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A partial order approach for summarizing landscape quality

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Abstract: We propose a simple mathematical framework to define consistently the environmental quality of a given landscape based on the relative abundances of the constituting land cover classes. Unlike traditional diversity measures, the new method does not evaluate the simple dispersion of the relative abundances of land cover classes, but assigns a weight to each land cover class according to the rank along a gradient of environmental quality. To clarify the ideas discussed, the method is illustrated with data from a pilot study to assess landscape changes in an Italian periurban area over the last 50 years.

Abbreviations: EQC - Environmental quality category, ILC - Index of landscape conservation status, LCC - Land cover class, LQP - Landscape quality profile.

Introduction

Landscapes could be recognised as a source of goods and services that contribute to human welfare, both directly and indirectly (Costanza et al. 1997, Daily 1997). However, the recent expansion and intensification of human land use have changed the kind and amount of such 'ecosystem services' provided by most landscapes. In many situations, human impact has depleted the ability of the landscape to provide services such as maintenance of fertile soils, biotic regulation, nutrient recycling, assimilation of wastes, sequestration of carbon dioxide, and maintenance of genetic information (Vitousek et al. 1986, Ehrlich and Ehrlich 1992, Paoletti et al. 1992, Odum 1993, Matson et al. 1997, Björklund et al. 1999).

Within this framework, there is a consensus about the need of environmental conservation programs aimed at protecting landscape integrity and functioning, thus preserving landscape quality. However, building a reliable picture of landscape quality is a complex task. Landscape evaluation is dependent on a large number of choices to be made. Therefore, trying to develop some standard methodology applicable over complex landscapes composed of different environments can be a challenging purpose. Although there are general landscape assessment criteria, the ranking of importance of these criteria and their precise interpretation may vary, thus changing the context of the analysis.

In this view, numerous techniques of landscape evaluation have been devised in recent years (McKenzie et al. 1992, Griffith and Hunsaker 1994, Weinstoerffer and Girardin 2000, Gulinck et al. 2001). Among others, the so-called 'ecological models' attempt to identify the relationships between landscape components, such as land cover classes, and environmental quality, using a wide range of environmental, ecological and socio-cultural factors. These relationships are then used to summarize overall landscape quality (Briggs and France 1980). Accordingly, one of the biggest problems in developing a synthetic index of landscape quality is that of weighting the contributions of specific landscape elements.

Weinstoerffer and Girardin (2000) evaluated the agricultural landscape quality of a farm in southern Alsace (France) by means of an indicator that measures the degree of agreement between landscape supply by farmers and landscape demand by the social groups. Supply and demand are both evaluated through four criteria: openness, upkeep, heritage, and diversity. Gulinck et al. (2001) proposed a methodological framework for landscape evaluation based on measurable indicators that can be derived mainly from land cover data and landscape structure characteristics. Such indicators need to be selected with reference to the particular objectives of the study and according to regional or local specificity and priorities.

Although both methods are able to evaluate the impact of land use patterns and intensity on landscape quality, the proposal of Weinstoerffer and Girardin (2000) requires many comprehensive data gathered from farmers (i.e., fields management practices). To the contrary, the method of Gulinck et al. (2001) can be effectively applied using existing cartographic information sources. In this framework, the aim of this paper is to propose a simple mathematical tool to consistently summarize the environmental quality of a given landscape based on the relative abundances of the constituting land cover classes (LCCs). For illustration, we use data from a pilot study to assess landscape changes in an Italian periurban area over the last 50 years.

The landscape quality profile

The ultimate aim of any summary statistics is to provide a manageable tool for characterizing and comparing different multivariate sets based on distinct objectives and motivations. However, it is generally understood that different indices may inconsistently rank a given pair of sets. Focusing on landscape quality assessment, imagine two artificial landscapes, A and B, composed of M and N land cover classes, respectively. In order to evaluate the quality of both landscapes, first, the LCCs of each landscape are reclassified into 5 environmental quality categories (EQCs) ordered along an ordinal scale ranging from 1 to 5, where 1 corresponds to the highest environmental quality and 5 to the lowest one. Next, the relative abundances of each EQC within each landscape are measured (Table 1). If our objective is to rank both landscapes with respect to their overall environmental quality, we face different options. For example, a straightforward way would consist in comparing both landscapes based on the relative abundance of the highest EQC. In this case, $EQC_{1(A)} = 0.15$ and $EQC_{1(B)} = 0.05$. Therefore, using this approach, landscape A is ranked higher than landscape B with respect to its environmental quality. An alternative solution might be to rank both landscapes based on the quality of the most abundant EQC. Here, in contrast to the previous approach, landscape B is ranked higher than landscape A, since $EQC_{max(A)} = 4$ whilst $EQC_{max(B)} = 3$.

This contradictory behavior raises the question: when is the overall environmental quality of a landscape higher than another *without reference to indices*? We have attempted to answer this question by defining a partial ordering method that is reminiscent of the Lorenz ordering

Table 1. Relative abundances of 5 hypothetical environmental quality categories (EQCs) composing the artificial landscapes A and B. The EQCs are ordered along an ordinal scale ranging from 1 to 5, where 1 corresponds to the highest environmental quality and 5 to the lowest one.

EQC	Relative abundances	
	A	B
1	0.15	0.05
2	0.20	0.05
3	0.15	0.35
4	0.30	0.25
5	0.20	0.30

used by economists to compare wealth distributions and by ecologists to compare the evenness or equitability of communities[1] (Patil and Taillie 1979, 1982, Taillie 1979, Gosselin 2001, Mosler 2001). The environmental quality of a given landscape can be described by a simple graphical device, the landscape quality profile (LQP). Imagine a landscape composed of N LCCs that are reclassified into M EQCs ($M \leq N$) ordered along a decreasing gradient of environmental quality so that the environmental quality of the i-th category is higher than the quality of category i+1 ($i = 1, 2, ..., M$). Given the ranked relative abundance vector of the M categories $\mathbf{p} = (p_1, p_2, ..., p_M)$ where $0 \leq p_i \leq 1$ and $\Sigma_i p_i = 1$, the LQP is obtained by plotting the cumulative relative abundance of the EQCs on the y-axis against the rank of the corresponding EQC. In other words, the polygonal path joining the successive points: $\pi_0 = (0, 0)$, $\pi_1 = (1, p_1)$, $\pi_2 = (1, p_1 + p_2)$, …, $\pi_M = (M, p_1 + p_2 + ... + p_M) \equiv (M, 1)$ is the LQP of the ranked relative abundance vector $\mathbf{p}$ (Figure 1).

Following this definition, the quality of landscape A is intrinsically higher than the quality of landscape B without reference to indices (written as A > B) if and only if landscape A has its LQP everywhere above that of landscape B. This is tantamount saying that the quality of landscape A is higher than that of landscape B, provided that B leads to A by a finite sequence of forward transfers of abundance from one EQC to another category with a strictly higher environmental quality. As a consequence, each measure that conforms to this 'landscape quality order' assumes a smaller value for landscape B than for landscape A. Notice that the proposed ordering method is only partial in that if A > B and B > C, then A > C. Nevertheless, two LQPs may intersect. That is, it is not necessarily true that for every A and B, either A > B or B > A.

1 The Lorenz order is actually a second degree stochastic dominance order of distributions scaled down by their means. To the contrary, the order we propose is a first degree stochastic dominance order that measures shifts in location, not in dispersion.

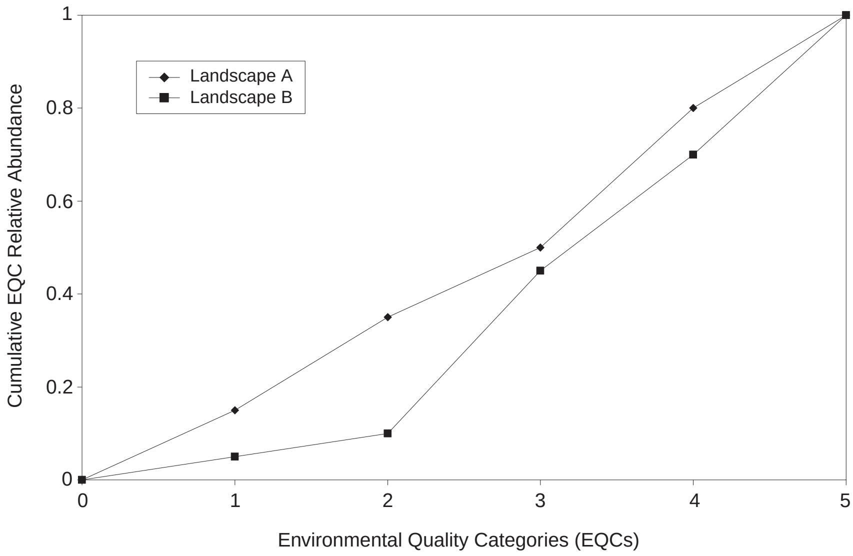

Figure 1. Landscape quality profiles of the artificial landscapes A and B of Table 1.

In this case, both landscapes are said to be non-comparable according to their LQPs. That is, A and B cannot be unambiguously ordered according to their overall quality since different measures of landscape quality *that conform to the proposed ordering method* rank them in contradictory ways.

Interestingly, a synthetic index for summarizing the quality of a given landscape was empirically proposed by Pizzolotto and Brandmayr (1996) as the normlaized area below the LQP. Denoting with x_i the cumulative relative abundance of the M EQCs such that $x_1 = p_1$, $x_2 = p_1 + p_2$, $x_M = p_1 + p_2 + ... + p_M$, Pizzolotto and Brandmayr (1996) proposed an 'index of landscape conservation status' (*ILC*) that can be expressed as

$$ILC = \frac{\left(\sum_{i=1}^{M} x_i\right) - 1}{M - 1} \qquad (1)$$

It is easily shown that *ILC* conforms to the proposed landscape quality order and ranges from 0 (if all LCCs composing the landscape are assigned to the EQC with the lowest environmental quality) to 1 (if all LCCs are assigned to the category with the highest environmental quality). From Equation (1) it follows that if A > B, then $x_{i(A)} \geq x_{j(B)}$ for any $i = j$, $i = 1, 2, ..., M$.

Notice that the operation of summarizing the landscape quality profile with a numerical index implies that, while the environmental quality categories initially come from a subjectively established rank order, in the profiles all ranked steps are quantitatively of the same weight. This seemingly counterintuitive procedure may be justified assuming that the LQP is constructed in a topological space rather than in a metric space in which, from a topological viewpoint, all (subjectively established) ECCs are equally weighted.

An example

To clarify the ideas discussed, data from a pilot study in Ariccia, a small village located about 30 km SE of the city of Rome (central Italy) was selected for analysis. This study is part of a broader landscape historical monitoring program to assess landscape changes around the major Italian towns over the post-war period.

The territory of Ariccia, approximately 1836 hectares, has an elevational extent from about 300 m a.s.l. on the lowest alluvial plains to 550 m a.s.l. According to Blasi (1994), its bioclimate is classified as Mesomediterranean. Until the 1970's, the study area used to be mostly rural, but in the last three decades, due to the intense commuter movements from Rome, the rural matrix has been considerably eroded by new settlements. The presence of an ancient hunting reserve called "Parco Chigi" that borders the northern side of the old town represents a rare example of residual forest of high naturalistic and scenic value. Holm oak (*Quercus ilex*) covers around 50% of the whole reserve, while the remaining area is composed of a combination of Holm oak and broadleaved deciduous trees, such as *Quercus cerris, Q. petraea, Carpinus betulus, Fraxinus ornus, Ostrya carpinifolia, Tilia cordata* and *Acer* sp.

Using panchromatic aerial photographs, two land cover maps of the study area at a scale of 1:25.000 were

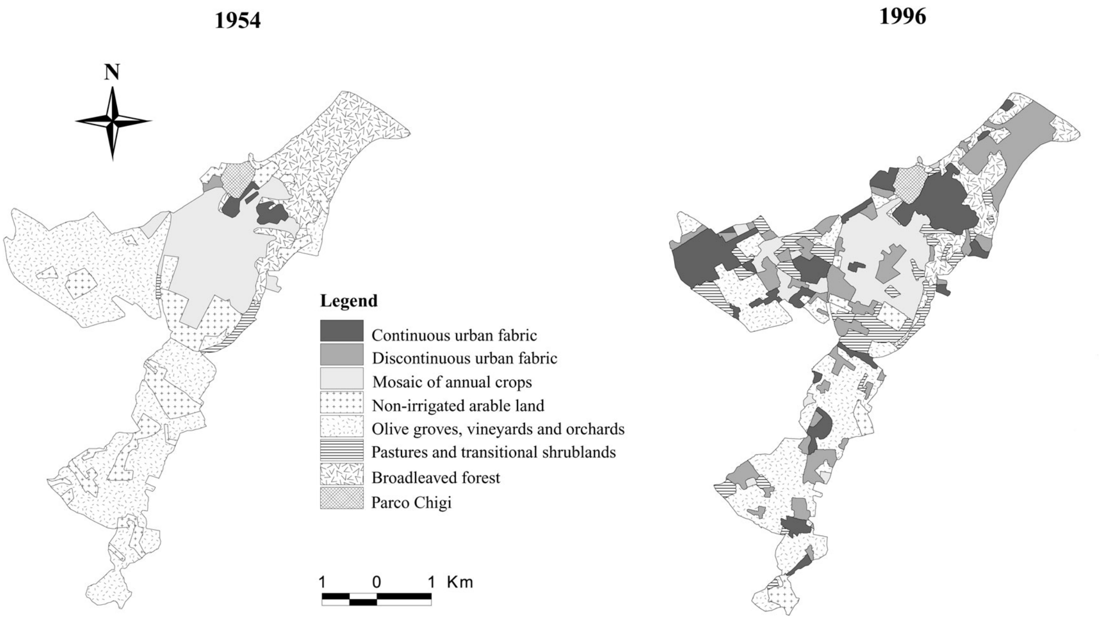

Figure 2. Land cover maps of the study area in 1954 and 1996.

produced for the periods 1954 and 1996 (Figure 2). Eight land cover classes were identified in both maps. In 1954, the study area can be described as a slightly fragmented rural matrix constituted by a mosaic of annual crops along with olive groves, vineyards and orchards. At higher altitudes, pastures and broadleaved forests prevail. In 1996, fragmentation and urbanization increased severely. In addition, following the abandonment of human activities such as grazing and agricultural practices, transitional shrublands became a significant constituent of the landscape, encompassing more than 10 percent of the study area. For a thorough analysis of the temporal dynamics of the study area over the period 1954-1996, see Campaiola et al. (2001).

Note that the land cover classification of Figure 2 is not a classification of landscape degradation or environmental quality. Therefore, in order to evaluate the overall quality of the study area, according to the results of an expert questionnaire, each land cover type was assigned an environmental quality rating between 1 and 5. Value 1 represents a natural land use type that is close to the potential natural vegetation of the study area. On the other extreme, value 5 represents a heavily disturbed LCC of limited value for nature protection. For a discussion on the application of potential natural vegetation as reference term for assessing the environmental quality of a given landscape, see Arrigoni and Foggi (1988) and Ricotta et al. (2002). As a result, both land cover maps were reclassified into 5 EQCs ordered along a gradient of increasing environmental degradation (Table 2).

Clearly, as stressed by Kienast (1993), current paradigms of nature conservation along with the particular research field of the experts are governing this quality rating. In our case, the expert panel was composed of five plant ecologists. Therefore, the experts opinions did not differ from each other by more than 1 score on the rank scale.

The information held by this new environmental quality classification was synthesized by the corresponding LQPs of Ariccia in 1954 and 1996 obtained by summing the relative abundances of the study area occupied by each EQC (Figure 3). Next, to map the environmental quality of Ariccia in 1954 and 1996 with scalars, the index of Pizzolotto and Brandmayr (1996) was computed from the LQPs of both periods.

The results show that $ILC_{(1954)} = 0.499$ and $ILC_{(1996)} = 0.358$. In other words, according to the index proposed by Pizzolotto and Brandmayr (1996), the overall landscape quality of the study area in 1954 was higher than the corresponding landscape quality in 1996. Nevertheless, in Figure 3, both LQPs intersect. Therefore, the analyzed landscapes are said to be non-comparable according to their LQPs. For instance, if we focus our attention solely on the EQC with the lowest environmental degradation value, we note that $x_{1(1954)} > x_{1(1996)}$ (i.e., $x_{1(1954)} = 0.182$, whereas $x_{1(1996)} = 0.109$). Conversely, due to the in-

Table 2. Relative abundances of the 8 land cover classes composing the study area in 1954 and 1996 along with the conversion table among land cover classes and environmental quality categories used for constructing the landscape quality profiles of Figure 3.

EQC	LAND COVER	1954		1996	
		Area (ha)	p_i	Area (ha)	p_i
5	Continuous urban fabric	31.7	0.017	307.5	0.167
5	Discontinuous urban fabric	6.2	0.003	348.1	0.190
4	Mosaic of annual crops	352.2	0.192	259.5	0.141
4	Non-irrigated arable land	267.4	0.146	57.9	0.032
3	Olive groves, vineyards and orchards	822.2	0.448	475.8	0.259
2	Pastures and transitional shrubland	22.6	0.012	186.6	0.102
1	Broadleaved forest	305.6	0.167	172.5	0.094
1	Parco Chigi	28.1	0.015	28.1	0.015
	Total	1836.0	1.000	1836.0	1.000

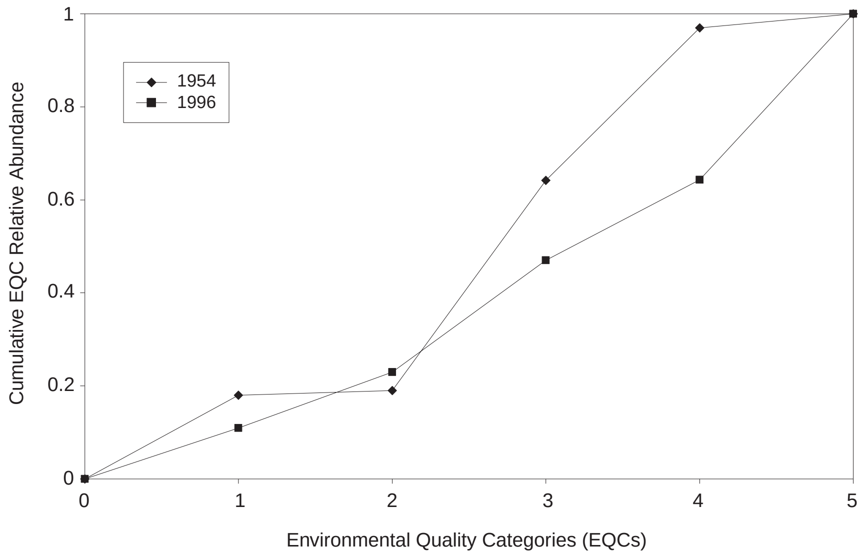

Figure 3. Landscape quality profiles of the study area in 1954 and 1996.

creased presence of transitional shrublands in the 1996 map, looking at the cumulative relative abundance of the first two EQCs, we obtain $x_{2(1954)} < x_{2(1996)}$ (i.e., $x_{2(1954)} = p_{1(1954)} + p_{2(1954)} = 0.194$, whereas $x_{2(1996)} = p_{1(1996)} + p_{2(1996)} = 0.211$).

During the period 1954-1996, the transformation of Ariccia from a prevalently rural landscape to a periurban suburb of Rome gave rise to two contrasting tendencies. On one hand, part of the forests and agricultural areas was substituted by new settlements of lower environmental quality. On the other hand, the abandonment of traditional activities, such as grazing and agricultural practices, resulted in a significant increase of transitional shrublands with higher environmental quality. As a consequence of these contrasting tendencies, the LQPs of the study area in both periods intersect and both landscapes cannot be intrinsically ranked based on the proposed landscape quality profile.

Conclusions

In this paper, we propose a simple mathematical framework to consistently define the overall environmental quality of a given landscape. Our approach incorporates a partial ordering technique similar to the partial ordering techniques used by ecologists within the framework of biological diversity theory (Patil and Taillie 1982, Tóthmérész 1995, Nijssen et al. 1998, Rousseau et al. 1999). For the mathematical analogies between the proposed ordering method and concentration measures, see Izsák and Papp (1998) and Mosler (2001). Unlike more traditional landscape diversity or evenness measures (McGarigal and Marks 1995), the proposed landscape quality profile does not evaluate the simple dispersion of the relative abundances of land cover classes, but gives importance to the rank of each LCC along a gradient of environmental quality (Pizzolotto and Brandmayr 1996). Based on the LQP, landscape A is ranked higher than landscape B with respect to its overall quality if and only if landscape A has its LQP everywhere above that of landscape B. We further demonstrated that the summary statistics termed 'index of landscape conservation' empirically proposed by Pizzolotto and Brandmayr (1996) conforms to the proposed landscape quality order. In this view, the ILC is theoretically justified for summarizing the environmental quality of a given landscape.

Nonetheless, the proposed ordering method should not be uncritically accepted. For instance, the shape of the landscape quality profile of a given landscape heavily depends on the classification schemes adopted both for constructing the land cover map and for reclassifying the land cover classes into environmental quality categories. There is not one ideal classification of land cover. Any classification is made to suit the needs of a particular category of users. In this sense, additional work is needed to evaluate the effect of adopting different classification schemes on the shape of the landscape quality profile. Finally, it is again worth stressing that there is no 'ultimate measure' of landscape quality, as in quantifying landscape quality many different and often contrasting demands are competing. Therefore, any rating into environmental quality categories should be interpreted with caution. Nonetheless, as suggested by Maasoumi (1986) and Mosler (2001) in a slightly different context, to *partially* solve this problem multivariate landscape quality indices may be used that conform to a multivariate version of the proposed partial order method.

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