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Trends in the use of landscape spatial metrics as landscape indicators: A review

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ABSTRACT

The paper gives an overview on the trends in the usage of landscape metrics as indicators for: land use changes, habitat functions (biodiversity, habitats), landscape regulating functions (fire control, microclimate control, etc.), and information functions (landscape aesthetics). We reviewed papers published in international peer-reviewed journals that are indexed by the Institute of Science Information (ISI) Web of Knowledge from 2000 to 2010. The terms "landscape metrics", "landscape indexes" and "landscape indices" were searched. Our analysis showed that application of the landscape metrics to characterize various ecosystem services and landscape functions has broadened during the last 10 years. Number of studies related to regulating and information functions of landscapes is increasing. However, the main exploitation field of the metrics is evaluation the change in land use/land cover.

1. Introduction

Landscape ecology is largely founded on the notion that environmental patterns strongly influence ecological processes (Turner, 1989). Landscape pattern is linked to biodiversity and other ecological values of the landscapes. A disruption in landscape patterns may compromise its functional integrity by interfering with critical ecological processes necessary for population persistence and the maintenance of biodiversity and ecosystem health (With, 1997). Human influence changes landscapes significantly, and this significantly impacts biodiversity (Moser et al., 2002). For these and other reasons, much emphasis has been placed on the development of methods for the quantification of landscape patterns, which is considered to be a prerequisite for the study of pattern–process relationships (Turner, 1990; McGarigal et al., 2002). Landscape metrics are one of the most popular methods for the quantification of landscape patterns. The application of these metrics has been very wide despite several drawbacks such as scale dependence, interpretability, etc. (Gustafson, 1998).

In recent years the concept of ecosystem services has received increasing attention in environmental science, policymaking and practical applications (Müller et al., 2010). Landscapes contain many important functions which provide a variety of "goods and services" (Bolliger and Kienast, 2010; De Groot, 2006). De Groot (2006) has divided landscape functions into the following categories: (1) regulation; (2) habitat; (3) production; (4) information; (5) carrier. In recent decades landscape metrics have been successfully used as indicators for landscape functions (Uuemaa et al., 2009). Thus there is a need to assess the usage of landscape metrics, but also an appropriate time for analysing future perspectives and potential improvements of landscape metrics.

The aim of this paper is to offer an overview of the most important trends in the usage of landscape metrics as indicators for: land use changes, habitat functions (biodiversity, habitats), landscape regulating functions (fire control, microclimate control, etc.) and information functions (landscape aesthetics).

2. Methods

We reviewed papers published in international peer-reviewed journals indexed by the Thomson Reuters Web of Knowledge from January 2000 to December 2010. The terms "landscape metrics", "landscape indexes" and "landscape indices" were searched. Of course there are many other terms that can yield additional sources but we assumed that if the term "landscape metrics" or a synonym were mentioned in the title, abstract or keywords, they would be one of the more important tools used in the study. Our focus was mainly on FRAGSTATS and similar programs related landscape metrics and not on the landscape metrics in wider meaning.

In this study we used three main groups from De Groot's (2006) classification of landscape functions: (1) habitat, (2) regulation, and (3) information, as landscape metrics have been used the most in evaluating these landscape functions. In addition to this, landscape metrics have been used to evaluate change in landscapes – land use/cover changes. The papers were classified into different groups according to the aims or titles of the studies. Each main group contained subcategories: land use/cover changes – general land use/cover changes, urban areas, forests, agricultural areas; habitat

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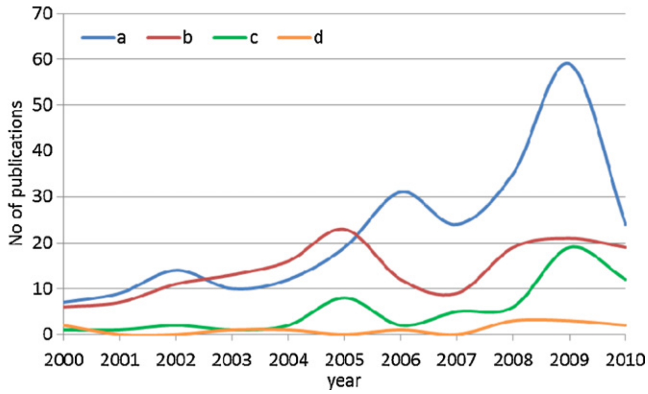

Fig. 1. The use of landscape metrics in international peer-reviewed scientific papers: (a) for the evaluation of land use/cover patterns or changes; (b) habitat functions; (c) regulation functions; (d) information functions. The analysis has been performed using journal papers from 2000 to 2010 indexed by the Thomson Reuters Web of Knowledge.

functions – general biodiversity/habitats, mammals, birds, amphibians, insects, plants; regulation functions – climate/microclimate, water quality, flood control, fire control, erosion control, disease control; information functions – aesthetics. All of the papers were grouped into only one category.

3. Results and discussion

3.1. Temporal and geographic distribution of studies

The term "landscape metrics" provided 510 results, "landscape indices" 150 results and "landscape indexes" 24 results in the Thomson Reuters Web of Science. Of these 684 studies, about 60 were overlapping, i.e. they were search results for two terms simultaneously and another 50 studies contained terms we searched for, but landscape metrics were not actually used in the studies. We eventually categorized 472 studies into four main groups as follows: general land use/cover changes – 244, habitat functions – 156, regulation functions – 59, and information functions – 13. The temporal change in the use of terms in the studies shows a slightly increasing trend for all four groups, however, most represent the land use/cover change (Fig. 1). In addition, there were about 100 studies that did not fall into any of these groups. These studies were reviews or dealt with different problems (scale, co linearity, classification) related to landscape metrics.

Four seventy-two studies that fell into four main categories were mapped according to study subject (Figs. 2 and 3). Over 50 countries were covered. The leading countries in exploiting landscape metrics are the U.S. and China. While China has the greatest number of studies on land use/cover changes, the U.S. also has many studies in the investigation of landscape habitat and regulating functions. In Southern American countries landscape metrics are more often used in forest studies/management, as deforestation is a critical issue there. The majority of studies on aesthetics have been carried out in Europe (7 studies). However, the European countries cover a variety of research fields (Fig. 3) and the highest number of studies has been performed in Spain and UK – 18 and 12, respectively.

We also compiled a brief overview of the journals that have published papers dealing with landscape metrics. Two journals – Landscape Ecology and Landscape and Urban Planning – came up most often in search results (68 and 59 papers, respectively), which is not a surprising result, as these two journals have played a leading role in improving our understanding of the relationships between spatial patterns and ecological processes. Forest Ecology and Management, Environmental Management, Environmental Monitoring and Assessment followed with a significantly lower number of studies – less than 20 studies in each journal. Most of the journals not mentioned in the table had 5 or less studies. Altogether there were 179 journals and conference proceedings.

3.2. Landscape metrics and evaluation of land use/cover patterns or changes

This category contained four subcategories: general land use/cover changes, forests, urban areas and agricultural areas (Table 1). One hundred and fourteen studies involved general changes, and urban areas were investigated in 57 and forests in 49 papers. Significantly less attention has been devoted to the agricultural areas (only 7 studies).

Most of the studies have been performed using remote sensing data, and analysed the changes during the past 30 years. It is well known that the results of the spatial analysis depend highly on the classification and the pixel size. Nevertheless it was not rare that the number of land use/cover classes and resolution was not mentioned in the study. This makes the comparison of the results very hard if not impossible. Moreover the interpretation of the results may also be difficult. We urge to always mention the pixel size and land use/cover classes used in the study. Most of the studies showed a clear trend towards increasing fragmentation. There were, however, also some exceptions which showed homogenisation of the landscape, mainly caused by the abandonment of land due to agricultural decline and the expansion of settlements (Geri et al., 2010; Rescia et al., 2010). Landscape metrics have offered the opportunity to evaluate the effect of protected areas (Esbah et al., 2010; Rescia et al., 2010), a rehabilitation program (Liu et al., 2009), hydroelectric cascade exploitation (Ouyang et al., 2009) and mining (Malaviya et al., 2010) on the landscape pattern. They have also been used to integrate landscape fragmentation analysis into regional planning (Girvetz et al., 2008) and to design ecological networks (Venturelli and Galli, 2006).

Fragmentation caused by urbanisation has been studied in several papers (Hahs and McDonnell, 2006; Jaeger et al., 2007; Yu and Ng, 2007; Weng, 2007). Jaeger (2000) proposed three new measures of fragmentation: degree of landscape division (*D*), splitting index (*S*), and effective mesh size (*m*), which characterize the anthropogenic penetration of landscapes from a geometric point of view. These metrics become very useful measures of urbanisation caused fragmentation.

In order to predict future trends in urban patterns, Cellular Automata (CA) in combination with landscape metrics has become useful (Herold et al., 2003). As urban areas change rapidly, landscape metrics have proven to be useful because they are quickly obtainable and comparable. Urban analysis is somewhat different from general land use change analysis, because the direction (urban–rural) of the analysis is mostly relevant, and higher spatial resolution is needed (Bhatta et al., 2010; Zhu et al., 2006). The average low-density house leaves a footprint of 200 m^2. Therefore in order to pick up the pattern created by low-density housing it is necessary to use at least 10 m spatial resolution. Our review of the papers showed that most research uses 30 m or larger pixel size, while in such analysis one should seriously consider using higher resolution data.

In forest management, landscape metrics have been mainly used to monitor changes and the effectiveness of management plans (Etheridge et al., 2006; Ribeiro and Lovett, 2009; Sano et al., 2009). Deforestation and forest fragmentation caused by logging, agriculture, urbanisation, etc. is an increasing problem worldwide and landscape metrics are very appropriate for detecting these changes quickly and at large scales.

As many wildlife species are core or edge specific, then it is essential to ensure the maintenance of these habitats. Edge depths

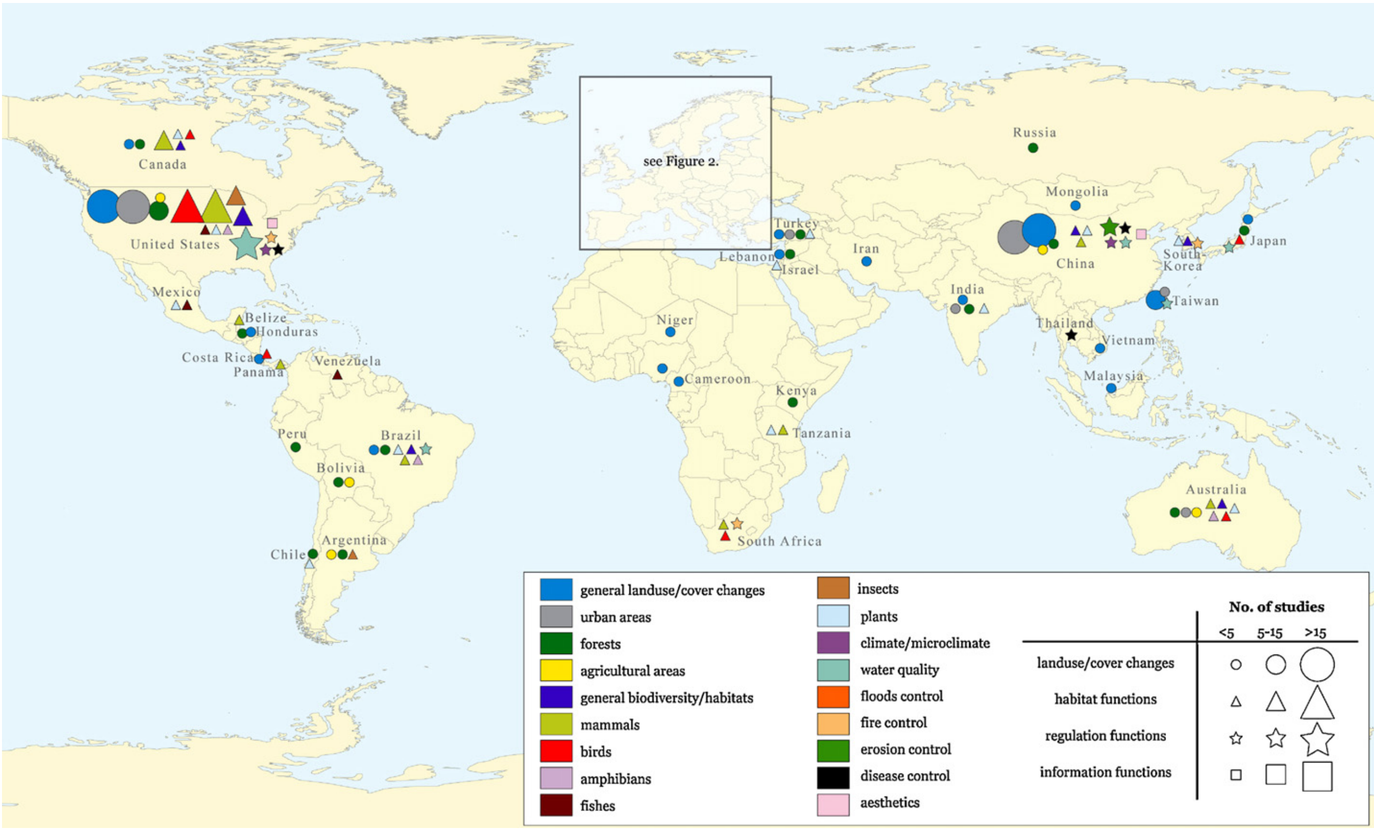

Fig. 2. No. of studies by research subject in the countries throughout the world (except Europe) (years 2000–2010). For Europe see Fig. 3.

can be specified by the user which makes the use of these metrics very efficient.

Surprisingly, there were very few articles focusing on agricultural areas (Table 1). There are some good examples where landscape metrics have been used for evaluation of the different policies on agricultural landscapes (Berger and Bolte, 2004; Pôças et al., 2011; Colson et al., 2011). However, in our opinion there should be more research on agricultural policies and whether they are fulfilling their goals. Traditional heterogeneous agricultural landscapes are disappearing because of the modern cultivation methods. Agricultural landscapes are mostly designed by farmers (Schaller et al., 2012). Shape metrics make it possible to efficiently assess the increase in the regularity of landscape pattern (Moser et al., 2002) and based on the evaluation results one can make amendments.

The overall increasing trend in exploiting landscape metrics' in evaluating land use changes shows their merits as change indicators in evaluating different land use management plans.

3.3. *Landscape functions*

3.3.1. *Habitat functions*

Landscape structure is crucial for the maintenance of diversity, both biodiversity and cultural diversity (Antrop, 2005b). Landscape

Table 1
No. of papers in different subcategories by year of publication.

Main category	Subcategory	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Evaluation of land use/cover patterns or changes	General land use/cover changes	5	6	8	6	8	10	14	12	20	27	12	128
	Urban areas	0	0	1	2	2	6	7	6	9	17	7	57
	Forests	2	3	4	2	1	3	10	5	5	12	5	52
	Agricultural areas	0	0	1	0	1	0	0	1	1	3	0	7
Landscape functions													
Habitat functions	Mammals	1	1	4	2	4	9	2	1	3	7	7	41
	Plants	0	0	3	3	2	5	4	2	5	6	5	35
	General biodiversity	1	1	2	2	3	5	4	1	5	2	5	31
	Birds	3	5	2	6	3	2	0	3	3	2	0	29
	Insects	1	0	0	0	1	2	1	2	2	3	0	12
	Amphibians	0	0	0	0	1	0	0	0	0	1	2	4
	Fishes	0	0	0	0	2	0	1	0	1	0	0	4
Regulation functions	Water quality	1	1	1	0	0	5	1	3	2	8	7	29
	Fire control	0	0	1	0	1	1	1	1	0	3	2	10
	Climate/microclimate	0	0	0	0	0	0	0	0	1	4	2	7
	Disease control	0	0	0	1	1	1	0	0	3	1	0	7
	Erosion control	0	0	0	0	0	1	0	1	0	2	1	5
	Floods control	0	0	0	0	0	0	0	0	0	1	0	1
Information functions	Landscape aesthetics	2	0	0	1	1	0	1	0	3	3	2	13

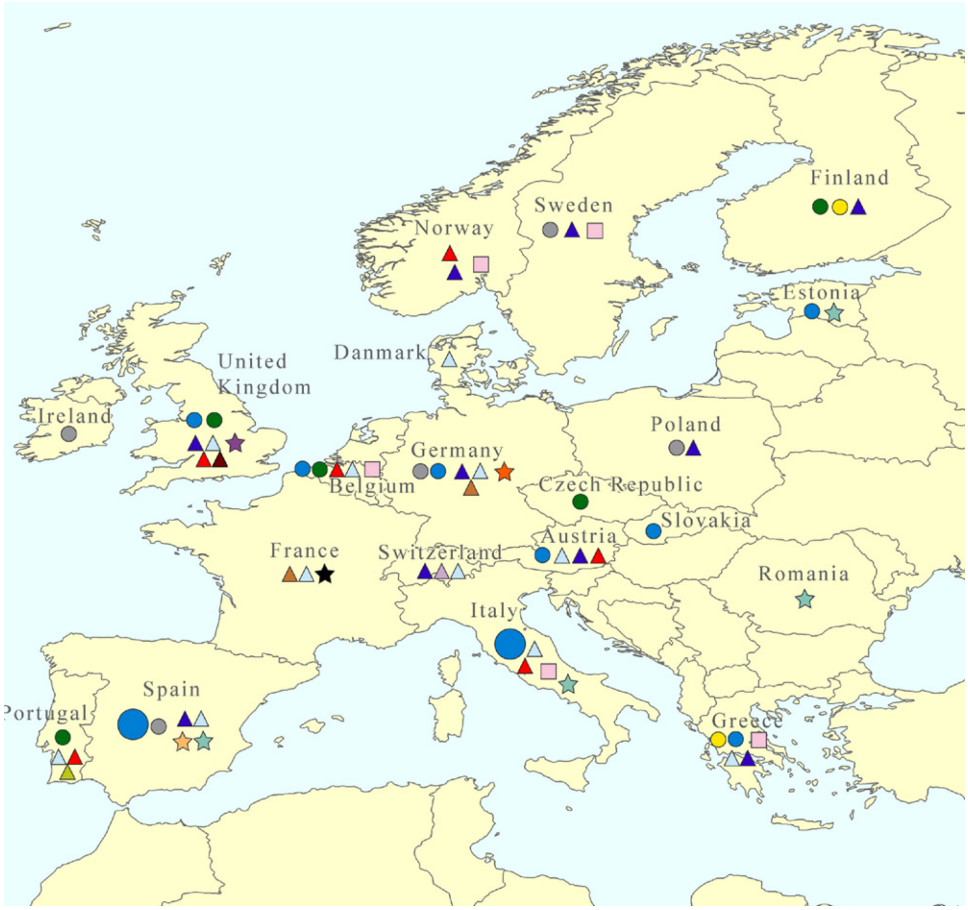

Fig. 3. No. of studies by research subject in Europe (years 2000–2010). For legend see Fig. 2; the scale of the items in the legend are the same.

metrics were initially designed for the quantification of the landscape pattern, which is considered to be a prerequisite for the study of pattern–process relationships (McGarigal et al., 2002), and they have undoubtedly been used very often in this field (Fig. 1; Uuemaa et al., 2009). There is no clear temporal trend in the number of publications in this field (Table 1). The number of publications does, however, fluctuate greatly, but there are too few studies in each group to draw any final conclusions. The highest number of studies has been performed about mammals (Table 1; Suppl. 1). In order to monitor the spatial distribution and habitat quality of different species, most of the studies use a modelling approach wherein landscape metrics are used as predicting variables (Leroux et al., 2007; Mikusinski and Edenius, 2006). Landscape composition (land use/cover proportion) appeared to play a more important role in mammalian biodiversity than configuration. However, many authors stress that increasing fragmentation caused by anthropogenic land-use change is one of the most frequently cited threats to species and genetic diversity worldwide (Martínez et al., 2010; McAlpine and Eyre, 2002). Therefore the effect of fragmentation on animal diversity is also most widely analysed. Several authors have also proposed a core set of metrics for biodiversity assessment (Schindler et al., 2008). These metrics could be used in establishing a landscape monitoring program to improve management decisions.

Surprisingly, the second most explored taxon was plants (Table 1; Suppl. 1). It is known that habitats composed of spatially heterogeneous abiotic conditions provide a great diversity of potentially suitable niches for plant species (Honnay et al., 2003). As concerns animal diversity, the shape of the patches appears to be quite irrelevant, but for plants the patch shape complexity is an effective measure of plant species richness (Gimona et al., 2009; Moser et al., 2002). Spatial heterogeneity may have differential effects on the distribution of native and non-native plant species richness (Kumar et al., 2006). Kumar et al. (2006) and Song et al. (2005) found that distribution patterns of invasive species can be determined with the help of landscape indices. Moreover, Viaud et al. (2008) showed that field pattern (size and shape) influences the pollen distribution. Connectivity is problematic in agriculture where the objective is to maintain the purity of cultivars, especially in the context of genetically modified crops (Viaud et al., 2008).

The relationship between landscape metrics and bird species richness and their habitat preferences has also been quite extensively studied (Table 1; Suppl. 1). Landscape metrics have been used most widely for the evaluation of the influence of environmental changes on bird richness (Lindenmayer et al., 2003; Thomson et al., 2008; Wrbka et al., 2008). Different studies have shown that bird species generally respond more strongly to the composition of land-cover classes than to the configuration of the landscape. From configuration metrics edge density has given good results in predicting abundance of birds (Fauth et al., 2000; Rehm and Baldassarre, 2007). Shape of the patches appears to play less role in bird diversity.

In addition to mammals, birds and plants, some studies have also been performed on insects, fishes and amphibians (Table 1). Most of the studies on insects focus on the relationships between pest distribution and landscape structure (Grilli, 2008; Radeloff et al., 2000). Many of the studies on insects are also related to epidemiology (see Section 3.3.2 below). We found only four studies on amphibians, and surprisingly, configuration metrics generally demonstrate closer relationships with amphibian habitat selection than composition metrics (Table 1; Hoss et al., 2010; Pellet et al., 2004).

Most of the studies are just measuring the structural edges of the habitats and not taking into consideration the functional part. Researchers should focus more on incorporating the contrast of edges into habitat analyses. There are multiple ways of determining the contrast between edges, for example using light conditions for weighing system.

There are many studies on different species habitat preferences and we think there is time for doing more synthesis analysis based on previous results for creating green corridor areas or evaluating whether protected areas are actually supporting the biodiversity conservation?

3.3.2. Regulating functions

The analysis of landscape regulating services is a new and promising area of research in landscape ecology, and also in the use of landscape metrics (Li and Mander, 2009). The most widely explored area in regulating functions was undoubtedly water quality (Table 1), which also showed a clear increasing trend in the number of publications. Landscape composition (particularly land use/cover proportions) has usually been revealed to be the most important parameter of water quality, and it demonstrates closer relationships with water quality parameters than configuration (Gergel, 2005; Moreno-Mateos et al., 2008; Uuemaa et al., 2005). The relationship between a watershed attribute and a landscape indicator may not be linear, and the potential for threshold responses must be considered (Gergel et al., 2002). It would be challenging to determine whether there are thresholds in some land use proportions or spatial arrangement beyond which the aquatic system changes irreversibly. Also using more detailed land use data (high resolution satellite imagery) in combination with LiDAR-data integrated into erosion models for analysing the impact of landscape factors of riparian zones to water quality should be under consideration.

The reduction of fire risk is one of the most important issues in forest management and planning, and metrics measuring fragmentation have provided good results in explaining the spreading of fires, and it has been found that fire severity is most dependent on forest composition, i.e. cover type, and is more likely to be low in forests with high patch density and diverse tree cover (Lee et al., 2009; Román-Cuesta et al., 2009). Landscape metrics have been successfully used to determine the spatial structure of fire-generated patterns, and most studies show that fire creates a more diverse and fragmented landscape pattern (Hudak et al., 2004).

We were unable to find any studies in which landscape metrics had been used as indicators for global climate change, but there were several studies on microclimate (Table 1). Most of these studies were on changes in land surface temperatures (urban heat islands) in urban areas and they showed that configuration metrics can be used for evaluating the intensity of urban heat islands in different areas (Liu and Weng, 2009; Zhao et al., 2010).

The impact of climate change will affect all types of land use, ecosystem services, and therefore also ecological processes (Opdam et al., 2009). Landscape pattern is linked to biodiversity and other ecological values of the landscapes and landscape ecology is largely founded on the notion that environmental patterns strongly influence ecological processes (Turner, 1989). Therefore there is need for integrating climate change into landscape ecological studies. Key challenges to modeling spatial and temporal processes in ecosystem ecology under changing climate conditions are the inclusion of individual species or functional types in ecosystem modeling (De Deyn et al., 2009), for example, how species range might expand or shift under climate change (Skidmore et al., 2011) and is it possible to predict or measure the shift from the previous land use and climate changes? Understanding the effect of climate change on landscape processes requires the combination of historical climate data and land use change data. Regional climate model (RCM) simulations have been applied to scenario computations for climatic change in the 21st century and RCM spatial resolution has continually increased (Skidmore et al., 2011). High resolution remotely sensed landscape variables for estimating species richness or other diversity measures can be used together with RCM-s, thus providing spatially explicit information about possible changes in biodiversity.

Although floods and soil erosion are an increasing problem in many parts of the world, there were only a few studies that have used landscape metrics in flood and erosion control (Table 1). All studies on soil erosion were performed in China (Fig. 2). The overall outcome showed that watershed landscape pattern has an impact on soil erosion, and landscape metrics can be useful for the assessment of soil erosion over large territories (Li, 2008; Ouyang et al., 2010; Wang and Li, 2010). We think that the landscape metrics are under exploited in this field because floods and soil erosion can be efficiently controlled by land use management (hedgerows, field pattern, etc.) and the spatial arrangement of land use is most easily detectable with the help of landscape metrics.

The structure of the landscape is also important to explain and understand the epidemiology associated with insects (Graham et al., 2004), and there are several papers in which landscape pattern has been associated with the spread of different disease-related insects and again fragmentation measures (patch density, largest patch index) appear to be most important indicators (Overgaard et al., 2003; Pradier et al., 2008; Yang et al., 2008; Suppl. 1). Landscape analyses make it possible to make predictions about how insect fauna will change as a result of landscape changes, and this enables better landscape planning for the suppression of populations of disease vectors (Overgaard et al., 2003).

3.3.3. Information functions

Although landscape aesthetics, landscape perception and local identity have been studied for many years (Franco et al., 2003; Kaplan and Kaplan, 1989; Ode et al., 2010a), the quantitative evaluation of the quality of a landscape remains a challenge because of the temporal dynamics of the landscape, the scale dependence of the view, 3-D difference, and differences between observers' abilities of perception (Li and Mander, 2009). The embedding of the concept of valuable landscapes in legislation such as the European Landscape Convention (Council of Europe, 2004) has led to the need for an 'objective' assessment of these values and the potential impact of changes to them, especially in Europe (Sang et al., 2008; Figs. 2 and 3). In recent years the number of studies in this field has increased (Table 1).

Numerous studies have found relationships between visual perception and landscape structure. People generally tend to prefer more open and heterogeneous landscapes where water is present (Franco et al., 2003; Dramstad et al., 2006; Palmer, 2004; Tveit, 2009). Moreover, Tveit et al. (2006) presented a framework with concepts describing visual landscapes and revealed a broad range of currently used visual indicators. This framework is a good basis for future research. In addition composition metrics Dramstad et al., 2006 found that spatial configuration is also related to people's landscape preferences, and these may therefore be suitable as indicators for the visual landscape. Landscape quality assessment highly depends on the data quality (Antrop, 2005a) and land cover is mostly used for this purpose. However, Ode et al. (2010b) underlined that landscape photographs can add information on the quality of land cover which is not reflected in land cover classes, for example land abandonment. Moreover, landscape metrics may fail to detect visible change in the land cover and landscape, especially when calculated on the whole area (Uuemaa et al., 2005; Ode et al., 2010b). Landscape metrics definitely cannot measure all the visual aspects of landscape but they can provide additional information in terms of monitoring aesthetic values of landscapes. In our opinion there is lack of studies where landscape metrics are tested as potential indicators for measuring different aspects of landscape visual character such as openness, naturalness, diversity, etc.

4. Conclusions

In order to understand the functioning of landscapes, landscape pattern must be considered, and indicators that address the spatial configuration of landscapes are therefore needed. The application of landscape metrics has broadened during the last 10 years, and the highest number of papers was found in leading journals on landscape ecology (Landscape Ecology, Landscape and Urban Planning, Forest Ecology and Management, etc.). The number of studies related to landscape regulation and information functions is increasing. The main field of exploitation of these metrics, however, remains the evaluation of the change in land use/land cover, and most studies have been performed in the U.S. and China. We also have a good done good job in understanding landscape's habitat functions. However, research should focus more on regulation functions because there is still a considerable lack of data on the many regulation functions and values of natural and semi-natural ecosystems and landscapes and, thus, we continue to take decisions on trade-offs between different land use options based on incomplete information (De Groot, 2006). In addition to this, more effort should be made for integrating our knowledge about regulating functions into studies about habitat regulations especially regarding to the climate change as one of the most important factors influencing ecosystems in the 21st century.

The main advantage of landscape metrics is their simplicity and speed of calculation, as rapid environmental changes demand easily obtainable indicators. Landscape metrics as a part of geospatial data analysis provide background information as well as scenario testing of environmental policies and monitoring goals set by international conventions and agreements.

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