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Land Use/Land Cover Assessment Over Time Using a New Weighted Environmental Index (WEI) Based on an Object-Oriented Model and GIS Data

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Abstract: For the first time, this paper introduces and describes a new Weighted Environmental Index (WEI) based on object-oriented models and GIS data. The index has been designed to integrate all the available information from extensive and detailed GIS databases. After the conceptual definition of the index has been justified, two applications for the regional and local scales of the WEI are shown. The applications analyze the evolution over time of the environmental value from land-use change for two different case studies in Spain: the Valencian Region and the L'Alcora municipality. Data have been obtained from the Spanish Land Occupation Information System (SIOSE) public database and integrate GIS information about land use/land cover on an extensive, high-detailed scale. Results demonstrate the application of the WEI to real case studies and the importance of integrating statistical analysis of WEI evolution over time to arrive at a better understanding of the socio-economic and environmental processes that induce land-use change.

Keywords: land use; indicator; GIS; assessment

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1. Introduction

Current efforts to define and establish environmental indicators stem from early debates about sustainability, popularized by the "Brundtland Report" and "Agenda 21" [1,2]. In recent years, environmental indicators have become a fundamental tool in environmental assessment at detailed, local, regional and national levels [3]. These environmental indicators significantly influence environmental management and the formulation of environmental policies [4], as well as monitoring and evaluation processes [5,6]. Environmental indicators have become important because they provide a sign that conveys a complex message, potentially from numerous sources, in a simplified and useful way [7]. Therefore, there is a growing need to establish appropriate environmental indicators based on truthful and verifiable information [8,9].

The use of indicators to emphasize the relevance of environmental data has many advantages. It is easier for scientists to understand and agree on the existing purpose of a particular monitoring program, and clients clearly understand what they are paying for and why [10]. It also helps to understand interactions between different groups of measurements, such as pollutant inputs, concentrations in sentinel organisms and biological effects [11]. However, it is a great challenge to determine which of the numerous measures of environmental systems characterize the entire system but are simple enough to be effectively and efficiently monitored and modeled [12].

Current and future work on environmental indicators should consider the following aspects [13]: (i) indicators are the product of numerous measuring processes that oversimplify environmental trends, while ignoring important social and political factors produced by the indicators; (ii) the establishment of new indicators should move away from rapid, ad-hoc and uncritical development, to follow a more careful process where indicators are contextualized based on the factors that produce them at different scales; and (iii) care must be taken in applying indicators in environmental management and policies.

In any case, the methodology underlying the definition and development of indicators must conform to scientific standards [3,14].

2. Land Use Environmental Value Assessment Using Indexes and Indicators

2.1. Environmental Indicators

There are numerous definitions of the concept "indicator". According to [15], an indicator is a measure of the observable part of a phenomenon that allows another unobservable portion of that phenomenon to be assessed. On the other hand, [16] points out that an indicator turns out to be the simplest way of reducing a large amount of data, keeping essential information to answer questions posed by the data.

Other authors describe an indicator as "something that provides a clue to an issue of greater importance or that makes a trend or phenomenon noticeable that is not immediately detectable" [17].

Indicators are often a compromise between scientific accuracy and available information at a reasonable price. Some researchers are inclined towards the definition of "indicator" from the vision of systems theory, which defines indicators as variables (and not values), that is, operational representations of an attribute that are defined in terms of a measurement procedure or determined observation [18].

One of the most widely used definitions in the literature indicates that indicators are statistics, statistical series or any form of indication that makes it easier for us to study where we are and where we are going with respect to certain objectives and goals, as well as to evaluate specific programs and determine their impact [19].

Mathematically, an indicator is defined as a function of one or more variables that jointly measure a characteristic or attribute of the individuals under study [20]. On the other hand, in [21], indicators are defined as pieces of information that summarize the characteristics of a system or highlight what is happening in the system.

According to the European Environment Agency, an environmental indicator is an observed value representative of a phenomenon under study [22]. Environmental indicators quantify information by aggregating multiple different data (necessary to obtain reliable information); therefore, they can be used to illustrate and communicate complex phenomena in a simpler way, including trends and progress over a certain period of time [23,24].

Environmental indicators are used to simplify the monitoring of complex ecological systems and are composed of objective and quantifiable variables that report on specific aspects of the environment, such as the number of threatened species or the presence of air pollutants [25].

Several studies have tried to establish the fundamental criteria when choosing an environmental indicator [6,12,26–32]. In these studies, up to 34 different criteria have been identified, the most common being: measurability, low resource demand, analytical soundness, policy relevance and sensitivity to changes within policy time frames. An analysis of these criteria can be found in [4].

Sometimes, environmental indicators are grouped into sets of indicators, which seek to give a holistic view of environmental sustainability [4]. These sets of indicators allow their users to organize and synthesize environmental data that are often complex and heterogeneous [33]. Some of the best-known sets of environmental indicators are: Key and Core Environmental Indicators [34], Convention on Biological Diversity Framework Indicators [35] and Sustainable European Biodiversity Indicators [36].

Some sets of environmental indicators can be reduced to an index, a number that further synthesizes the measure of environmental sustainability [37].

Composite indicators or indices are a mathematical combination of a set of simple indicators that summarize a multidimensional concept in a simple or unidimensional index based on an underlying conceptual model. They can be quantitative or qualitative, depending on the analyst's requirements [38].

Similarly, in [39], compound indicators are defined as mathematical combinations of simple indicators that do not have a common unit of measurement.

The number of composite indicators grows every year, and they are applied in different areas of interest, since they have the ability to explain complex concepts [39]. The European Union and the Organization for Economic Cooperation and Development (OECD) are pioneering organizations in the development of initiatives related to these concepts in different fields of study (innovation/technology, society, globalization, environment, economy, etc.), generating a collection of documentation that serves as a starting point for its study [38]. Organizations such as the United Nations and the European Commission have developed highly interesting composite indicators [40–46].

The construction of composite indicators is usually carried out in multiple areas of public management, such as the economy and its various sectors (industry, agriculture, services, etc.), social development, scientific research and comprehensive analysis of the environment, among others [38,39,47–59].

The increasing number of these tools is a clear symptom of their political importance and their operational relevance in decision-making [60–62].

However, there are certain limitations of composite indicators that must be known in order to improve their design and avoid possible criticism about their construction [20,39]. Table 1 lists the main advantages and disadvantages of composite indicators [38,39].

Table 1. Main advantages and disadvantages of the composite indicators.

Advantages	Disadvantages
• Can summarize complex, multi-dimensional realities with a view to support decisionmakers. • Are easier to interpret than a battery of many separate indicators. • Can assess progress of countries over time. • Reduce the visible size of a set of indicators without dropping the underlying information base. • Make it possible to include more information within the existing size limit. • Place issues of country performance and progress at the center of the policy arena. • Facilitate communication with the general public (i.e., citizens, media, etc.) and promote accountability. • Help to construct/underpin narratives for lay and literate audiences. • Enable users to compare complex dimensions effectively.	• May send misleading policy messages if poorly constructed or misinterpreted. • May invite simplistic policy conclusions. • May be misused, e.g., to support a desired policy, if the construction process is not transparent and/or lacks sound statistical or conceptual principles. • The selection of indicators and weights could be the subject of political dispute. • May disguise serious failings in some dimensions and increase the difficulty of identifying proper remedial action if the construction process is not transparent. • May lead to inappropriate policies if dimensions of performance that are difficult to measure are ignored.

Some of the best-known composite indicators or environmental indices are: the Environmental Performance Index [9,63], Environmental Vulnerability Index [64], Living Planet Index [65] and Ecological Footprint [66].

Most composite environmental indicators measure multidimensional concepts about a group of countries for later comparison between them (rankings), being difficult to find environmental indices on smaller scales.

2.2. Environmental Indicators Based on Land Use

Land use is one of the main causes of the transformations of the terrestrial ecosystem [67,68], and these changes affect climate [69], biodiversity [70] and landscape ecology [71,72]. Furthermore, it is also a key factor in the context of policy and reporting schemes [73].

Due to these different approaches, the terminology related to land use is diverse. For example, two basic definitions, land cover and land use, are often mixed up or used synonymously. "Land cover" refers to the physical material on the surface of the land, while "land use" most often refers to the functional dimension and describes how the area is used for urban, agricultural, forestry and other purposes.

Two main approaches can be found in the literature that address environmental indicators based on land use [74]. The first has to do with the amount of land occupied and/or transformed for a certain activity. The second is based on models that quantify impacts in terms of variation in soil properties.

The amount of land occupied and/or transformed is multiplied by characterization factors that reflect changes in soil properties for each type of land occupation and transformation. Soil quality can be measured using a single indicator, such as soil organic matter [75], soil organic carbon [76], soil erosion [77], or multiple indicators (for example, using LANCA® models (Land Use Indicator Value Calculation in Life Cycle Assessment) [78] and LUCI (Land Utilization and Capability Indicator) [79].

But the difficulty of having the necessary data to apply one or another indicator on many occasions means that each country implements its own method of evaluating land use [49,80]. Continuously and depending on the information available, new indicators and indices based on land use are appearing [81,82].

Recent studies show the importance of using updated data in order to study the territory with environmental indexes and indicators related to land cover/use or landscape ecology. Practically all of these investigations are supported by the use of official databases of the area to be analyzed.

For example, in [83], the landscape composition and configuration changes of an area in southern Ecuador were evaluated with data from the United States Geological Survey (USGS). To perform a spatiotemporal analysis of land-use and land-cover change in the Atlantic forests of Brazil [84], obtained available data from a free-access dataset developed by a consortium of Brazilian and international research institutes, universities, private organizations, and NGOs aiming to generate national coverage of land cover/use information. In China, national databases are also used to study environmental aspects based on land use/land cover changes [85]. The continuous acquisition of images by orbital satellites also provides enough information to be able to evaluate land cover change and habitat configuration from the visual comparison of the generated maps [86–88].

3. Materials and Methods

Environmental indices and indicators based on GIS analysis of land use/land cover are usually based on qualitative values of different parameters assigned to the different plots into which the study area has been divided [68,83,84,86,88]. In these situations, the number of soil categories is usually small (between five to eleven), and it is easy to make comparisons between corresponding maps from different years. However, these indices do not allow for the performing quantitative assessments of environmental quality changes, beyond analysis of land uses per unit area. More elaborated environmental indices quantify environmental value based on land use changes. This is the case in [81], which studies the variation in the degree of anthropization through analysis of a single factor called the Relative Integrated Anthropization Index (INRA). This index includes five different categories of soil anthropization, with relative values changing between 0 and 1.

Subsequent studies have modified the INRA index to include more categories. In [89], 27 additional subcategories are added, providing a greater degree of detail in the definition of the INRA index. The relative value of anthropization assigned to each of these new categories is obtained as a result of applying multiple-criteria decision analysis, obtained by expert judgement.

Recent studies focus on the application of fuzzy logic methodologies for the evaluation of land use. The overall suitability assessment of land units is based on the definition of weighting factors of the relevant characteristics. In these methodologies, the choice of weight values is of critical importance. These weights are usually decided on the basis of expert knowledge considering local advice, experimental data or previous land evaluation methods [90].

This paper introduces a new environmental index named WEI (Weighted Environmental Index), based on land use analysis techniques, that allows all the information obtained from official public databases to be integrated on a detailed scale. The WEI definition and its application to a practical case is shown below.

3.1. Available Data

3.1.1. Description of Mapping Techniques Using GIS

Land occupation mapping is thematic mapping that represents two distinct but interrelated components: the occupation of land surface according to its biophysical properties, called land cover, and the characterization of the territory according to its socioeconomic dedication, called land use. Therefore, mapping of land uses and covers involves the natural and socioeconomic factors used in a given space and time [88]. Its main objective is the planning and monitoring of resources, such as the changes that affect natural cover caused by land use. This process is generally driven by natural phenomena and anthropogenic activities, which affect the natural ecosystem.

Geographical information systems (GIS) are useful tools for the elaboration of land use and cover mapping. They offer an important advantage by integrating different information technologies such as remote sensing (RS) and global navigation satellite systems (GNSS). This integration allows for a more efficient study of changes and the quantification of the dynamics of land use [91]. The National Geographic Institute of Spain (IGN) coordinates, in parallel, two projects aimed at structuring information on land use and coverage: Corine Land Cover and SIOSE.

3.1.2. Corine Land Cover

The Corine Land Cover project, established by the European Union and coordinated by the European Environment Agency, is aimed at homogenizing information on all of Europe, to facilitate the performance of territorial analysis, the state of the environment and natural resources, and the establishment of European policies.

This information, integrated into an international geographic information system, is structured as a hierarchical data model of 44 classes at level 3 and 58 classes at level 4. It is defined on a 1:100,000 spatial scale and has a minimum polygonal surface of 25 hectares. The first product was obtained in 1990 and later updates have been made in 2000, 2006, 2012 and 2018 [92,93].

3.1.3. SIOSE

The need for more detailed information on land use on a national scale led to the development of the Spanish Land Occupation Information System (SIOSE) in 2005. This system has been structured as an object-oriented conceptual data model, with 40 simple classes and 46 compound classes; its spatial scale is 1:25,000. Its work unit is polygons, with a minimum mappable surface of 2 hectares for agricultural, forest and natural areas; 1 ha for urban areas and bodies of water; and 0.5 hectares for crops. The conceptual model includes two super classes: land use and cover. The coverage can be of a simple type when it is unique within the polygon, or composite when the polygon includes two or more types of simple or composite coverage in turn. However, land use refers to the type of socioeconomic activity and does not necessarily correspond to a physical aspect. For example, a forest cover can have one more use types of use (recreational or/and economic [93]). In this way, the SIOSE model does not describe a single coverage for each polygon but can assign one or multiple simple or composite coverages for a single polygon through its attributes and occupancy percentages. Consequently, SIOSE offers more detailed information geared towards user needs [92] (Figure 1).

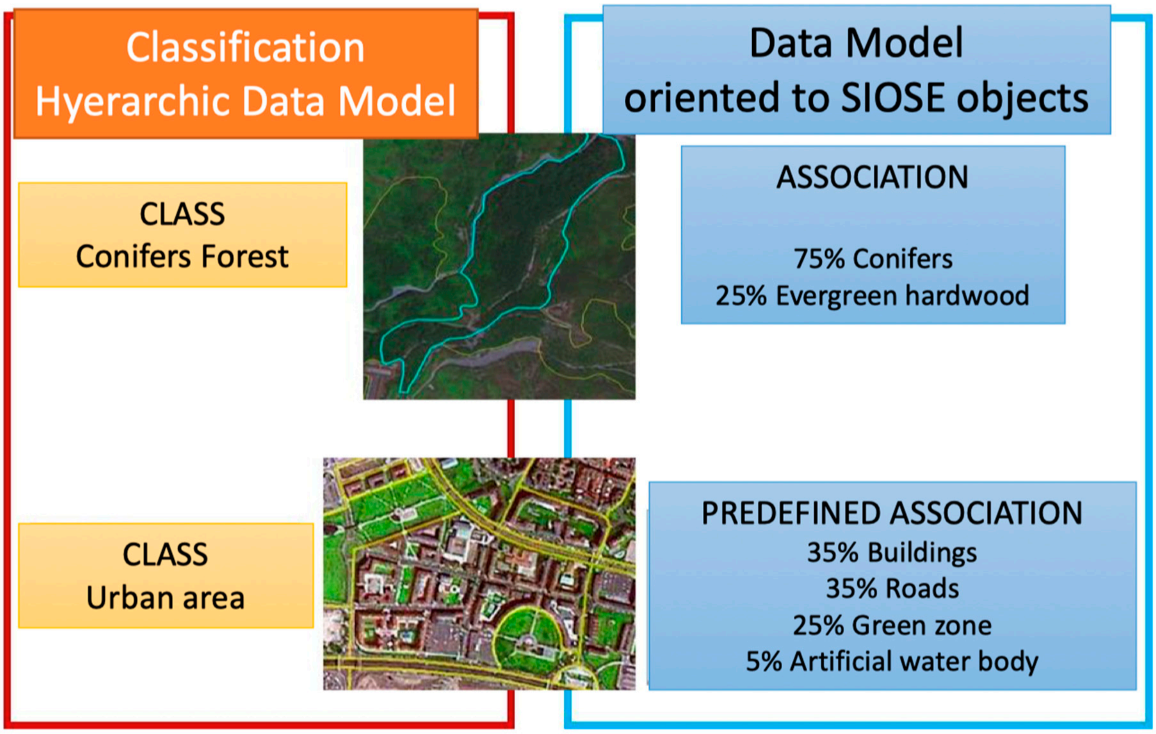

Figure 1. Example of classification using a hierarchical data modeling system and the Spanish Land Occupation Information System (SIOSE) system.

3.2. *The Weighted Environmental Index (WEI). Conceptual scheme.*

This work introduces the Weighted Environmental Index (WEI), a new index for the analysis of environmental value based on land use.

This new index has been defined to fulfill the following characteristics:

1. WEI must integrate all the characteristics of indices that vary continuously in space.
2. WEI values should be justified in a simple way from pre-established classifications of land use.
3. It must be able to be used to carry out land use assessments based on information integrated into geographic information systems (GIS).
4. It must be able to be used both in general studies carried out on a large scale and in detailed studies that use cartography obtained by very high-resolution GIS techniques.
5. Its application in the same geographical area at different times should allow for trend analysis to determine the impact of correction measures that are implemented through territorial, urban or environmental planning tools.

The process of determining environmental index values for each land use (EI_j) has been carried out, taking into account the joint consideration of the following five evaluation factors (F_i):

F_1: Anthropic or natural nature of activity developed in soil.
F_2: Water consumption associated with land use.
F_3: Soil degradation (use of chemicals).
F_4: Environmental sustainability of land use (stability of the ecosystem).
F_5: Landscape value of activity carried out in the analyzed area.

The determination of values of the evaluation factors for each land use is carried out individually so that a quantitative value is assigned for each factor F_i and land use j, in such a way that:

$$0 \leq F_{ij} \leq 100 \quad (1)$$

For each one of the land use categories included in the SIOSE legend, the corresponding environmental index (EI_j) has been obtained as the value of the weighted average of each of the values assigned to each of the previous factors (F_i), considering the corresponding weights (α_i), as shown in Equations (2) and (3):

$$EI_j = \sum_{i=1}^{5} \alpha_i F_{ij} \qquad i = 1 \ldots 5 \; j = 1 \ldots ncat \quad (2)$$

$$\sum_{i=1}^{5} \alpha_i = 1 \quad (3)$$

where:

EI_j: environmental index of land use j ($0 \le E_{ij} \le 100$)
α_i : assigned weights to factor i
F_i: evaluation factor i
ncat: land use categories

The application of environmental index values (EI_j) is carried out on a discretization in irregular polygons of variable surface that together constitute the entire area under study:

$$A_{total} = \sum_{k=1}^{npol} A_k \quad (4)$$

where:

A_{total}: total area of study
A_k: area of polygon k
npol: total number of polygons in the discretization

Therefore, once the values of the environmental indices corresponding to each land use have been established, the weighted environmental index of a certain polygon (WEI_k) is determined based on the values of the environmental index of each land use included inside the polygon, considering as weights the proportion of the area assigned to each land use with respect to the total area of the polygon, as shown in Equation (6).

$$\beta_{jk} = \frac{A_{jk}}{A_k} \qquad k = 1 \ldots npol \quad (5)$$

$$WEI_k = \sum_{j=1}^{n_{jk}} \beta_{jk} EI_j \qquad j = 1 \ldots n_{jk} \quad (6)$$

where:

WEI_k: weighted environmental index of polygon k.
EI_j: environmental index of land use j.
A_{jk}: area assigned to land use j inside the polygon k.
β_{jk}: land use weighting factor j in polygon k.
n_{jk}: number of land uses (j) inside polygon k.

The value of the weighted environmental index obtained by Equation (6) adopts values that vary between 0 and 100, so that values close to 0 indicate a very low environmental value, while values close to 100 indicate a high environmental value. This is in accordance with the five evaluation factors (F_i) considered in the definition of the environmental index for each type of land use.

Thus, WEI_k values are determined from EI_j values, which depend on the values assigned to the evaluation factors (F_i) and the weights associated with each factor (α_i). Therefore, the value of the WEI index depends on the corresponding values of the evaluation factors (F_i) and their corresponding weights (α_i). The values of F_i and α_i should be decided by the modeler on the basis of expert knowledge considering local advice.

Table 2 shows the values of the weighted environmental index for each land use (WEI_k) included in the SIOSE legend as a result of the linear combination of the five evaluation factors (F_i) considered in the definition of the index. The values of each environmental factor are the ones that have been used for demonstration purposes in the two case studies shown in this paper (Valencia Region and L'Alcora municipality), which are described in detail below. In both case studies, equal values of the weights associated with each factor ($\alpha_i = 0.2$) have been considered.

The values shown in Table 2 can be modified or adapted by the user in each case. The user is responsible for justifying the values of F_i and α_i, for which the existence of particular conditions in the area under study that could modify the proposed values must be taken into account. These values have been designed so final results in terms of the WEI index allow the evolution of environmental value on a certain region to be studied, prioritizing the natural uses of the soil with low water consumption, low soil degradation, high sustainability of the ecosystem and high landscape value, following a Multi-Criteria Decision Analysis (MCDA) technique. MCDA is currently used to establish the value of environmental indicators [94–97]. When analyzing a territory, it is necessary to take into account that sustainability assessment is a multi-criteria decision process that comprises of economic, social, and environmental practice [98]. The purpose of MCDA is to compare and rank alternative options and to evaluate environmental consequences according to the criteria established [99]. One of its greatest strengths is the possibility of using the criteria with their own dimensions. The main weakness of MCDA is the subjectivity of the weighting step that is needed to value the different criteria [100].

Table 2. Basic values of the evaluation factors (F_i) for every land use considered by the SIOSE and final value of the Weighted Environmental Index for a single-use polygon (WEI_k).

Code	Land Use Description	F_1	F_2	F_3	F_4	F_5	WEI_k
EDF	Buildings	20	40	20	15	5	20
ZAU	Artificial green zone and Urban trees	60	65	70	80	75	70
LAA	Artificial water body	65	85	85	65	50	70
VAP	Road, Parking or Pedestrian area	20	40	20	15	5	20
OCT	Other constructions	20	40	20	15	5	20
SNE	Soil without edifications	35	50	50	50	15	40
ZEV	Extraction zones	0	50	0	0	0	10
CHA	Rice crops	60	10	80	45	55	50
CHL	Other crops different from rice	60	65	80	75	70	70
LFC	Citrics	60	65	80	75	70	70
LFN	Non citrics	60	65	80	75	70	70
LVI	Grapes	60	65	80	75	70	70
LOL	Olives	60	65	80	75	70	70
LOC	Other woody crops	60	65	80	75	70	70
PRD	Meadows	80	80	90	100	100	90
PST	Pastureland	80	80	80	80	80	80
FDC	Hardwood deciduous	100	100	100	100	100	100
FDP	Evergreen hardwoods	100	100	100	100	100	100
CNF	Conifers	100	100	100	100	100	100
MTR	Scrub	70	70	70	70	70	70
PDA	Sandy beaches	100	100	50	100	100	90
SDN	Bare soil	70	50	20	20	40	40
ZQM	Burned areas	0	50	0	0	0	10
RMB	Ravines	20	50	20	50	60	40
ACM	Marine cliffs	100	50	50	100	100	80
ARR	Rocky soil	80	50	30	30	60	50

Table 2. *Cont.*

Code	Land Use Description	F_1	F_2	F_3	F_4	F_5	WEI_k
CCH	Stone quarry	80	50	40	40	40	50
CLC	Lava flow	90	30	30	40	60	50
HPA	Marshes	80	50	30	80	60	60
HSA	Continental salines	90	30	40	80	60	60
HMA	Marshes	90	60	70	90	90	80
HSM	Marine salines	90	60	70	90	90	80
ACU	Water flows	100	100	100	100	100	100
ALG	Lakes and lagoons	100	100	100	100	100	100
AEM	Dams and artificial lakes	10	100	100	100	90	80
ALC	Coastal lagoons	100	100	100	100	100	100
AMO	Seas and Oceans	100	100	100	100	100	100
	Non predefined	50	50	50	50	50	50
OVD	Olives and grapes	60	65	80	75	70	70
AAR	Residential agricultural settlement	40	50	60	50	50	50
UER	Family orchard	60	65	75	70	80	70
UCS	Urban center	30	30	10	20	10	20
UEN	Urban expansion area	30	30	10	20	10	20
UDS	Discontinous	30	30	10	20	10	20
IPO	Well sorted industrial area	30	30	10	20	10	20
IPS	Non sorted industrial area	30	30	10	20	10	20
IAS	Isolated industrial area	30	30	10	20	10	20
PAG	Agricultural, livestock	60	60	70	50	60	60
PFT	Primary forest	100	100	100	100	100	100
PMX	Extractive Mining	10	10	10	10	10	10
PPS	Fish farm	30	60	60	50	50	50
TCO	Commercial and offices	20	20	20	20	20	20
TCH	Hotels	20	20	20	20	20	20
TPR	Recreational park	20	20	20	20	20	20
TCG	Camping	20	40	40	50	50	40
EAI	Institutional administrative	20	20	20	20	20	20
ESN	Medical and sanitary	20	20	20	20	20	20
ECM	Cementery	20	20	20	20	20	20
EDU	Education	20	20	20	20	20	20
EPN	Penitentiary	20	20	20	20	20	20
ERG	Religious	20	20	20	20	20	20
ECL	Cultural	20	20	20	20	20	20
EDP	Sport	25	15	20	20	20	20
ECG	Golf course	40	10	70	50	80	50
EPU	Urban park	60	65	70	80	75	70
NRV	Streets and roads	10	10	10	10	10	10
NRF	Train	10	10	10	10	10	10
NPO	Port	10	10	10	10	10	10
NAP	Airport	10	10	10	10	10	10
NEO	Eolic plant	10	10	10	100	20	30
NSL	Solar plant	10	10	10	100	20	30
NCL	Nuclear plant	0	0	0	0	0	0
NEL	Electric plant	0	0	0	0	0	0
NTM	Thermal plant	0	0	0	0	0	0
NHD	Hydroelectric plant	10	10	10	10	10	10
NTC	Telecommunications plant	0	0	0	0	0	0
NDP	Waste and drinking water plant	10	20	10	100	10	30
NCC	Channels	0	0	0	0	0	0
NDS	Desalinization plant	0	0	0	0	0	0
NVE	Landfills	0	0	0	0	0	0
NPT	Treatment plant	0	0	0	0	0	0
UEN	Urban expansion area	30	30	10	20	10	20
UDS	Discontinous	30	30	10	20	10	20
IPO	Well sorted industrial area	30	30	10	20	10	20

Table 2. *Cont.*

Code	Land Use Description	F_1	F_2	F_3	F_4	F_5	WEI_k
IPS	Non sorted industrial area	30	30	10	20	10	20
IAS	Isolated industrial area	30	30	10	20	10	20
PAG	Agricultural, livestock	60	60	70	50	60	60
PFT	Primary forest	100	100	100	100	100	100
PMX	Extractive mining	10	10	10	10	10	10

The application of the WEI to each land use considered by the SIOSE legend allows a classification to be established based on the discrimination by ranges shown in Table 3:

Table 3. Environmental value as a function of the WEI range.

WEI Range	Environmental Value
$0 \leq WEI_k < 40$	Low
$40 \leq WEI_k < 70$	Medium
$70 \leq WEI_k \leq 100$	High

4. Results and Discussion

Two applications of the WEI for regional analysis (Valencian Region) and for detailed analysis at a municipal level (L'Alcora) are shown below. Data used for these studies included the SIOSE information available for the Valencia Community in 2005, 2009 and 2015 downloaded from the Spanish National Geographic Institute (IGN) platform with geodetic reference system ETR89 and transverse Mercator universal projection geographic system (UTM) in time zone 30. This information was based on the photointerpretation of SPOT5 images, orthophotos from the National Plan for Aerial Orthophotography (PNOA), IGN official cartography databases and information provided by the Autonomous Community on land uses at different scales (SIOSE2015).

Using spatial analysis data techniques, a report was generated from the results obtained from a query to the SIOSE data model in which information on the percentage of occupation, the surface in hectares and type of ground cover was obtained for each polygon mapped the Valencian Region in 2005, 2009 and 2015. This information was the basis for the analysis and generation of the WEI, and later it was linked to the GIS through a polygon identifier for spatial representation of the evolution of this index on the three considered dates. The values of the evaluation factors (Fi) and the weights (α_i) are the same in both cases. The evaluation factors used in both analyses are shown in Table 2, and they were selected by expert judgment considering equal weight to every evaluation factor.

4.1. Large Scale Analysis: Valencian Region (2005–2015)

The Valencian Region is one of the 17 autonomous communities into which Spain is divided. It is made up of three provinces (Alicante, Castellón and Valencia), with its capital in the city of Valencia. It is located to the east of the Iberian Peninsula, on the coast of the Mediterranean Sea. It has an area of 23,255 km^2 and a population of 5,003,769 inhabitants, according to the National Statistical Institute (INE). Its economy is based mainly on the service sector (70%), followed by industry, construction and finally agriculture. The latter has significantly lost its importance in the last five decades [101]. To analyze the evolution of environmental status at a regional level, the new WEI has been applied to the Valencian Region for which an extensive set of data obtained from the SIOSE database was available. These data referred to the land use on the whole territory for the 2005–2015 period. Following the methodology explained in Section 3.2, the WEI for every polygon has been computed.

Figure 2 shows the spatial distribution of the WEI for 2005, 2009 and 2015. The spatial distributions of the WEI allow us to easily identify the position of the areas of highest and lowest environmental value.

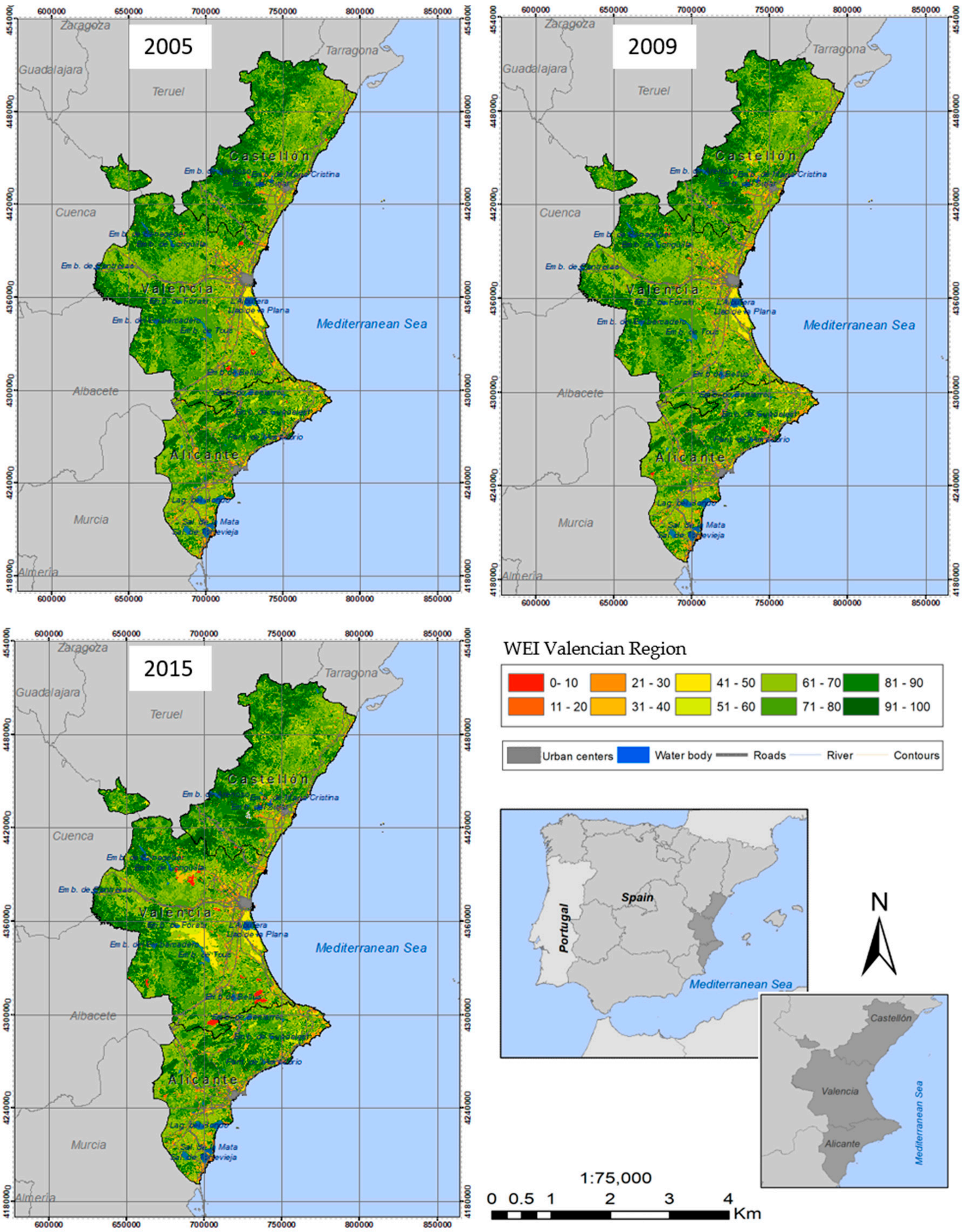

Figure 2. WEI values in the Valencian Region in 2005, 2009 and 2015.

Results in Figure 2 show that the lowest environmental value (WEI < 50) is found in the surroundings of Valencia city, located at the center of the eastern coast of the study area. Higher WEI values (WEI > 80) are almost exclusively found on the non-altered mountains located inland where human actions are not relevant.

The application of the WEI to the Valencian Region demonstrates that WEI can be successfully used to analyze environmental status at a regional level if enough accurate data are available.

Additionally, WEI allows us to analyze the evolution over time of environmental value. Figure 3 shows the WEI differences map between 2005 and 2015 for the whole Valencian Region.

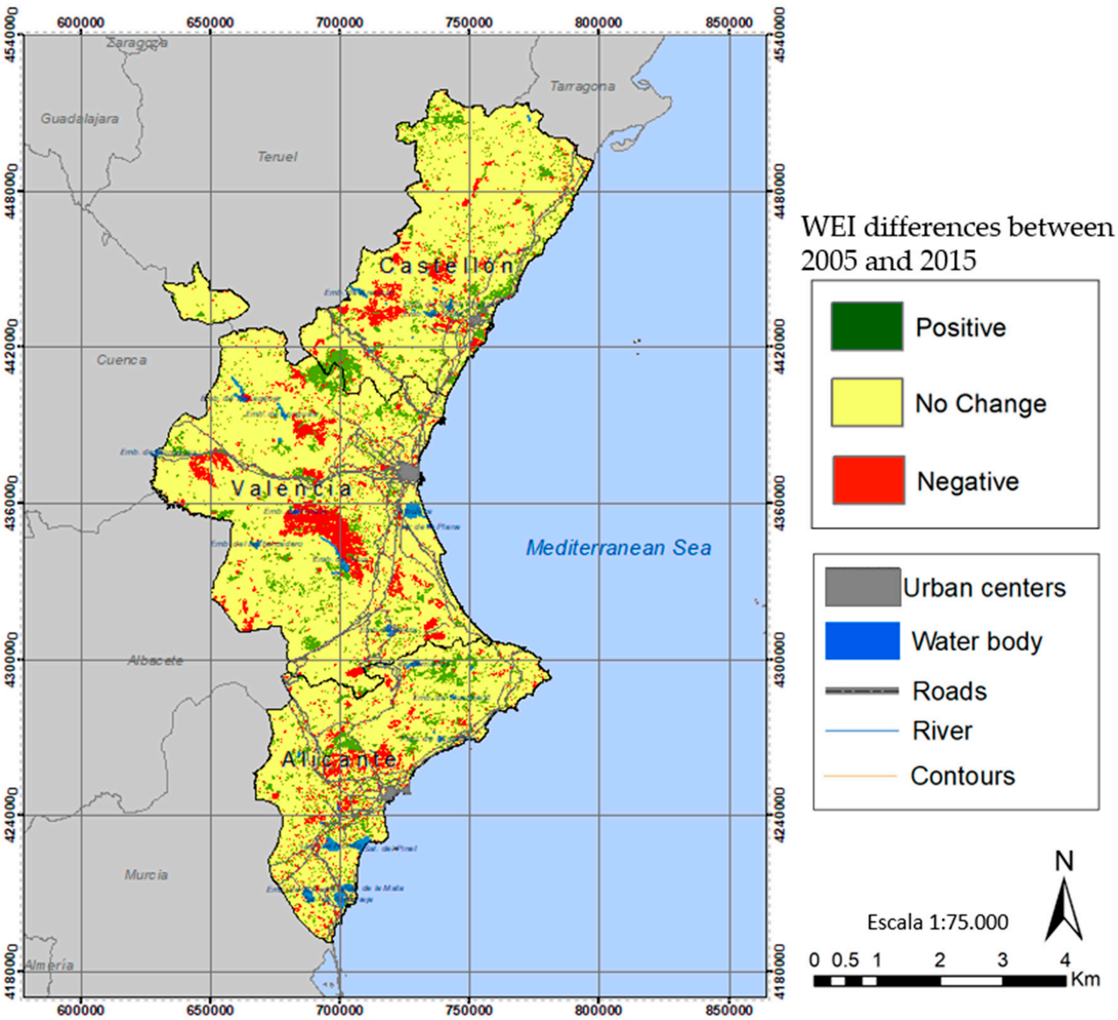

Figure 3. WEI differences between 2005 and 2015. Valencian Region.

In Figure 3, green values represent areas for which the WEI has increased during this ten-year period, while red values represent areas where the WEI has decreased. As a result of the analysis, a large area located inland at a western region from Valencia city where WEI values had decreased was detected. A specific analysis was performed to investigate the reasons for this sudden change, leading to the conclusion that the WEI had been affected by a change in the criteria used by SIOSE to map and define the land use of polygons of this area. Regarding the accuracy of the data, WEI acts as a tool for checking the land use databases provided by SIOSE. The irregularities detected are due to (i) recoding of land use, (ii) grouping of polygons or (iii) errors in the database for specific years.

It has been precisely when applying the WEI to the Valencian Region that inconsistencies in the numerical values of the SIOSE database, which were unnoticed before, have been detected.

Furthermore, the spatial distribution of WEI differences allows us to easily identify the position of areas that have improved or worsened their environmental value during the ten-year period. A statistical analysis can be performed, comparing the WEI value inside each polygon in which the area is discretized.

In addition to the results and cartography shown, which are both of great value in the visualization of the results, statistical analysis of the temporal evolution of the WEI provides very valuable results from the point of view of land use management and the impact of the policies implemented in the territory. Due to the extremely large size of the Valencian Region, an example of this statistical analysis is shown below, applying the WEI to the municipality of L'Alcora.

4.2. Municipal Scale Analysis: L'Alcora municipality (2005–2015)

Using the same values of the evaluation factors (F_i) and weights (α_i), the WEI has been applied to analyze land use evolution over time at a local level in the municipality of L'Alcora (Spain). The municipality of L'Alcora is located within the province of Castellón with an area of 95.26 km^2. It has a population of 10,405 inhabitants, and its main economic sector is the ceramic industry [102].

The municipality of L'Alcora has been selected to verify the suitability of using the WEI at a municipal level, as its socioeconomic structure includes a large number of land uses associated with the territorial distribution of urban use, industrial use, agricultural use and forestry use. In this way, in the municipality of L'Alcora, it is of great interest to carry out analysis of the evolution of land use to assess the relationships between the growth (or maintenance) of industrial use, economic development and employment of the area and the status and environmental value of the territory.

Similar to how it was done in Section 4.1 and following the methodology explained in Section 3.2, the WEI for every polygon has been computed. Figure 4 shows the spatial distribution of the WEI for 2005, 2009 and 2015. The spatial distributions of the WEI allow us to easily identify the position of the areas of highest and lowest environmental value within the municipality.

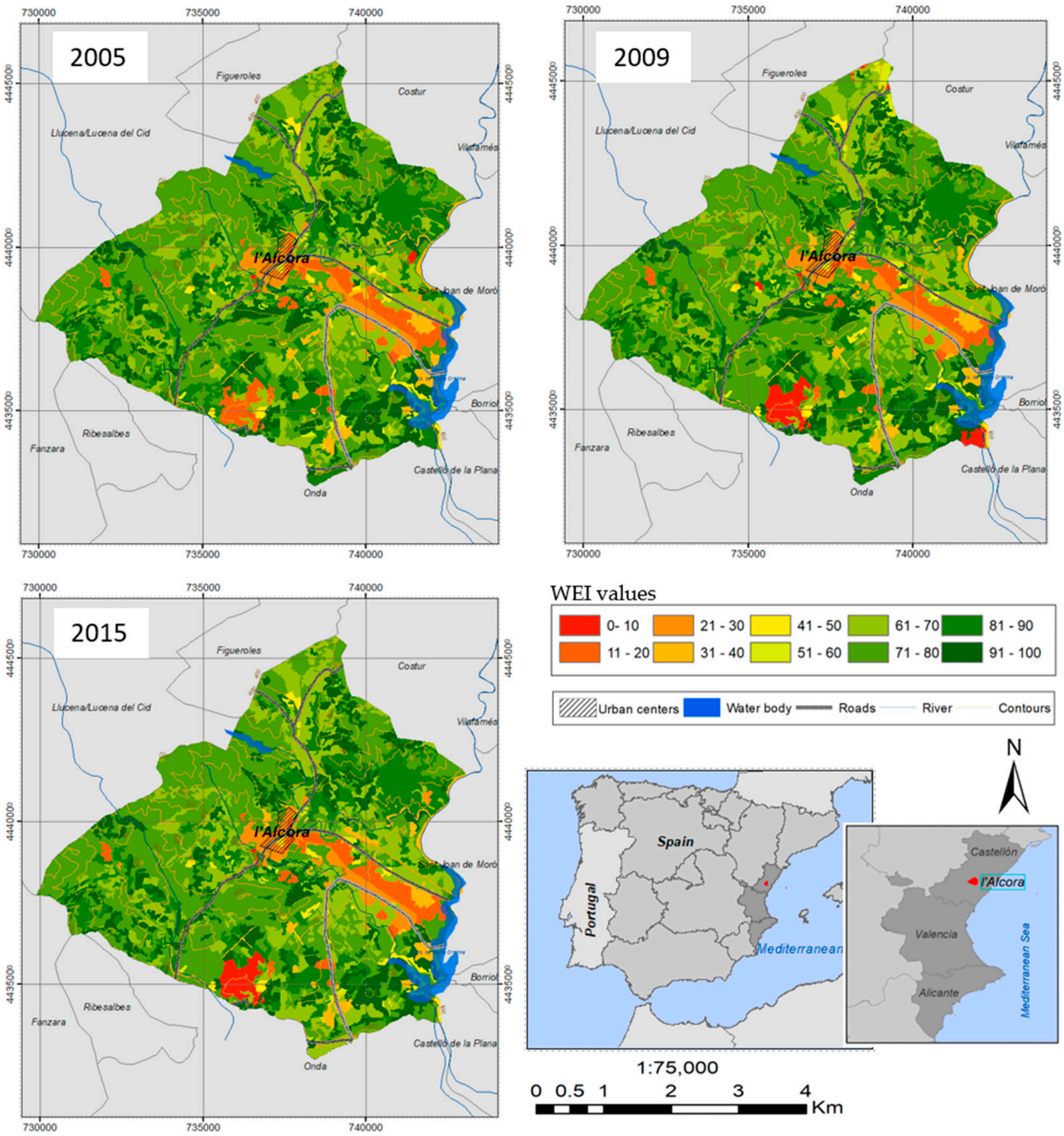

Figure 4. WEI values in L'Alcora municipality in 2005, 2009 and 2015.

Roughly speaking, low environmental value areas (WEI < 40) correspond to urban use and roads, while high environmental value areas (WEI > 80) correspond to forest land. It has been observed that low-WEI areas tend to concentrate along the main road that crosses the municipality.

Unlike the case of the Valencian Region shown in Section 4.1, the adequate size of the study area allows us to perform a detailed statistical analysis that is now useful to better understand the evolution over time of the WEI inside the L'Alcora municipality.

Evolution over time of WEI values can be analyzed by comparing the values of the WEI for every polygon. Results are shown in Figure 5, which shows the WEI differences map between 2005 and 2015 for the municipality of L'Alcora. Though no changes are observed along the main road, a decrease in WEI values has been detected in agricultural and forest land disseminated throughout the territory. This fact can be numerically objectivized by computing the average value of the WEI inside the study area as the weighted average of the WEI inside each polygon, considering each polygon's area as weights.

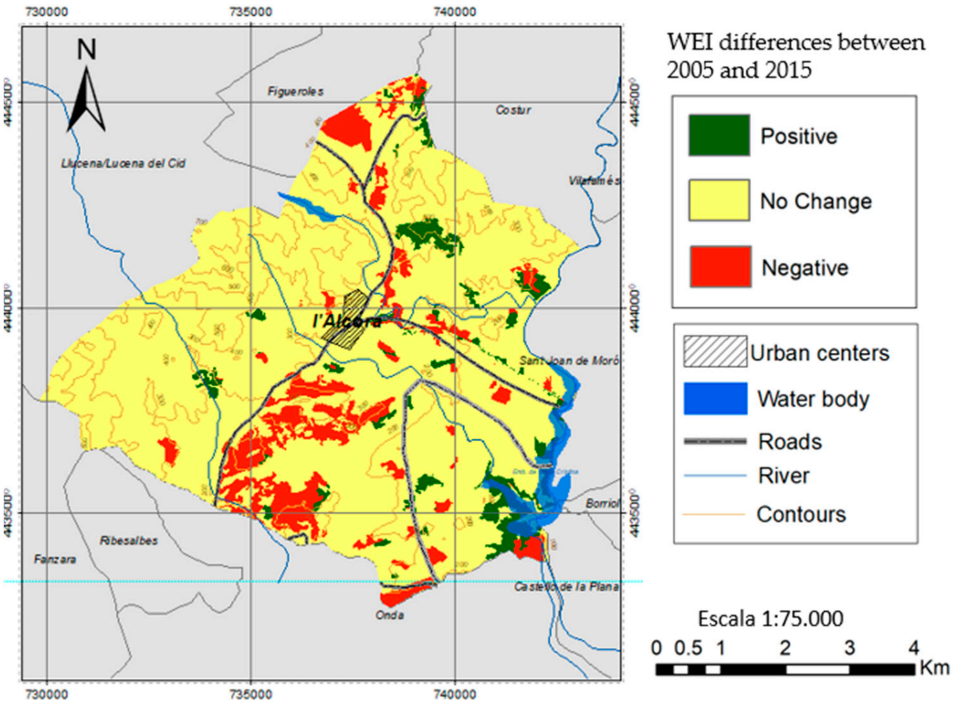

Figure 5. WEI differences between 2005 and 2015. L'Alcora municipality.

Figure 6 shows the evolution of the Average WEI for L'Alcora over the 2005–2015 period. In 2005, the Average WEI was 73.50, while in 2009 this same parameter was equal to 73.13, representing a 0.5% loss in a 4-year period. However, the evolution of the WEI between 2009–2015 shows that the situation has stabilized, and the WEI has remained almost constant since 2009 without significant variations. Whether this fact is due to the implementation of protective environmental policies or a mere consequence of the economic crisis must be analyzed specifically by other studies.

An in-depth analysis of the evolution over time of the WEI can be carried out by taking advantage of the extensive information provided by SIOSE inside every polygon. The use of this object-oriented database in L'Alcora municipality divides the territory into 899 polygons (in 2005), 909 polygons (in 2009) and 912 polygons (in 2015), and the statistical distribution of their WEI provides a comprehensive view of the evolution of environmental status over the period 2005–2015.

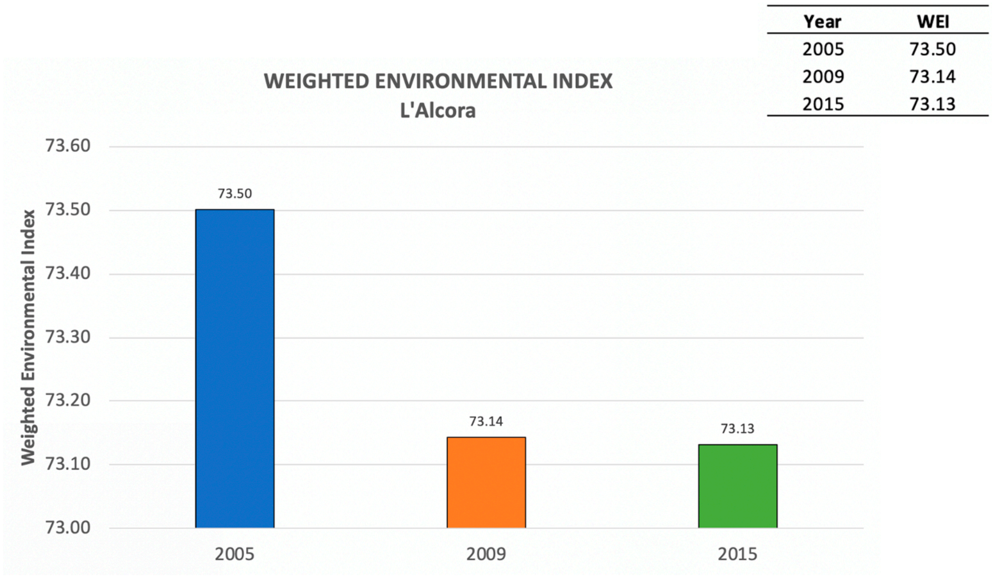

Figure 6. Average WEI evolution over time in L'Alcora municipality (2005, 2009 and 2015).

Table 4 shows the values of the deciles of the WEI distribution functions for each one of the years under study and the summary of the basic statistics. Figure 7 graphically shows this information as the correspondent cumulative distribution functions (CDFs).

Table 4. Deciles of the WEI distribution function in the L'Alcora municipality (2005, 2009 and 2015).

WEI	Absolute Frequency (Number of Polygons)			Class Area (Has)			Class Area (%)		
	2005	2009	2015	2005	2009	2015	2005	2009	2015
[0,10[	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
[10,20[	6	11	7	29.86	202.28	159.77	0.31%	2.12%	1.68%
[20,30[	38	39	39	676.94	565.99	567.12	7.11%	5.94%	5.96%
[30,40[	20	23	25	129.38	136.45	160.58	1.36%	1.43%	1.69%
[40,50[	36	32	31	310.85	213.98	220.96	3.26%	2.25%	2.32%
[50,60[	20	20	16	53.15	114.38	85.15	0.56%	1.20%	0.89%
[60,70[	47	50	56	302.21	313.94	442.93	3.17%	3.30%	4.65%
[70,80[	417	417	421	3762.61	3732.63	3992.15	39.51%	39.20%	41.92%
[80,90[	202	200	201	2846.46	2822.30	2558.72	29.89%	29.64%	26.87%
[90,100]	113	117	116	1411.71	1421.22	1335.81	14.82%	14.92%	14.03%
Total	899	909	912	9523.18	9523.18	9523.18	100%	100%	100%

As no dramatic changes in land use have been observed during the period 2005–2015, the shape of the CDFs is similar for the three different dates. As expected, the shape of the CDFs shows a trend in high WEI values, which is in accordance with the high Average WEI value obtained before, which was higher than 73 for every year. It has been observed, though, that the largest area for low WEI values was found in 2009.

This fact is also seen when comparing the shape of the CDFs, computing the differences between the correspondent deciles for each year. Table 5 and Figure 8 show the details of these calculations and their graphical representation, respectively.

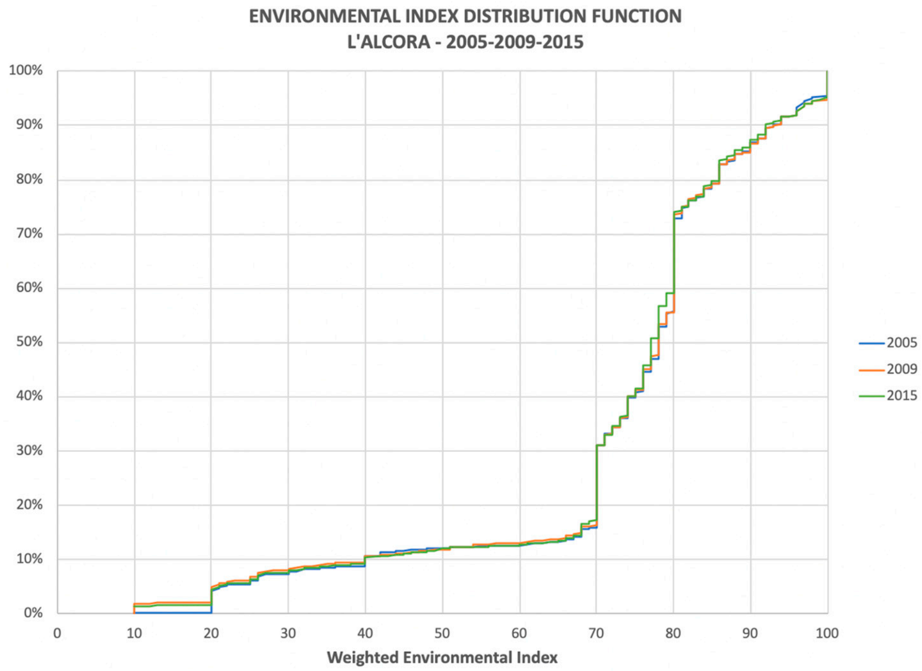

Figure 7. WEI cumulative distribution functions (2005, 2009 and 2015) in the L'Alcora municipality.

Table 5. WEI cumulative distribution functions' (CDFs) decile differences evolution (2005, 2009 and 2015).

WEI	Class Area (%)			Differences (%)		
	2005	2009	2015	2009–2005	2015–2009	2015–2005
[0,10[	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
[10,20[	0.31%	2.12%	1.68%	1.81%	−0.45%	1.36%
[20,30[	7.11%	5.94%	5.96%	−1.17%	0.01%	−1.15%
[30,40[	1.36%	1.43%	1.69%	0.07%	0.25%	0.33%
[40,50[	3.26%	2.25%	2.32%	−1.02%	0.07%	−0.94%
[50,60[	0.56%	1.20%	0.89%	0.64%	−0.31%	0.34%
[60,70[	3.17%	3.30%	4.65%	0.12%	1.35%	1.48%
[70,80[	39.51%	39.20%	41.92%	−0.31%	2.73%	2.41%
[80,90[	29.89%	29.64%	26.87%	−0.25%	−2.77%	−3.02%
[90,100]	14.82%	14.92%	14.03%	0.10%	−0.90%	−0.80%

Analysis of the evolution over time of the deciles of the CDFs is shown in Figure 8 and lead to interesting results. Figure 8a shows the CDF's decile values. The maximum value for each year (2005, 2009 and 2015) has always been obtained for the WEI class [70,80[, but only in 2015, this class reached values higher than 40%. To fully understand the evolution over time of environmental value inside the L'Alcora municipality using the WEI, Figure 8b,d must be analyzed carefully. These figures show the incremental analysis of the CDF's decile evolution through the analyzed time period, allowing us to obtain specific results for the L'Alcora municipality.

Figure 8b shows that between 2005 and 2009, a significant loss of environmental value was observed. The lowest WEI class [10,20[increased its area by 1.81% due to the loss of area of other low-WEI classes. As shown in Figure 8c, between 2009 and 2015 a significant loss (−2.77%) of a high-WEI class [80,90[was changed into a lower class [70,80[at almost exactly the same rate (2.73%). Additionally, a significant loss of the highest WEI class [90,100] (−0.90%) was observed together with the increase (1.35%) of a lower WEI class [60,70[.

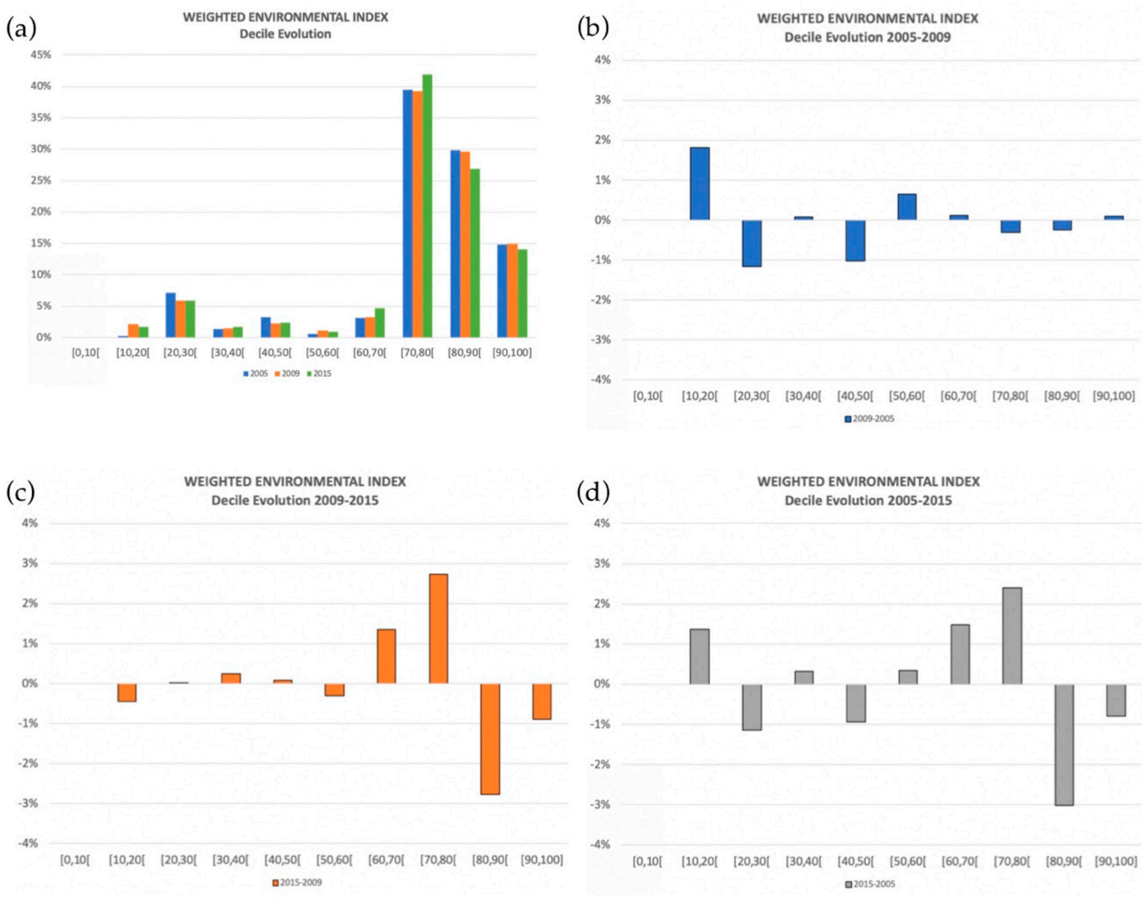

Figure 8. WEI CDF's decile differences evolution. (**a**) Decile values; (**b**) incremental analysis of the CDF's decile evolution between 2005 and 2009; (**c**) incremental analysis of the CDF's decile evolution between 2009 and 2015; (**d**) incremental analysis of the CDF's decile evolution between 2005 and 2015.

A very significant result is shown in Figure 8d, which shows the comparison between the CDF's deciles in the 2005−2015 period. The largest difference in the whole analysis (−3.82%) was found in the loss of the highest WEI classes [80,90[+[90,100], which were turned into lower WEI classes, finally leading to a decrease in the average WEI, which has been described above.

5. Conclusions

A new Weighted Environmental Index (WEI) based on the SIOSE object-oriented model and using GIS data has been introduced for analyzing environmental status through the evolution of land use over time. The versatility of the WEI is based on the fact that the user can define or modify the values of the evaluation factors (F_i) in order to adapt them to the case study under analysis. The methodology is completed by defining each specific land use weighting factor (β_{jk}), providing great versatility for analyzing land use/land cover change over time.

A demonstration of the application of the WEI to two different case studies (at regional and municipal levels) has been shown. The application of the WEI to these two case studies has demonstrated that the WEI is a powerful tool for analyzing land use change over time and has two major advantages over other environmental indexes. Firstly, the WEI is built based on periodically updated official data, so it avoids subjectivity. Secondly, the WEI can be applied to the analysis of land use change at different scales, and its application allows for the performing of local, regional or even national analyzes and comparisons. Additionally, the WEI is a flexible tool that covers a whole range of situations since it is able to analyze land use evolution over time based on the SIOSE object-oriented model and GIS data.

The application of WEI allows for the performing of detailed statistical analyses, leading to key conclusions about land use changes inside the study area and their environmental implications, quantifying and analyzing trends of environmental quality. The WEI index is based on the definitions of the values of evaluation factors (F_i) and their corresponding weights (α_i). The values of F_i and α_i should be decided by the modeler on the basis of expert knowledge considering local advice, following the methodology used by previous and simpler environmental indices identified in scientific literature. Strategically selecting and justifying the appropriate values of evaluation factors and weights allows us to use the WEI both for overall and fast screening or for precise and in-depth evaluation purposes [103].

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