, and cautions need to be taken when extended to other locations. LWLI can be used in the watersheds with similar soil and rainfall. If the soil and the rainfall are heterogeneous at a watershed, it is required to improve the index by giving weights to them when calculating the value of LWLI.

Lastly, the simple model developed here suggests that landscape arrangement may be one of the most impor-

tant factors that need to be considered in characterizing ecological processes when source and sink landscapes are of uneven distribution in a watershed (Gergel, 2005). The model can be employed to compare the contribution of landscape pattern to soil erosion and nutrient losses. The larger LWLI is related to higher risk of soil erosion and nutrient losses. Thus, the watershed with high risk on soil erosion and nutrient losses could be identified.

5 Conclusions

Landscape ecology has grown into one of the most important fields in ecological research. The further development, however, is strongly hindered by the inadequacy in the integration of landscape patterns and ecological processes. One of the important reasons is that the traditional landscape pattern analysis mostly depends on the landscape metrics. Exploring the relationships between landscape pattern and ecological processes is the key topic in landscape ecology. Based on the source-sink principle in an ecological process, a new landscape index was developed in this study. The index has improved the understandings on the relationship between landscape pattern and ecological processes. It provided a simple and dynamic methodology to study landscape patterns and ecological processes.

LWLI can be applied to assessing the risk of nutrient losses (or non-point source pollution) and soil erosion. By using LWLI, a scientific basis can be developed for landscape pattern design and planning. However, the index is established for non-point source pollution and soil erosion assessment. When apply it to other fields, the nature of the processes should be taken into consideration. In addition, this model was established with the hypothesis that a homogeneous landscape is involved, thus, it is required to improve the model by assigning weights to those parameters when calculating LWLI, given that the soil and the rainfall are heterogeneous at a watershed.

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