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Stochastic Evaluation of Landscapes Transformed by Renewable Energy Installations and Civil Works

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Abstract: Renewable energy (RE) installations and civil works are beneficial in terms of sustainability, but a considerable amount of space in the landscape is required in order to harness this energy. In contemporary environmental theory the landscape is considered an environmental parameter and the transformation of the landscape by RE works has received increasing attention by the scientific community and affected societies. This research develops a novel computational stochastic tool the 2D Climacogram (2D-C) that allows the analysis and comparison of images of landscapes, both original and transformed by RE works. This is achieved by a variability characterization of the grayscale intensity of 2D images. A benchmark analysis is performed for art paintings in order to evaluate the properties of the 2D-C for image analysis, and the change in variability among images. Extensive applications are performed for landscapes transformed by RE works. Results show that the 2D-C is able to quantify the changes in variability of the image features, which may prove useful in the landscape impact assessment of large-scale engineering works.

Keywords: renewable energy; stochastic analysis of images; landscapes transformation; landscape visual impact assessment; optimizing landscape architecture

1. Introduction

Globally, the scale of the transformation caused to landscapes from renewable energy (RE) developments is larger than ever. Indicatively, in countries with high wind energy utilization rates, the percentage of land area in which wind turbines are clearly visible is 18% in Spain [1], 21% the Netherlands [2], and 46% in Scotland [3]. Regarding solar parks, the percentage is 4.8%, in the only national-scale study, to date, with data from Spain. These studies demonstrate the scale of the visual intrusion of wind and solar energy into landscapes and justify why strong opposition on visual-impact grounds has emerged against RE projects [4,5]. This friction, between RE and landscape has consistently been the cause of delays in the development of RE projects and has raised the issue of landscape management in Europe [6] and globally. It is important to note that 40% of the citizens in Greece think that RE infrastructure causes significant visual disturbance in the landscape [7] and the prospect of installing RE infrastructures in Greece has led to the formation of many opposing activist groups, e.g., in south Aegean islands [8], Crete [9], Pindos [10], Pilio [11], and Samothraki [12].

Some basic contributors to the generation of significant visual impact from RE projects are the large requirements of land use, more evident in the case of solar energy [13,14], as well as the great dispersion of facilities and equipment that is characteristic of wind energy [15]. However, these characteristics are also present, to an extent, in hydroelectric projects, which in contrast to wind and solar developments have not been opposed significantly from a landscape-impact perspective, even though hydroelectricity is the type of RE with the highest installed capacity globally [16]. One important aesthetic difference between solar and wind developments on the one hand and hydroelectric developments on the other hand, is that hydroelectricity produces a new landscape which is to a great degree seemingly natural. The hydroelectric landscape mainly consists of an artificial lake—a reservoir, in contrast to wind and solar developments, in which the new landscapes developed, are dominated, visually, by human-made industrial machines. Thus, wind and solar energy projects have been significantly critiqued on industrializing landscapes.

To mitigate this industrial intrusion and facilitate the expansion of RE, several different objective methods have been developed to quantify and evaluate visual impact from RE, ranging from photomontage and digital representation to GIS viewshed analyses [17]. These methods can be divided into two broad categories, those focusing mainly on the quantitative aspect of landscape impact and those that focus on qualitative.

Qualitative methods commonly focus on the identification and explanation of the aesthetic elements of renewable energy landscapes. They include several different approaches, such as the evaluation of the psychometric effect of transformations of landscapes [18], visualization techniques [19], and multicriteria analysis that include both qualitative and quantitative analysis [20,21]. Quantitative methods are usually based in visibility analyses using GIS, to calculate the extents of the area affected [22,23]. In these methods the basic parameters that are considered determinant of this impact are: viewing distance, atmospheric clarity, and color contrast with background [24,25]. They are used mostly to optimize the sitting of a new RE project or to evaluate its landscape impact in the form of an environmental impact analysis.

Other methods to evaluate the landscape and visual impact assessment [26–31] rely on an appreciation of the existing landscape, a holistic understanding of the developed proposals considering the original landscape character, the magnitude of change, the sensitivity to change and the potential to mitigate impacts.

The proposed method of image analysis, aims to analyze the landscape transformation caused by the installation of RE infrastructures and other civil works in the natural landscape, through stochastic analysis. Based on this methodology, we examine the impact of RE works in a given landscape by visualizing and analyzing edited versions of original landscapes. This transformation of images is not uncommon as it is typical to create 3D or 2D images in architecture and landscape design of future works prior to construction in order to evaluate their landscape integration. Here however, we provide an additional tool that may aid in the characterization of the degree of the integration.

2. Methodology

2.1. Stochastic Analysis in 2d

Image processing typically involves filtering or enhancing an image using various types of functions in addition to other techniques to extract information from the images [32]. Image segmentation is one of the basic problems in image analysis. The importance and utility of image segmentation has resulted in extensive research and numerous proposed approaches based on intensity, color, texture, etc., which are both automatic and interactive [33]. A variety of techniques have been proposed for the quantitative evaluation of segmentation methods [34–41]. This analysis for image processing is based on stochastic tool based in climacogram (variability vs. scale).

Stochastic calculus helps in developing a unified perception of natural phenomena and expel dichotomies like random vs. deterministic. It seems that rather both randomness and predictability coexist and are intrinsic to natural systems which can be deterministic and random at the same time, depending on the prediction horizon and the time scale [42,43].

A variety of processes exhibit Long-Term Persistence (LTP) behaviour [43] such as temperature, humidity, surface wind, precipitation, atmospheric pressure, river discharges etc. [44]. Particularly, all these processes are characterized by high unpredictability due to the clustering of events. The behavior of some processes to exhibit high unpredictability due to the clustering of events was first identified in nature by H.E. Hurst in 1951 while working at the River Nile, although its mathematical description is attributed to A. N. Kolmogorov who developed it while studying turbulence in 1940. Koutsoyiannis [42] named this behavior as Hurst-Kolmogorov dynamics (HK), to give credit to both contributing scientists.

The proposed methodology for image processing, the 2D-Climacogram (2D-C), has been developed within the context of LTP and has been successfully applied to images for the analysis of geophysical properties of rocks and geological formations [45] and Earth topography [46] but it is the first time that this methodology has been employed to analyze the transformation of the landscape, whether this transformation significantly alters the natural variability.

For this purpose, each image is digitized in 2d based on grayscale color intensity and the climacogram is calculated based on the geometric scales of adjacent pixels. Assuming that our sample is an area $n\Delta \times n\Delta$, where n is the number of intervals (e.g., pixels) along each spatial direction and Δ is the discretization unit (determined by the image resolution, e.g., pixel length), the empirical classical estimator of the climacogram for a 2d process can be expressed as:

$$\underline{\hat{\gamma}}(\kappa) = \frac{1}{n^2/\kappa^2 - 1} \sum_{i=1}^{n/\kappa} \sum_{j=1}^{n/\kappa} \left(\underline{x}_{i,j}^{(\kappa)} - \underline{\overline{x}} \right)^2 \tag{1}$$

where the "^" over γ denotes estimate, κ is the the dimensionless spatial scale, $\underline{x}_{i,j}^{(\kappa)} = \frac{1}{\kappa^2} \sum_{\psi = \kappa(j-1)+1}^{\kappa j} \sum_{\xi = \kappa(i-1)+1}^{\kappa i} \underline{x}_{\xi,\psi}$ is the sample average of the space-averaged process at scale κ, and $\underline{\overline{x}} = \sum_{i,j=1}^{n} \underline{x}_{i,j}/n^2$ is the sample average. Note that the maximum available scale for this estimator is $n/2$.

The LTP or HK behaviour can be summarized by the Hurst parameter as follows. The isotropic HK process with an arbitrary marginal distribution (e.g., for the Gaussian one, this results to the well-known fractional-Gaussian-noise, Mandelbrot and van Ness, [47]), i.e., the power-law decay of variance as a function of scale, is defined for a 1d or 2d process as:

$$\gamma(k) = \frac{\lambda}{(k/\Delta)^{2d(1-H)}} \tag{2}$$

where λ is the variance at scale $k = \kappa\Delta$, d is the dimension of the process/field (i.e., for a 1d process d = 1, for a 2d field d = 2, etc.), and H is the Hurst parameter ($0 < H < 1$). For $0 < H < 0.5$ the HK process exhibits an anti-persistent behaviour, $H = 0.5$ corresponds to the white noise process, and for $0.5 < H < 1$ the process exhibits LTP.

The algorithm developed by Dimitriadis [45] processes in MATLAB rectangular images. In particular, for the current analysis, the images are cropped in 400 × 400 pixels, 14.11 × 14.11 cm, in 72 dpi.

2.2. Illustration of Stochastic Analysis in 2d

The pixels analyzed are actually represented by numbers based on their grayscale color intensity. Figure 1 present the steps of analysis, Figure 1a shows an example of pixels in 2d picture, Figure 1b shows grouped pixels at scale k = 2 and Figure 1c shows grouped pixels at scale k = 5 used to calculate the climacogram.

An example of climacograms generated by data sets with different statistical characteristics is presented in Figure 2a,c. Typical examples of the results related to data are presented in Figure 2b,d. Figure 2a,c show a random time series in red and time series partly shifted in blue showing clustering behavior which mimic LTP. The presence of clustering in the blue series is demonstrated by the climacogram behavior which shows a marked difference for the random series (in red). Specifically the variance of the standardized series is notably higher than that of the random series at all scales, indicating a greater degree of variability of the process (Figure 2b,d in blue). Likewise between the two shifted series (Figure 2a,c in blue) the one with the more pronounced clustering behavior (Figure 2a, in blue) is also characterized by a greater degree of variability (Figure 2b in blue).

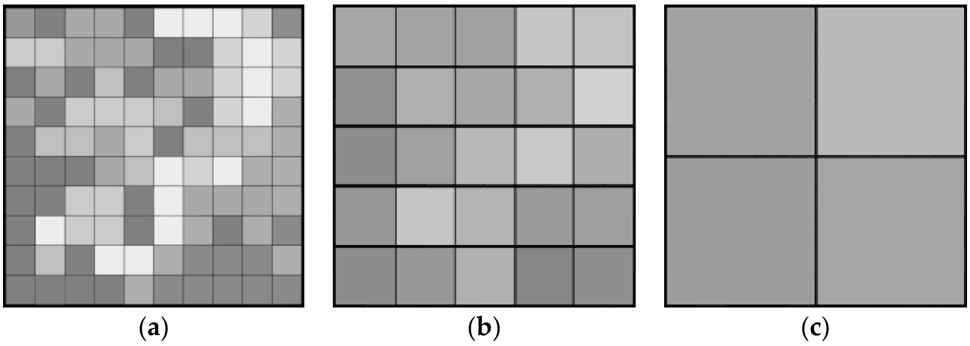


Figure 1. Steps of image analysis. (**a**) Example of pixels in 2*d* picture; (**b**) grouped pixels at scale $k = 2$; (**c**) grouped pixels at scale $k = 5$ used to calculate the climacogram.

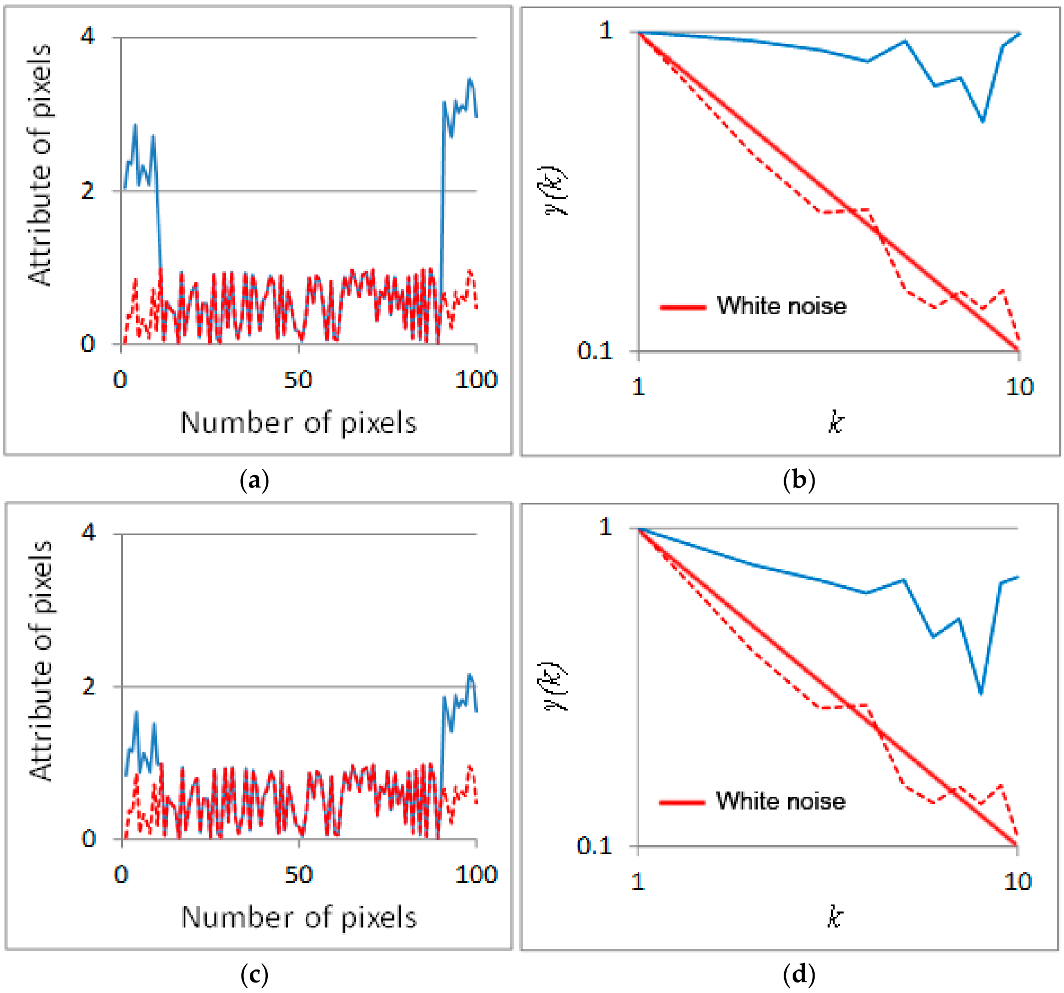
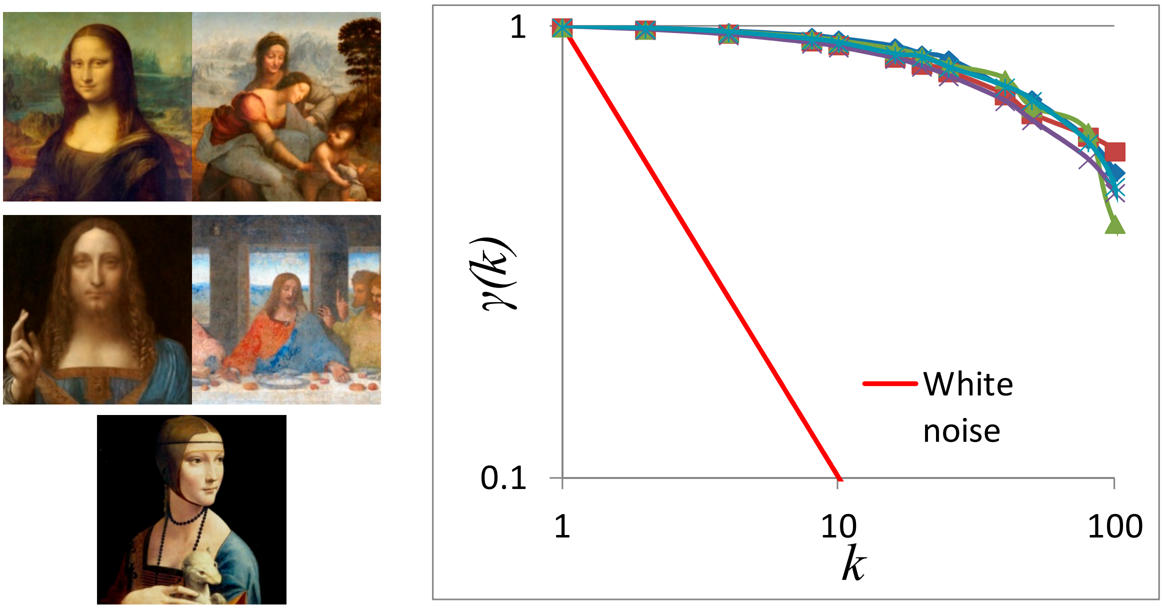


Figure 2. (**a**,**c**) Examples of data series with different statistical characteristics in one dimension; Colum (**b**,**d**) Standardize climacograms of data series of (**a**,**c**).

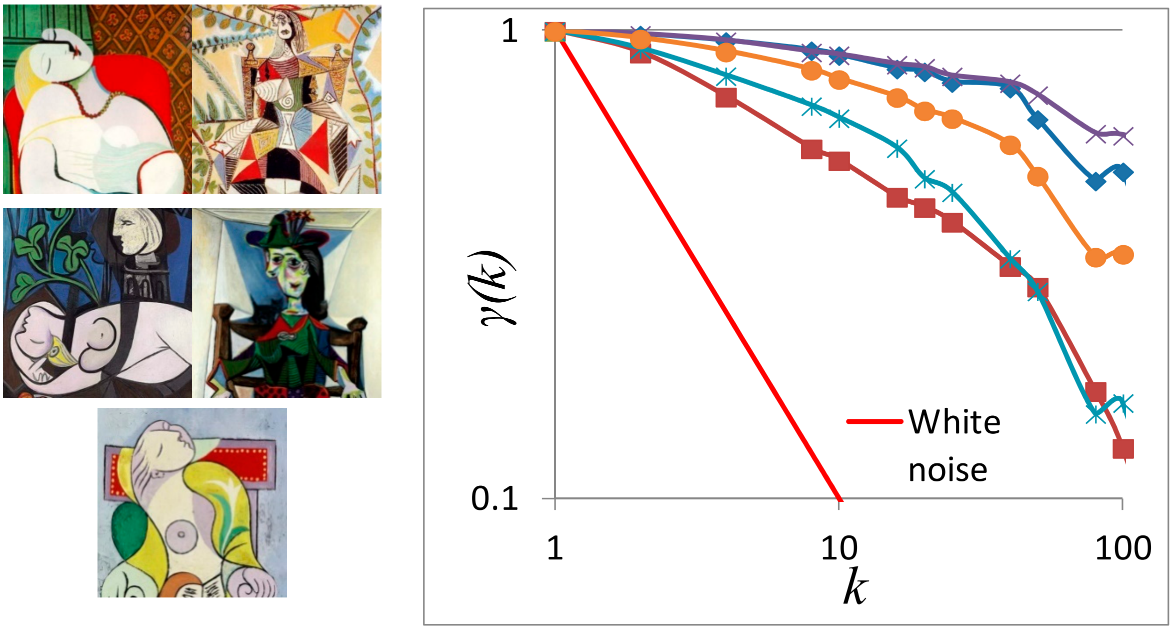
3. Benchmark Application in the Analysis of Art Paintings

The following evaluation of art paintings is intended as a benchmark for the study of the variability behavior of landscape images. In order to assess the algorithm's performance, we use as a basis the results from analysis of well-known art paintings arising from different artistic movements, whose characteristics are well understood [48]. This analysis examines six important painters based in chronological order: Leonardo di ser Piero da Vinci (1452–1519) Figure 3 and Figure S3, Michelangelo Merisi da Caravaggio (1571–1610) Figure S4, Rembrandt Harmenszoon van Rijn (1606–1669) Figure S5, Vincent van Gogh (1853–1890) Figure S6, Pablo Picasso (1881–1973) Figure 4 and Figure S7, Wassily Kandinsky (1866–1944) Figure S8.



(**a**) (**b**)

Figure 3. (**a**) Paintings of Leonardo da Vinci (1452–1519); (**b**) Standardized climacograms of the art paintings of Leonardo da Vinci.



(**a**) (**b**)

Figure 4. (**a**) Paintings of Pablo Picasso (1881–1973); (**b**) Standardized climacograms of the art paintings of Picasso.

Averages of the climacograms of the examined artworks of the painters are presented in Figure 5. It appears that the works by Leonardo da Vinci and Kandinski, even if they have totally different content, exhibit stochastic similarity (Figures S3 and S8). Instead, Picasso's artworks (in stochastic view) display a wide range of fluctuations (Figure 4). Patterns can be observed in terms of the dependence structure among the different artistic movements as well, with Renaissance and Baroque painters having a strong persistence structure (average $H \approx 0.89$), and modern works by Van Gong, Picasso and Kandinski corresponding to a weaker (but still HK-type) structure (average $H \approx 0.85$). Although we see many different stochastic structures of the examined paintings which are generally accepted as great artworks (Figure 5), therefore a general stochastic structure of beauty is not revealed by 2D-C.

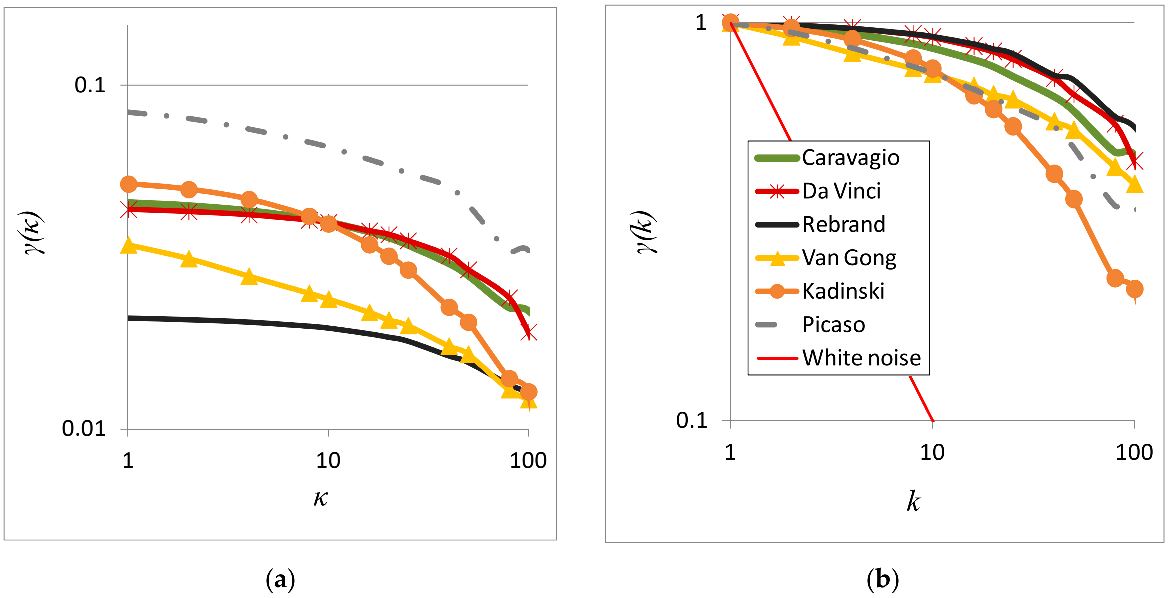


Figure 5. (**a**) Averages of the climacograms of the artworks; (**b**) Averages of the standardized climacograms of the artworks.

Thus, we can see that evaluating the image with climacograms provide us with insights in to the stochastic properties of artworks and justifies the further analysis of a more practical problem as the transformation caused to landscapes from RE installations.

4. Application in Analysis of the Transformation of Landscape by RE Installations and Civil Works

In order to analyze the transformation produced by RE technologies to landscapes, images of natural landscape are used. The selected landscapes are suitable for the installation of RE projects, and we add RE installations of civil works to transform them.

Climacograms of the transformed landscape describe some aspects of the landscape transformation. Figures S10–S24 in supplementary material of the paper show the variation of the climacograms corresponding to different RE installations and civil works.

Figures S12–S16, S18 and S19 show that when the natural landscape is replaced by either the city landscape or RE installations the variability of the original image is decreased at scale $\kappa = 1$ as expected. Instead, if the RE installation has a "smooth" landscape background as wind turbines in the sky (Figures S23 and S24) solar panels in fields (Figures S21 and S22) or solar panels in the desert (Figure S20), the variability of the original image is increasing.

We also notice that the results are related to the shape and the nature of the landscape but a general rule cannot be obtained by these case studies. For example, there is a different stochastic behavior in solar panels. Standardized climacograms of solar panels show stronger dependence structure (Figures S17 and S20–S22) compared to the natural landscape, and weaker in Figures S15, S18 and S19. On the contrary, standardized climacograms of wind turbines in the landscape show weaker dependence structure compared to the original landscape, i.e., clustering behavior (Figures S14, S18, S19, S23 and S24).

4.1. Evaluating Future Scenarios of Landscape Transformations by Civil Works

In the first application of the methodology, we examine the impact of RE works in a given landscape by considering edited versions of the original landscape [49].

Thus, in the original landscape Figure 6 and Figure S11–S24 we transform using Photoshop CS5 software and we evaluate them according 2D-C.

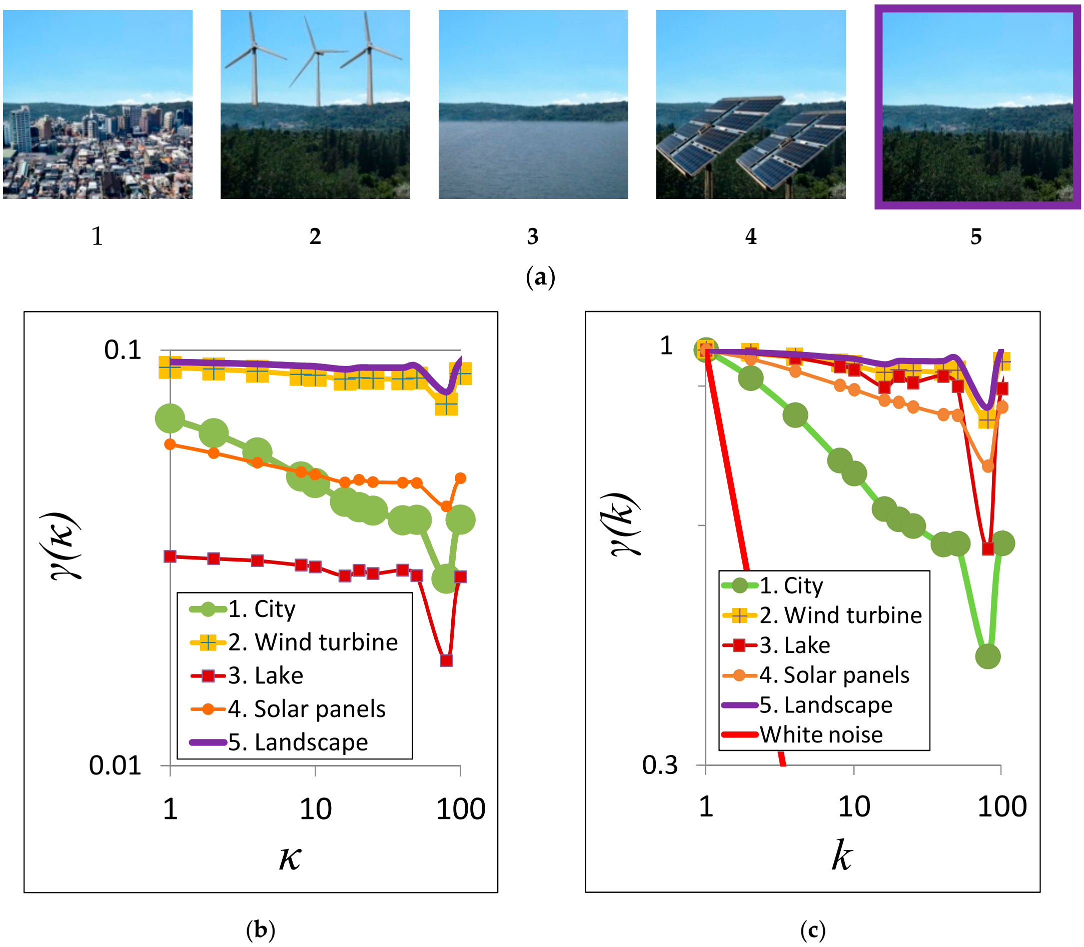


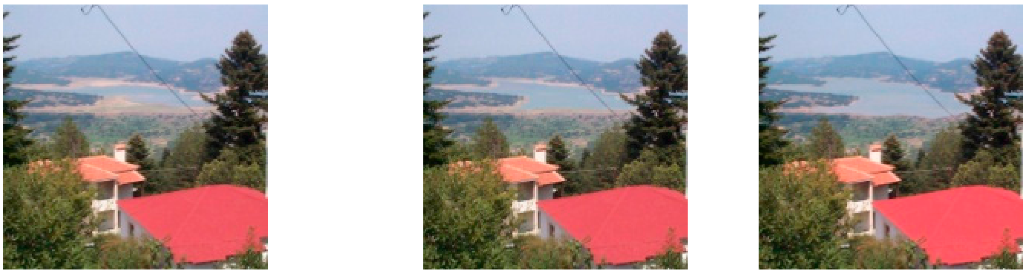
Figure 6. (**a1**–**a4**) Transformed landscape (**a5**) Original landscape (**b**) climacograms of images (**a1**–**a5**) (**c**) standardized climacograms of images (**a1**–**a5**).

Figure 6b shows that replacing this natural landscape by either the city landscape or RE installations, the variability of the original image is decreased at scale $\kappa = 1$, as expected. Furthermore, in order to make a fair comparison of the depended structure associated with each transformation, we evaluate the standardized climacograms of Figure 6c. It can be seen that the city landscape shows the weaker dependence structure, i.e., clustering behavior, compared to the natural landscape, whereas the RE installations exhibit a weaker dependence than that of the natural landscape yet as stronger one compared to a highly urbanized landscape.

4.2. Landscape Analysis, the Case of Plastiras Lake

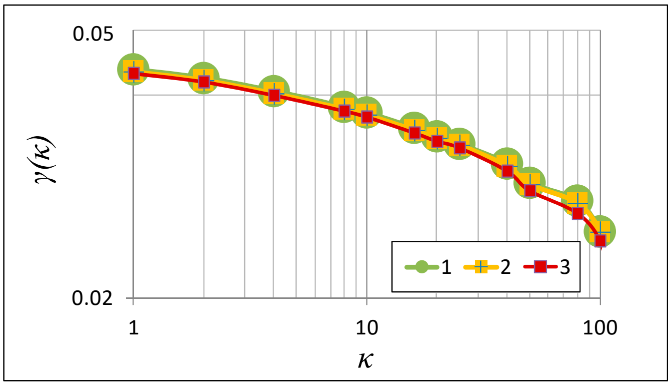
The Plastiras Lake is an artificial lake in central Greece constructed in 1959. The concept of the specific dam construction was the production of electricity and the irrigation of the Thessalic Plain. The water levels of the lake showed many fluctuations due to water abstractions for hydroelectricity and irrigation proposes. Consequently, not long after its construction, the aesthetic degradation occurring when the water level drops and the dead zone is revealed, became part of different studies concerning the lake [50–53].

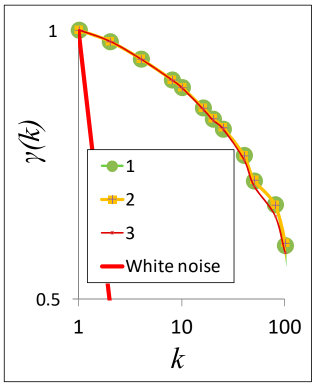
The Plastiras Lake landscape can be generally separated in two parts, the northern and southern, which have a totally different morphology. The northern part resembles a natural lake Figure 7a (in which when the level of the lake is decreased the observer sees a subnormal dead zone) and the south part of the landscape which is closer to that of an artificial lake Figure 8a (in which when the level of the lake is decreased the observer sees a normal dead zone) [54]. Through the attempt to evaluate the differences in the landscape, and due to the change of the water level, the southern part of the lake was considered more interesting than the northern part in terms of landscape quality. The above phenomenon was discussed and interpreted in related papers [55,56].



1 **2** **3**

(**a**)





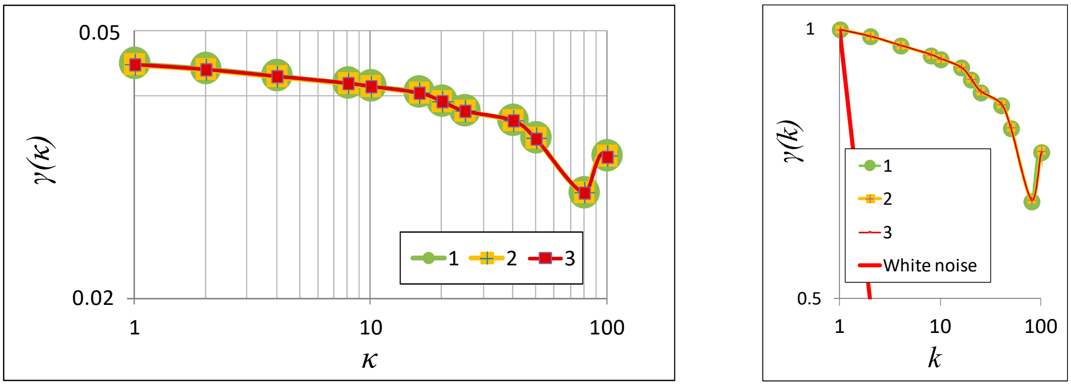
(**b**) (**c**)

Figure 7. (**a1**–**a3**) Transformation of landscape of Plastiras caused by the fluctuation of the lake water elevation in the area of subnormal dead zone; (**b**) climacograms and (**c**) standardized climacograms of images (**a1**–**a3**).

1 **2** **3**

(**a**)

Figure 8. *Cont.*



(**b**) (**c**)

Figure 8. (**a1**–**a3**) Transformation of landscape of Plastiras caused by the fluctuation of the lake water elevation in the area of normal dead zone; (**b**) climacograms and (**c**) standardized climacograms of images (**a1**–**a3**).

According to the analysis made based on the physical properties, the appearance of the landscape and the questionnaires of the observers, the result was that between normal dead zone and subnormal dead zone, the transformation of the latter zone when the level of the lake decreased was a problem for the aesthetic value of the landscape [57].

Applying 2D-C in transformed images of the Plastiras landscape, a change of the landscape due to the appearance of the subnormal dead zone is noticed despite being small (Figure 7). On the contrary, the climacograms of the lake without dead zone and of the lake with normal dead zone are almost identical (Figure 8).

5. Discussion and Conclusions

The meaning of beauty is linked to the evolution of human civilization. Since the beginning of civilization, human minds have been embodying their creativity in different forms of art or architecture in the search for beauty, from prehistoric cave paintings to the various forms of contemporary art. These works of art create feelings and disseminate ideas and messages, underlying or upfront, through their communication with the intellect. In different stages of history, the meaning of beauty has even been in the frontline of the struggle of human civilizations for progress, expressing social and political ideas that were far from being implemented in the societies of those times [48].

But what does it mean that something is more beautiful than something else and how more beautiful is it? If this concept has to do with nature, the problem is unresolved because (according to Kant) nature is the pinnacle of beauty [58]. Moreover, Kant noted that “no objective rules of taste can be given which would determine what is beautiful through concepts” [59].

Nonetheless, our work aims at comparative analysis of transformations of natural landscapes that are considered of high aesthetic value, and not to draw universal aesthetic conclusions. Thus, this paper examines the transformation of the landscape and not the beauty of the landscape per se. In landscape analysis, the transformation of the landscape is against the concept of sustainability as “there is an additional focus on the present generations’ responsibility to regenerate, maintain and improve planetary resources for use by future generations.” [60]. In modern environmental analysis, the natural landscape is also considered an environmental resource. Therefore, the transformation of the landscape with RE installations, needs to be taken into account as a parameter of the multicriteria design of the RE projects.

This paper introduces a new computational tool (2D-C), as opposed to subjective evaluation, in comparative landscape analysis. 2D-C is a tool capable of characterizing the degree of variability in images using stochastic analysis, and thus, the change in variability vs. scale, among images. As a benchmark, the 2D-C was tested in images of art paintings and subsequently, it was applied to landscapes transformed by new RE installations of civil works in order to quantitatively characterize the degree of visual change by each intervention, with respect to the natural variability of the original landscape.

This methodology can be applied in image processing comparing RE installations and civil works in order to quantitatively evaluate the transformation in variability vs. scale of the landscape. The analysis allows for the following observations.

1. The evaluation of images with 2D-C can be useful in landscape aesthetics problems as the quantitative analysis can serve as a basis for objectivity in the evaluation of landscape changes.
2. 2D-C can evaluate one image of the landscape by a specific view point in a specific time. Thus, we cannot have a holistic approach of the landscape. However, as methods of the landscape analysis seek a global approach identifying landscape with multicriteria analysis, 2D-C could serve as a new quantitative criterion.
3. 2D-C provides only a relative score among the transformed images, while sources of uncertainty relating to objective segmentation of images need also to be further studied. Nevertheless, 2D-C can serve as a robust stochastic tool for comparisons, with promising results regarding the possible generalized application to image analysis.

At present this paper provides a methodological contribution which is novel. Therefore, conclusions mainly relate to the insights we gain from specific case studies. A big data analysis would be required in order to move from the methodological contribution to factual information on the impact of RE installations. More data and studies are necessary to examine whether these results are positively correlated with aesthetical parameters.

Supplementary Materials: This supplementary material contains image analysis climacograms of art paintings and landscapes transformed by renewable energy installations and civil works. The following are available online at http://www.mdpi.com/1996-1073/12/14/2817/s1. Figure S1: Landscapes. withought renwable energy instalations, Figure S2: Transformation of the landscape of Plastiras lake, Figure S3: (a) Paintings of Leonardo da Vinci (1452–1519); (b) Standardized climacograms of the art paintings of Leonardo da Vinci; (c) climacograms of the art paintings of Leonardo da Vinci, Figure S4: (a) Paintings of Michelangelo Merisi da Caravaggio (1571–1610); (b) Standardized climacograms of the art paintings of Caravaggio; (c) climacograms of the art paintings of Caravaggio, Figure S5: (a) Paintings of Rembrandt Harmenszoon van Rijn (1606–1669); (b) Standardized climacogram of the art paintings of Rembrandt; (c) climacograms of the art paintings of Rembrandt, Figure S6: (a) Paintings of Vincent van Gogh (1853–1890); (b) Standardized climacogram of the art paintings of Vincent van Gogh; (c) climacograms of the art paintings of Vincent van Gogh, Figure S7: (a) Paintings of Pablo Picasso (1881–1973); (b) Standardized climacogram of the art paintings of Picasso; (c) climacograms of the art paintings of Picasso, Figure S8: (a) Paintings of Wassily Kandinsky (1866–1944); (b) Standardized climacogram of the art paintings of Kandinsky; (c) climacograms of the art paintings of Kandinsky, Figure S9: (a) Averages of the examinee paintings by different artists; (b) Standardized climacogram of the art paintings; (c) climacograms of the art paintings, Figure S10: (a1) Shape of the landscape; (a2) Landscape withought sky; (a3) original landscape (b); (c) standardized climacograms of images (a1)–(a3); (d) climacogram of images (a1)–(a3), Figure S11: (a1) (a2 (a3) Landscape with different sky; (b) (c) standardized climacograms of images (a1)–(a3); (d) climacogram of images (a1)–(a3), Figure S12: (a1) City above the horizon; (a2) City below the horizon; (a3) original landscape; (b) standardized climacogram of images (a1)–(a3); (c) climacogram of images (a1)–(a3), Figure S13, (a1)–(a4) Cities in the landscape (a1) Original landscape; (b), (c) standardized climacograms of images (a1)–(a5); (d) climacogram of images (a1)–(a5), Figure S14: (a1)–(a4) Wind turbines in the landscape; (a5) Original landscape; (b) standardized climacograms of images (a1)–(a5); (d) climacogram of images (a1)–(a5), Figure S15: (a1) Solar panels in the landscape; (a2) Original landscape; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S16: (a1) Lake in the landscape; (a2) Original landscape; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S17: (a1) Lake in the landscape; (a2) Solar panels in the landscape (3); Original landscape (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a3), Figure S18: (a1) Wind turbine in the landscape; (a2) Lake in the landscape; (a3) Solar panels in the landscape; (a4) original landscape; (b), (c) standardized climacograms of images (a1)–(a4); (d) climacogram of images (a1)–(a4), Figure S19: (a1) Lake in the landscape; (a2) Solar panels in the landscape; (a3) Wind turbine in the landscape; (a4) original landscape; (b) standardized climacograms of images (a1)–(a4); (c) climacogram of images (a1)–(a4), Figure S20: (a1) Solar panels in the landscape; (a2) original landscape; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S21: (a1) Solar panels in the landscape; (a2) original landscape; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S22: (a1) Solar panels in the landscape; (a2) original landscape; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S23: (a1) Wind park in the landscape; (a2) landscape without renewable energy installations;

(b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S24: (a1) Wind park in the landscape; (a2) landscape without renewable energy installations; (b) standardized climacograms of images (a1)–(a2); (c) climacogram of images (a1)–(a2), Figure S25: (a1)–(a3) Transformation of landscape of Plastiras caused by the balance of the lake in the area of subnormal dead zone; (b) (c) standardized climacograms of images (a1)–(a3); (d) climacogram of images (a1)–(a3), Figure S26: (a1)–(a3) Transformation of landscape of Plastiras caused by the balance of the lake in the area of normal dead zone; (b) (c) standardized climacograms of images (a1)–(a3); (d) climacogram of images (a1)–(a3).

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