

Article

# Multitemporal Analysis of Soil Sealing and Land Use Changes Linked to Urban Expansion of Salamanca (Spain) Using Landsat Images and Soil Carbon Management as a Mitigating Tool for Climate Change

Marco Criado <sup>1</sup>, Fernando Santos-Francés <sup>1</sup>, Antonio Martínez-Graña <sup>2,\*</sup>, Yolanda Sánchez <sup>2</sup> and Leticia Merchán <sup>1</sup>

<sup>1</sup> Department of Soil Sciences, Faculty of Agricultural and Environmental Sciences, University of Salamanca, Avenue Filiberto Villalobos, 119, 37007 Salamanca, Spain; marcocn@usal.es (M.C.); fsantos@usal.es (F.S.-F.); leticiamerchan@usal.es (L.M.)

<sup>2</sup> Department of Geology, Faculty of Sciences, University of Salamanca, Plaza de la Merced s/n., 37008 Salamanca, Spain; yolanda.ss@usal.es

\* Correspondence: amgranna@usal.es; Tel.: +34-923-294-496

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**Abstract:** The lack of urban sustainability is a widespread deficiency in urban agglomerations. To achieve adequate land use, we present a methodology that allows for: 1) the identification of the impacts caused by urban expansion since 1956 to the present in Salamanca (Spain); and 2) the promotion of a more sustainable future in urban development. A multi-temporal assessment of land use was made by remote sensing, while sustainability criteria were analyzed using the multicriteria analysis (MCA) with Geographical Information Systems (GIS). In addition, we established recommendations for soil carbon management in semi-arid ecosystem soils that contribute to climate change mitigation. The results show an increase of the urbanized area from 3.8% to 22.3% in the studied period, identifying up to 15% of buildings in zones with some type of restriction. In 71% of the cases, urbanization caused the sealing of productive agricultural soils (2519 Ha), almost 20% of which were of the highest quality. In last few decades, an excessive increase of built-up areas in comparison to population dynamics was identified, which causes unnecessary soil sealing that affects the food production and the capacity to mitigate climate change by managing the carbon cycle in the soil.

**Keywords:** city expansion; climate change; land use management; soil organic carbon; soil sealing

## 1. Introduction

The progressive increase of population and its agglomeration in cities [1], which by 2050 is estimated at 68% [2] and by the end of the twenty-first century at 90% [3], is one of the important current challenges for humanity. Unmeasured and unplanned urbanization causes multiple negative impacts on society and economy (for example, sealing of fertile soil [4], deaths related to pollution and heat [5,6], problems of urban mobility [7], or greater exposure to natural risks, this being further enhanced by climate change [8,9]) and in the environment (loss or alteration of areas of ecological quality and reduction of biodiversity [10], air, soil and water pollution [11–14], or alteration of precipitation patterns [15] and local temperature [16]). The impact of urban agglomerations on climate change is evident due these agglomerations being the largest greenhouse gases emitting and resource consuming group, which may compromise economic development, food security and/or social justice [17–19].

Historically, cities have generally spread without planning or restriction criteria, linked to economic development that originated in disorganized cities as a result of a massive unplanned experiment

in landscape change [20]. Soon after, the first effects on the population and the environment linked to the binomial industrialization–urbanization were manifested. Gradually, society demanded more respectful and responsible practices with the environment, which caused the acceptance of sustainable development being the only development model that guarantees social welfare, which requires adequate and sustainable urban development [21–23].

Sustainable urban planning has been a topic that has gained increasing interest in recent years [24]. To understand the expansion that cities have undergone, many authors have used satellite image (especially Landsat images) interpretation techniques to monitor changes in land uses linked to urbanization [25–28]. Regarding how to face the problem related to urban sustainability, there are many approaches and themes studied in literature. The multicriteria analysis (MCA) is widely used and accepted due to the fact that it integrates diverse environmental and socioeconomic parameters as decision factors into the study, being very useful in the early stages of urban planning [29–31]. Other studies are based on improving specific aspects with a relevant contribution to urban sustainability. Rode et al. [32] evaluated the impact of transport network accessibility on the sustainability of a city, focusing on the relationship between urban typology and respective cost. In relation to this, other authors gave a broader sense to this idea, and addressed the "networked city" [33], including the relationship between sustainability and urban growth in the city, and infrastructure and basic services' spatial configurations [34]. Energy optimization is another block of the urban sustainability pillar, hence, there is abundant literature on multiple topics such as buildings' energy efficiency or renewable energy network implementation [35–37]. Green spaces and their contribution to sustainability have also been widely studied [38–40]. Other studies propose to take into account the factors that will be affected by climate change in urbanization processes and may cause future risks for the population, for example Berry et al. [41], who considered sea level rise as a key element in coastal cities. Finally, some authors have developed tools to assess and verify the sustainability of different elements of the city, such as buildings and green architecture [42,43], transport networks [44] and water supply [45], among other aspects, such as social justice [46].

However, advancing in the field of sustainability through the execution of different creative, ambitious and innovative measures has been the main handicap of governments and planners, generally linked to "more classic" planning procedures [47]. Nevertheless, it is increasingly common for some cities and countries to implement innovative measures and designs covering different factors such as public health [48] and sewerage [49], energy [50] or green area [51] management. In addition, multiple concepts have been developed that aim to achieve a sustainable city model, well cataloged by De Jong et al. [52], who provide an interesting analysis of each one, as well as the synergies between sustainable city models and their weaknesses and uncertainties.

Soil occupation and soil sealing are indissoluble phenomena in city expansion, being one of the main soil degradation causes. Both are accepted as necessary for human development, but have serious negative environmental and socioeconomic effects with long-term consequences. Soil sealing is the most intense form of land occupation and it causes an irreversible environmental impact [53]:

- *Pressure on water resources:* Soil water supports plants, saves irrigation costs, reduces the incidence of droughts and reduces the risk of flooding. When the earth is covered with impermeable materials, the amount of rain that the soil is capable of absorbing is reduced. Instead of filtering through the soil and replenishing aquifers and groundwater, heavy rain causes surface runoff and increased surface water flow. Soil sealing in natural flood zones is another problem, because the water retention capacity in alluvial plains is reduced. Soil sealing can also have consequences for the local climate due to the reduction of evapotranspiration areas (much of the volume of rain that the land receives depends, in turn, on the evaporation of water into the atmosphere from the soil and plants) [54,55].
- *Food security threat:* Historically, cities were built near the most fertile soils to guarantee enough food. However, conversely, urban explosion has devoured these high-quality areas. There is even a tendency to stop cultivating the unsealed land in urban surroundings. The reduction of

available arable land imposes greater pressure on agricultural production. In addition, the world population grows and increases the demand for food, which must be solved with limited and shrinking arable land [56].

- *An obstacle to manage the soil carbon cycle:* Soil contains more organic carbon than the atmosphere and vegetation put together (760 and 560 Gt, respectively), and is estimated to accumulate around 75% of terrestrial organic carbon [57]. Every year, the soil captures a part of human CO<sub>2</sub> emissions. Carbon storage depends on the balance between gains and losses, which are dominated by biotic factors, such as biomass production, microbial abundance, environmental variables (climate), soil characteristics, including texture and lithology as well as soil management. The destruction of the upper soil horizon in urbanization causes the release of part of the organic carbon in the form of greenhouse gases due to mineralization, and ruins centuries of work of natural processes which form arable land. Because of this, attention to soil organic carbon (SOC) cycle is increasing [58–60]. The reforestation of degraded forest lands and the adoption of recommended management practices (RMP) in farmland and cropland have been argued as effective options for carbon sequestration in soils, and both generate additional environmental and socioeconomic benefits [61]. The option of carbon sequestration and improvement in soil productivity through the implementation of RMP in croplands can be economically and environmentally more profitable than reforestation, unless reforestation is carried out in deep soils of marginal areas. Certain changes in agricultural practices (conservation tillage) or the conversion of some unproductive croplands into grasslands or forests can increase carbon sequestration in soils [62]. In the studied area, RMP were adopted, such as minimum tillage techniques, conservation tillage, covert crops, mulch, fallow with vegetation, crop rotation, the addition of exogenous organic matter, the use of high yield varieties and greater biomass, and the responsible use of chemical fertilizers or the conversion of some unproductive farmland into grasslands or forests, which can increase carbon sequestration in soils.

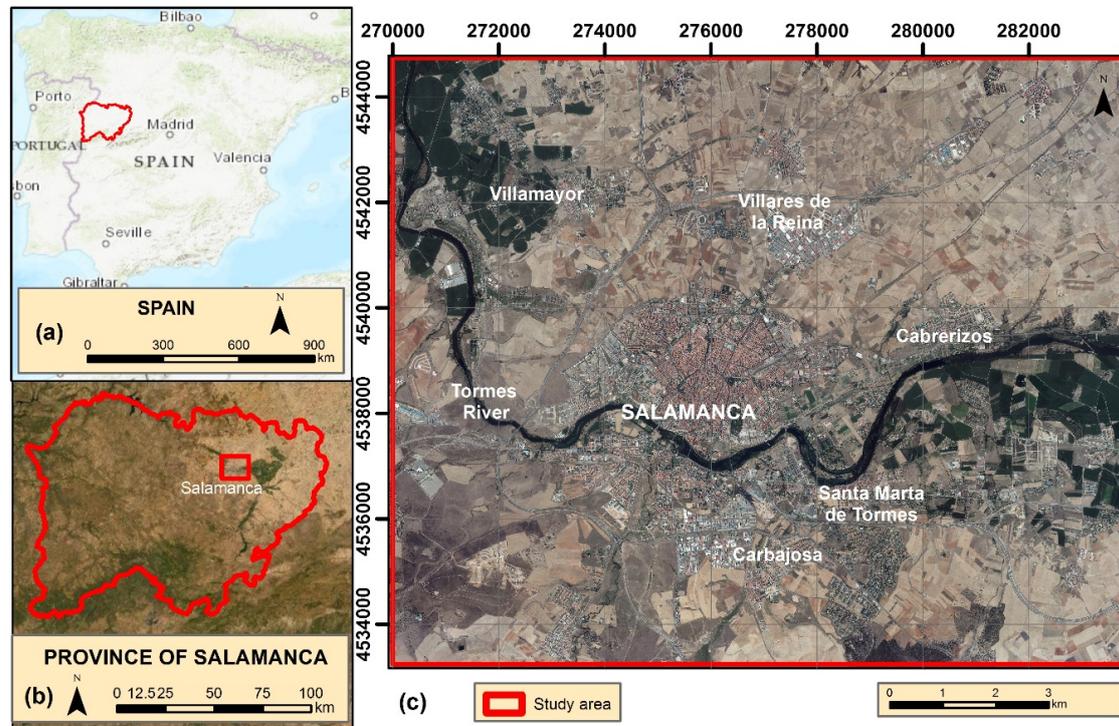
In conclusion, the correct soil management and the adaptation of the urban system for environmental protection and climate change mitigation objectives are necessary if we want to preserve our environment and well-being, and avoid the adverse scenarios that are foreseen in relation to global warming. Therefore, the objectives of this work are: (1) to analyze the urban expansion sustainability since the period 1956 to 2018 in the study area; (2) to find the most suitable areas for the urbanization and extension of Salamanca and its surroundings; (3) to study the land capability of soils and evaluate the urban dynamics and their repercussions on food production; (4) to determine the SOC present in the studied soils in order to recommend an adequate soil management in croplands that help mitigate climate change; (5) to propose a method based on Geographical Information Systems (GIS) that through (i) the multi-temporal analysis of satellite images, (ii) the study of sustainable interest criteria (ecological, agricultural, cultural and population protection) by means of a multi-criteria analysis and (iii) the knowledge of the soils, allows to achieve the previous objectives.

## 2. Materials and Methods

### 2.1. Study Area

Salamanca is located in Western Spain (Figure 1) which, together with its surroundings (Santa Marta de Tormes, Carbajosa de la Sagrada, Villamayor, Villares de la Reina and Cabrerizos are the main municipalities of the Salamanca outskirts), houses around 200,000 inhabitants [63]. It is the largest urban agglomeration of its environment, eminently agricultural and livestock, and in the last few decades has featured an aging population, with rural exodus to the city, hence Salamanca has been continuously gaining population since the middle of the last century, in contrast to the strong and prolonged decline at the regional scale. The study area (with an extension of 15.899 Ha) has progressed from housing 20% of the province population at the start of the study period to almost 60% today, that is to say that the population has multiplied by 2.5, rising from 80,000 inhabitants to the current

190,000 [63]. In addition, the city of Salamanca has a great historical, artistic and cultural heritage, which led it to be declared a World Heritage Site by UNESCO [64], and a prestigious University (University of Salamanca) with 8 centuries of history, which allows the city to have great activity and a cultural mix, making it versatile and cosmopolitan.



**Figure 1.** Study area: (a) Location of Salamanca province in Spain; (b) Study area situation in Salamanca Province; (c) Salamanca and suburbs with the most relevant local elements.

## 2.2. General Methodology

The proposed methodology consists of three main parts (multi-temporal study of satellite images, multi-criteria analysis and evaluation of soil SOC), whose particular methodologies and materials used are detailed below in their respective sub-sections. Figure 2 shows a flow chart of the established methodology. After the collection of satellite images, the supervised classifications are carried out and the multi-temporal evolution of land use is analyzed. Through field work, the multi-criteria analysis is designed and carried out and the carbon stock in soils is estimated. With the results of the multi-temporal evolution and the multi-criteria analysis, we can evaluate the sustainability of urban expansion in the past and establish guidelines for sustainable growth of urban areas in the future, as well as evaluate the impact of soil sealing according to its agricultural quality. Finally, based on the SOC study, recommended management actions are proposed for agricultural soils that will allow for the mitigation of climate change.



with aerial images (source: Geographic Institute of Spain [70]) taken on a similar date that the aerial image used for classification.

#### 2.4. Multi-Criteria Analysis through Analytic Hierarchy Process (AHP)

The areas that could entail restrictions to urbanization due to their environmental, agricultural and cultural characteristics, as well as those that may pose a risk to the population, are delimited by means of a Restrictive Areas Identification Index (RAII), which is calculated through MCA based on Analytic Hierarchy Process (AHP) [71–73]. Four criteria ( $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$ ) are studied to calculate the RAI (Equation (1)). Firstly, based on the field work, the different factors that make up each criterion are classified internally (0–5) according to their characteristics, assigning high weights to the areas with the highest environmental, agricultural or cultural quality or those with the highest risk for the population. The lowest weights are given to the areas with the lowest quality and risk. This is carried out with the aim of incorporating the spatial variation experienced by each factor throughout the study area into the evaluation. Secondly, using the AHP, the relative weights of each criterion ( $k_1$ ,  $k_2$ ,  $k_3$  and  $k_4$ ) are obtained in relation to the rest of the criteria:

$$\text{RAI} = k_1 * C_1 + k_2 * C_2 + k_3 * C_3 + k_4 * C_4 \quad (1)$$

where  $k_i$  is the relative importance weight for each criterion as a result of the AHP, and  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$  represent the ecological criterion, agrolological criterion, cultural criterion and population protection criterion, respectively.

The ecological criterion ( $C_1$ ) identifies the areas of highest quality in ecological, environmental and landscape terms. These spaces keep the qualities of the autochthonous ecosystems and conserve the natural processes in the vicinity of urban areas, contributing, in addition, to the reduction of global warming by retaining the carbon in the vegetation and avoiding the oxidation of soil carbon [74]. To do this, the area was studied and natural habitats were mapped [75]. The areas where natural habitats are conserved received the highest weighting (5), while the rest received the lowest (0). On the other hand, the landscape is increasingly taken into account in territorial planning due to the multiple benefits it provides [76]. The areas of Salamanca and its surroundings were scored according to their landscape quality (Very high: 5; High: 4; Moderate: 3; Low: 2; Very low: 1).

The agrolological criterion ( $C_2$ ) evaluates the agricultural quality of the soils, as it is important that the most fertile soils are protected for an irreversible use such as the urbanization process [77]. According to the Land Capability Classification [78], soils are scored according to their agricultural quality: Class II (5); Class III (3); Class IV (2); Class V-VI (1) and Class VII (0).

The historical, artistic and cultural heritage conservation must be another priority in urban planning due to its intrinsic value [79]. Through the cultural criterion ( $C_3$ ), archaeological sites and areas or goods of cultural interest were mapped. These areas received a weight of 5, while the rest received 0.

The population protection criterion ( $C_4$ ) assesses the natural risks that society are exposed to, and are increasingly vulnerable to, in a way that restricts the urbanization of those areas where these risks may occur. In Salamanca and its surroundings, the natural risks are flooding, and to a lesser extent, rockfall. To establish the areas affected by flood risk, the data from a previous study are used [80], while the areas affected by rockfall are delimited by field work and the study of the slopes and dips of the terrain. These areas were weighted according to risk: (Very high: 5; High: 4; Moderate: 3; Low: 2; Very low: 1; Non-existent: 0).

The AHP is a structured technique for the organization and analysis of complex decisions. The evaluation of indicators and their weights must be determined according to their importance using paired comparisons. The AHP is composed of several steps [71–73]. Firstly, the problem is decomposed into its components in a hierarchy of goal, criteria and factors. Secondly, consultations are held to obtain the views of local experts regarding the hierarchy structure that occurs between the criteria in

the pairwise comparison. To this end, two experts from each stakeholder group, all of whom belong to public bodies, were surveyed. The average results of the survey were employed to determine the importance of each criterion. The comparison was described regarding integer values from 1 to 4 (Table 1), where a higher number means that the chosen criterion is considered more important against another criterion. Thirdly, the pairwise comparison of the four criteria generated at the second stage is organized into a square matrix: the pairwise comparison matrix (Table 2). Fourthly, the pairwise comparison matrix is normalized and the relative weights ( $k_i$ ) of each criterion are calculated. Fifthly, the consistency of the normalized comparison matrix assessments is evaluated using the consistency ratio (CR). The CR is composed of a consistency index (CI) and a random index (RI). The CI is calculated using the consistency measure (CM) (Equation (2)). The RI is estimated by Equation (3). The CR is the relation between CI and RI (Equation (4)). In Table 2, the column  $k_i$  contains the relative weights for each criterion. In the CM column is the consistency measure valor for each criterion, from which the CI is derived, whose value was 0.004 ( $\lambda_{\max} = 4.0125$ ). The RI was 0.99. Finally, the CR is 0.004, a value very close to 0, indicating the high consistency of the judgements made in the MCA.

$$CI = (\lambda_{\max} - n) / (n - 1) \quad (2)$$

$$RI = 1.98^{*(n-2)} / n \quad (3)$$

$$CR = CI / RI \quad (4)$$

where  $\lambda_{\max}$  is the sum of the consistency measure (CM) divided by  $n$ , and  $n$  is the number of criteria.

**Table 1.** Quantification of importance based on concordance between the criteria.

Level of Prevalence	Definition	Description
1	Similar prevalence	Criteria (x, j) contribute equally to urban sustainability
2	Moderate prevalence	Criterion (x) slightly prevails over criterion (j) in urban sustainability
3	High prevalence	Criterion (x) dominates criterion (j) in urban sustainability
4	Total prevalence	Criterion (x) contributes exclusively to urban sustainability with respect to the other criterion (j)

**Table 2.** Determination of the weights of each criterion using the Analytic Hierarchy Process (AHP) pairwise comparison matrix.

Analytical Hierarchy Method (j) (x)	C1: Ecological	C2: Land Capability	C3: Cultural	C4: Population Protection	$\Sigma (x_{jj})/n$	Relative Weight $(k_i) \frac{\Sigma (x_{ij})/n}{\Sigma (x_{ij})}$	CM
C1:Ecological	1	2	3	1	7	0.35	4.00
C2: Land Capability	0.5	1	2	0.5	4	0.20	3.75
C3: Cultural	0.33	0.5	1	0.33	2.16	0.10	4.30
C4:Population protection	1	2	3	1	7	0.35	4.00
				$\Sigma (x_{ij})$	20.16	–	

Finally, the RAI, used to identify the restrictive areas, was calculated using the relative weights obtained from the MCA (Equation (5)). The RAI Index is reclassified into 4 degrees, and the degree that contains the high values is considered in the grouping of the areas of interest, that is, those that

present environmental, cultural or agricultural interest or a risk to the population. These are therefore considered restrictive for urbanization.

$$RAII = 0.35 * C_1 + 0.20 * C_2 + 0.10 * C_3 + 0.35 * C_4 \quad (5)$$

### 2.5. Evaluation of the Soil Organic Carbon Stock

As a complement to this analysis of sustainable expansion of the city, we also intend to establish guidelines for a more adequate management of soil that contributes to climate change mitigation and food production assurance. For this purpose, the potential of the study area soils was analyzed, for which 75 soil samples from the surroundings of Salamanca were collected. We carried out routine analyses of the soil samples, determining the types and associations of soil, and the main agricultural interest soil parameters. From the soil map, a land capability map that allows evaluating the agricultural soil sealing and its relationship with the urban expansion and food production was completed. On the other hand, to determine the relationship between land use and climate change, the soil organic carbon content (SOC) and the bulk density of the soil samples (0–30 cm) were analyzed to estimate the soil organic carbon stock (SOCs). The SOC organic carbon stock ( $\text{MgC} \cdot \text{ha}^{-1}$ ) was calculated as follows (Equation (6)):

$$\text{SOCs} = \text{SOC}/100 * \text{BD} * \text{D} * 10000 \quad (6)$$

where SOC is the organic carbon concentration (%), BD is the bulk density ( $\text{Mg} \cdot \text{m}^{-3}$ ) and D is the thickness of the stratum (0.30 m). Organic carbon was analyzed by oxidizing carbon with dichromate acid [81]. Bulk density was determined with the paraffin method [82].

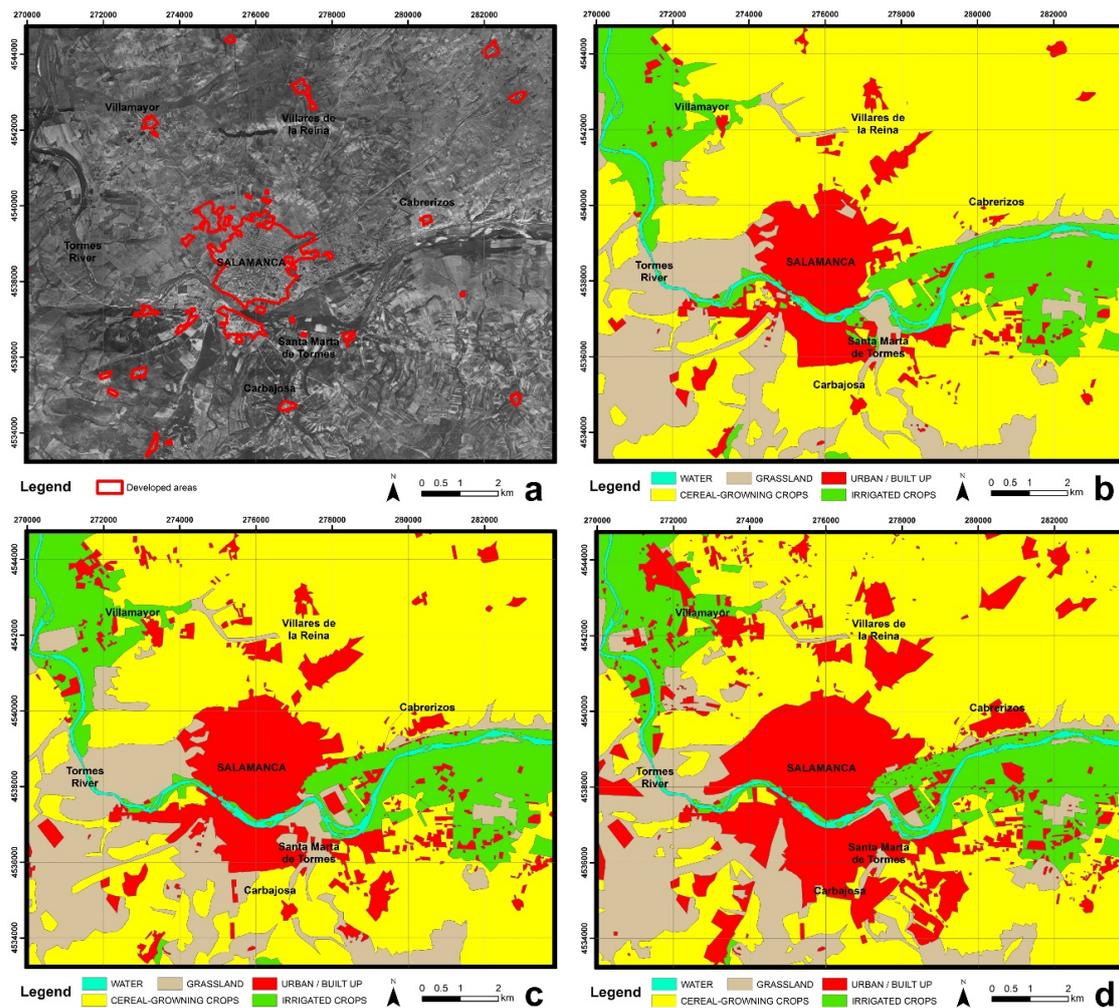
## 3. Results

### 3.1. Land Use Changes

The supervised classifications in which the evolution of the five land uses is defined show adequate levels of agreement: very good for the classifications of 1985 (Kappa = 0.71) and 1998 (Kappa = 0.78) and excellent for that of 2018 (Kappa = 0.85). Land cover maps corresponding to each studied period can be found in Figure 3. Table 3 summarizes the space–time evolution of each cover class. Two trends are clearly observed: 1) a progressive increase of built-up areas; 2) a decrease of croplands. Built-up extension increased from 3.8% to 22.3% from 1956 to the present. On the other hand, crop area decreased from 72.9% in 1985 to 60.8% in 2018, so much so that the cropland extension losses would be greater if we could compare them for the period 1956–2018. There was greater waste of cropland area for the period 1985–2018 in cereal-growing crops (10.0% of the study area) than in irrigated crops (2.1%), with 1583 Ha and 339 Ha, respectively. Grasslands and wastelands show little variation over time, and interactions with cereal crops were observed. The water extension, belonging exclusively to the Tormes River, is relatively similar, although we detect extension decreases over time, which may be due to the riverbank forest's improvement, which covers more and more riverbed areas.

**Table 3.** Extension (Ha) and percentage of different land cover categories in each period.

	Water		Grassland		Cereal-Growing Crops		Irrigated Crops		Urban/Built-up	
	Area	%	Area	%	Area	%	Area	%	Area	%
<b>1956</b>	–	–	–	–	–	–	–	–	596	3.8
<b>1985</b>	238	1.5	2423	15.3	9288	58.5	2290	14.4	1630	10.3
<b>1998</b>	230	1.4	2604	16.4	8755	55.2	2059	13.0	2219	14.0
<b>2018</b>	226	1.4	2455	15.5	7705	48.5	1951	12.3	3532	22.3



**Figure 3.** Land use evolution: (a) Built up areas in 1956; (b) 1985; (c) 1998; (d) 2018.

As for the sealing of soils in the main municipalities, this increased considerably, being more pronounced in the surroundings of Salamanca from 2000. Over the period of study, the sealed soil progressed from 13.3% (519 ha) to 41.7% (1634 ha) in the municipality of Salamanca; from 0.6% (6 ha) to 33.3% (333 ha) in Santa Marta de Tormes; in Carbajosa from 0.8% (7 Ha) to 34.6% (296 Ha); from 8.5 Ha (0.5%) to 296 Ha (18.4%) in Villamayor; from 16.5 Ha (0.8%) to 302 (15.1%) in Villares de la Reina; while in Cabrerizos it increased from 0.4% (4.1 Ha) to 11.8% (120 Ha).

The most significant transformations in land use are summarized in Figure 4 and Table 4. For the period 1985–1998, there was a land cover transformation in almost 7% of the area (1088 Ha), while in the 1998–2018 period, the affected area was 1935 Ha (12% of the study area), thus in the last three decades about 20% of the studied area would have suffered land cover changes. The main changes are related to croplands and grasslands, which were generally built-up. It highlights, in both periods, the transformation of cereal-growing crops in urban areas, which signify the 36% of total transformations (1089 Ha). In addition to this, 253 Ha (8%) previously dedicated to irrigated crops were built. A total of 510 Ha of grasslands and wastelands were built in this period (17% of land cover changes). The rest of the significant transformations take place between the crops and grasslands areas, especially the conversion of cereal-growing crops in grasslands and wastelands with 664 Ha (22%), which is related to the lower quality and production that croplands zones leave.

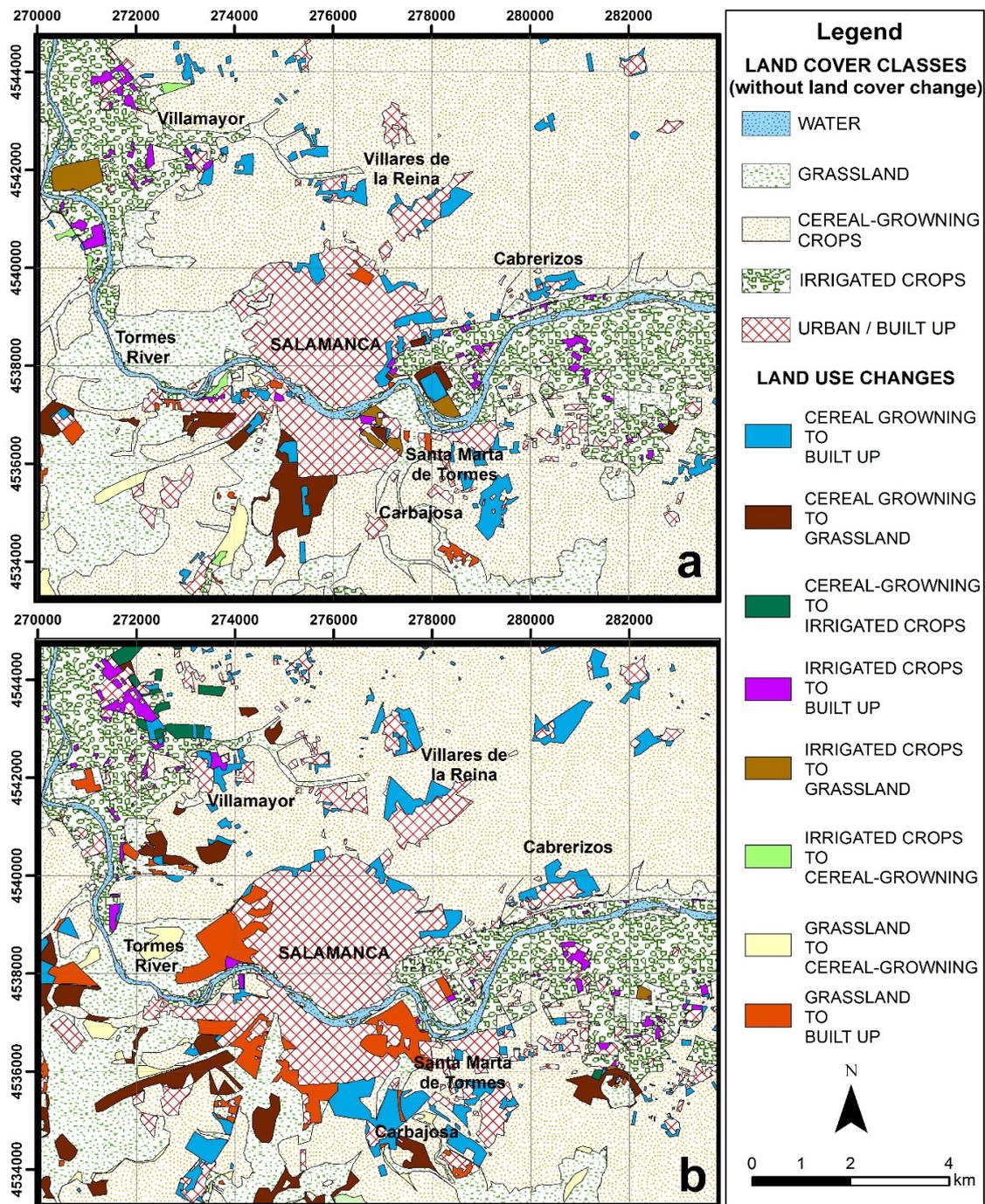


Figure 4. Main land cover transformations: (a) The period 1985 to 1998 (b) and 1998 to 2018.

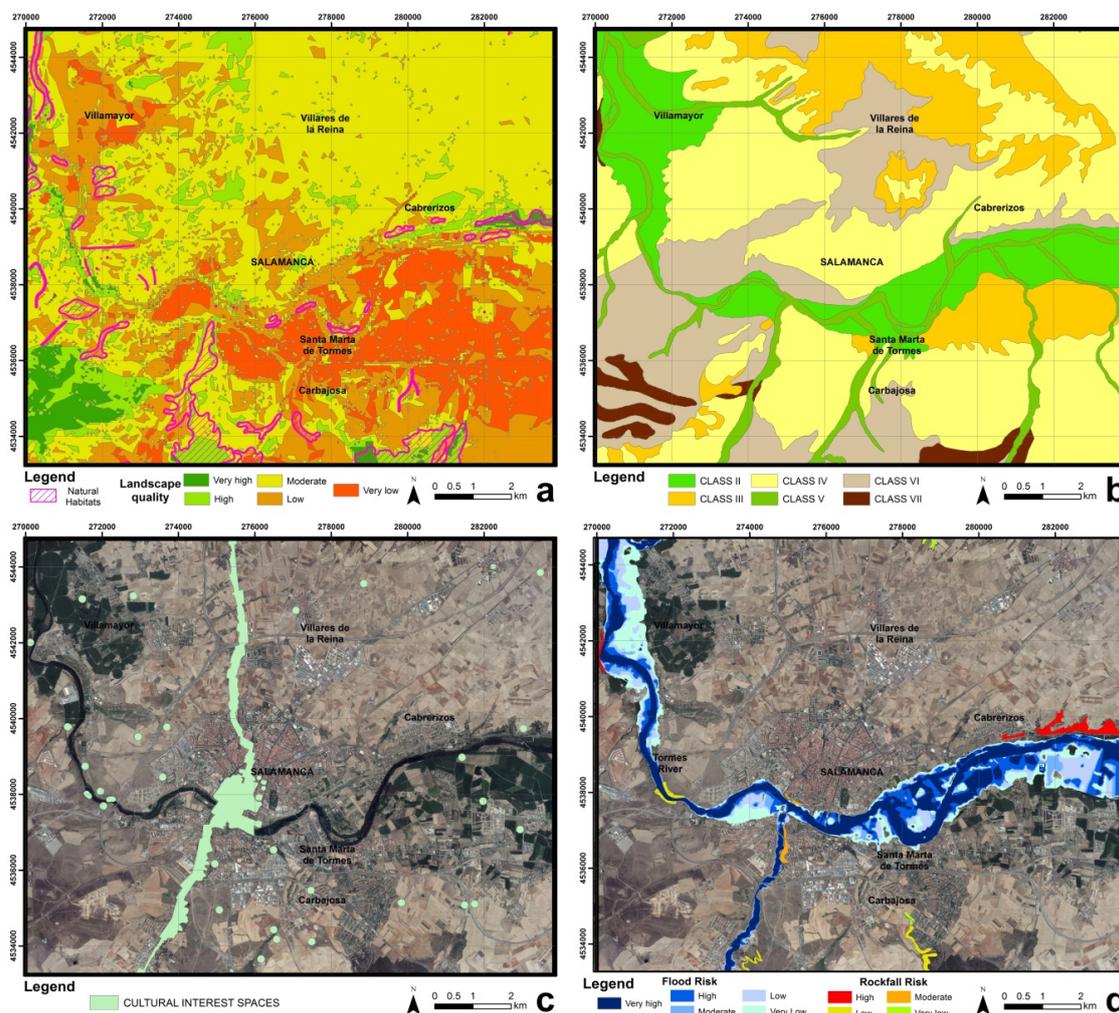
Table 4. Main land cover transformations in each period: 1985 to 1998 (left) and 1998 to 2018 (right).

Land Cover	Water		Grassland		Cereal Crops		Irrigated Crops		Built up	
Water	–		NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>
Grassland	NR <sup>1</sup>	NR <sup>2</sup>	–		96 <sup>1</sup>	135 <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	68 <sup>1</sup>	442 <sup>2</sup>
Cereal crops	NR <sup>1</sup>	NR <sup>2</sup>	241 <sup>1</sup>	423 <sup>2</sup>	–		6 <sup>1</sup>	71 <sup>2</sup>	414 <sup>1</sup>	684 <sup>2</sup>
Irrigated crops	NR <sup>1</sup>	NR <sup>2</sup>	95 <sup>1</sup>	8 <sup>2</sup>	29 <sup>1</sup>	14 <sup>2</sup>	–		117 <sup>1</sup>	136 <sup>2</sup>
Built up	NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	NR <sup>1</sup>	NR <sup>2</sup>	–	

<sup>1</sup> Land cover changes (1985–1998); <sup>2</sup> Land cover changes (1998–2018); NR: No representative land cover change.

### 3.2. Urban Sustainability Analysis

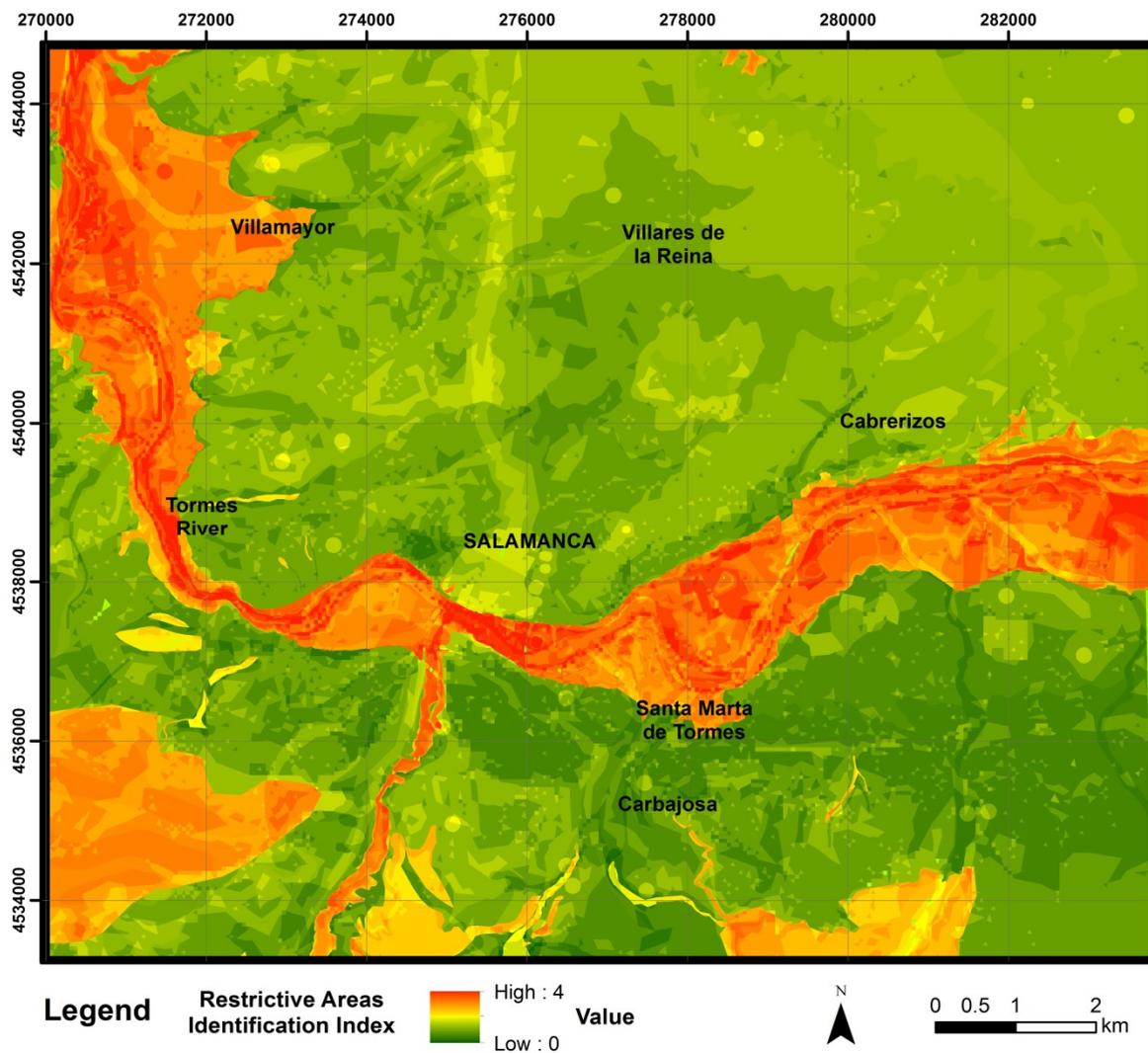
After analyzing the land cover evolution, it is appropriate to evaluate the urban expansion: 1) it was in agreement with the highest quality environment elements (natural habitats, land capability, high landscapes quality areas and cultural interest spaces); and 2) it took into account the population protection criteria (natural risks). It also identified the areas that should not be built in future city extensions to guarantee these objectives. Figure 5 represents the different factors evaluated by the RAI to delimit the areas with limitations to urbanization. The natural habitats have an extension of 683 Ha and are related to Tormes riverbed riparian formations, and to Mediterranean grasslands and forests (Figure 5a). Highest landscape quality spaces (981 Ha) are located in areas of greater natural vegetation and orography (Figure 5a). Figure 5b shows the soils according to their land capability, where the 1872 Ha occupied by the highest quality soils stand out. Figure 5c delimits the historical, artistic and cultural interest spaces (471 Ha), where the old city of Salamanca and the Roman road "Ruta de la Plata" stand out. Finally, 1552 Ha were identified as flood risk zones, and areas with rockfall risks (145 Ha) were associated exclusively with river scarps (Figure 5d).



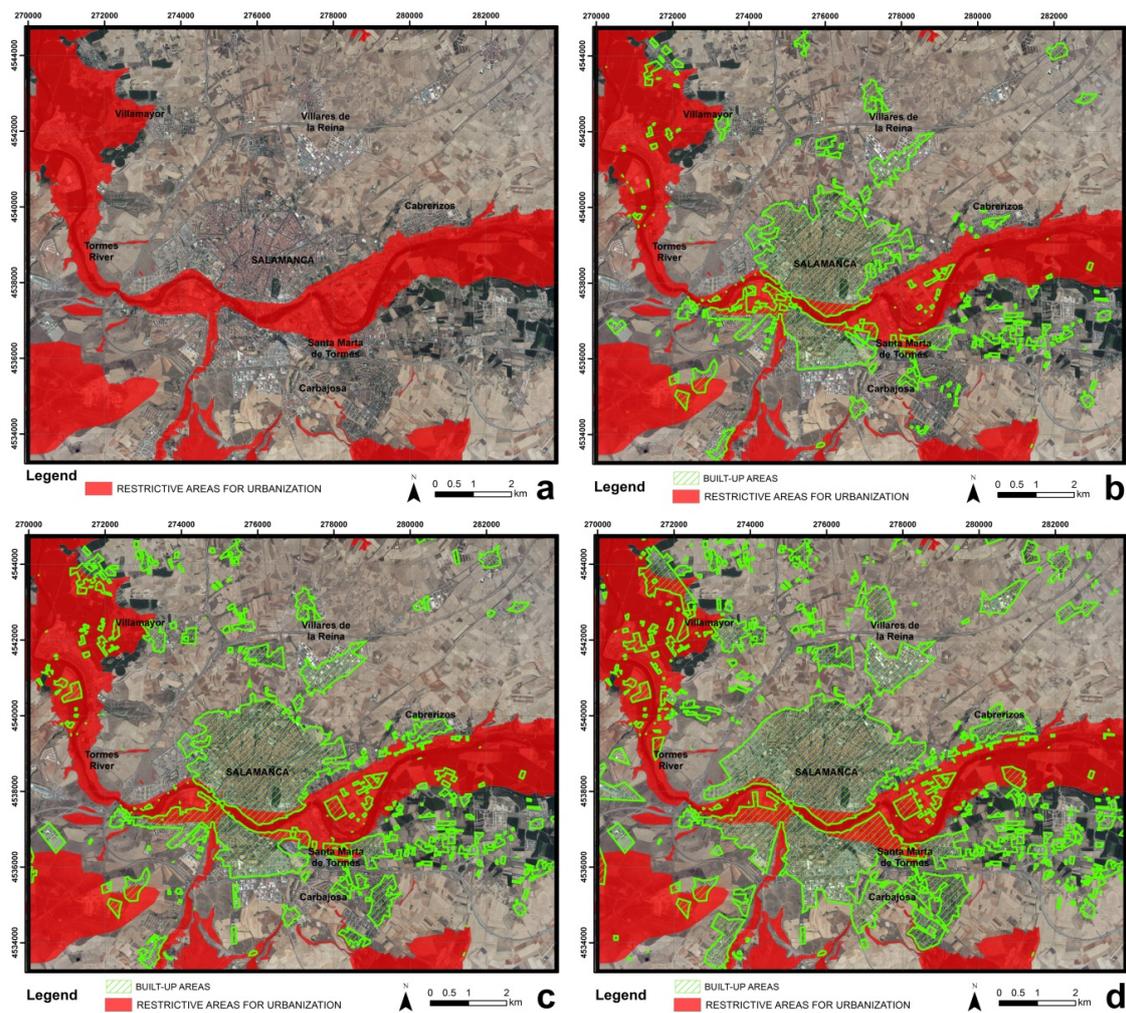
**Figure 5.** Multicriteria analysis studied factors: (a) natural habitats and landscape quality; (b) land capability of the soils; (c) areas with cultural protection; (d) flood risk and rock fall risk spaces.

The results obtained by the RAI Index show the restriction to urban expansion presented by the different areas of Salamanca and its surroundings. These limitations are more pronounced when the value of the index is close to four (Figure 6). Figure 7 shows the extension (3747 Ha) of these restrictive zones (Figure 7a) and how urbanization has evolved throughout the studied period in these areas.

The built-up spaces in areas with limitations were shown to be gradually growing: 218 Ha in 1985 (Figure 7b); 347 Ha in 1998 (Figure 7c); and 541 Ha in 2018 (Figure 7d), which means that 15% of the current buildings are on restrictive areas. In relation to agricultural soils sealing (Class II, III and IV), 2466 Ha have been lost. New buildings have also prospered in areas with natural risks: up to 187 Ha built in flood zones, compared to six hectares in rock-fall risk areas. The impact on areas with the highest landscape quality (43 Ha), and on natural habitats (29 Ha, especially pastures of community interest) is lower.



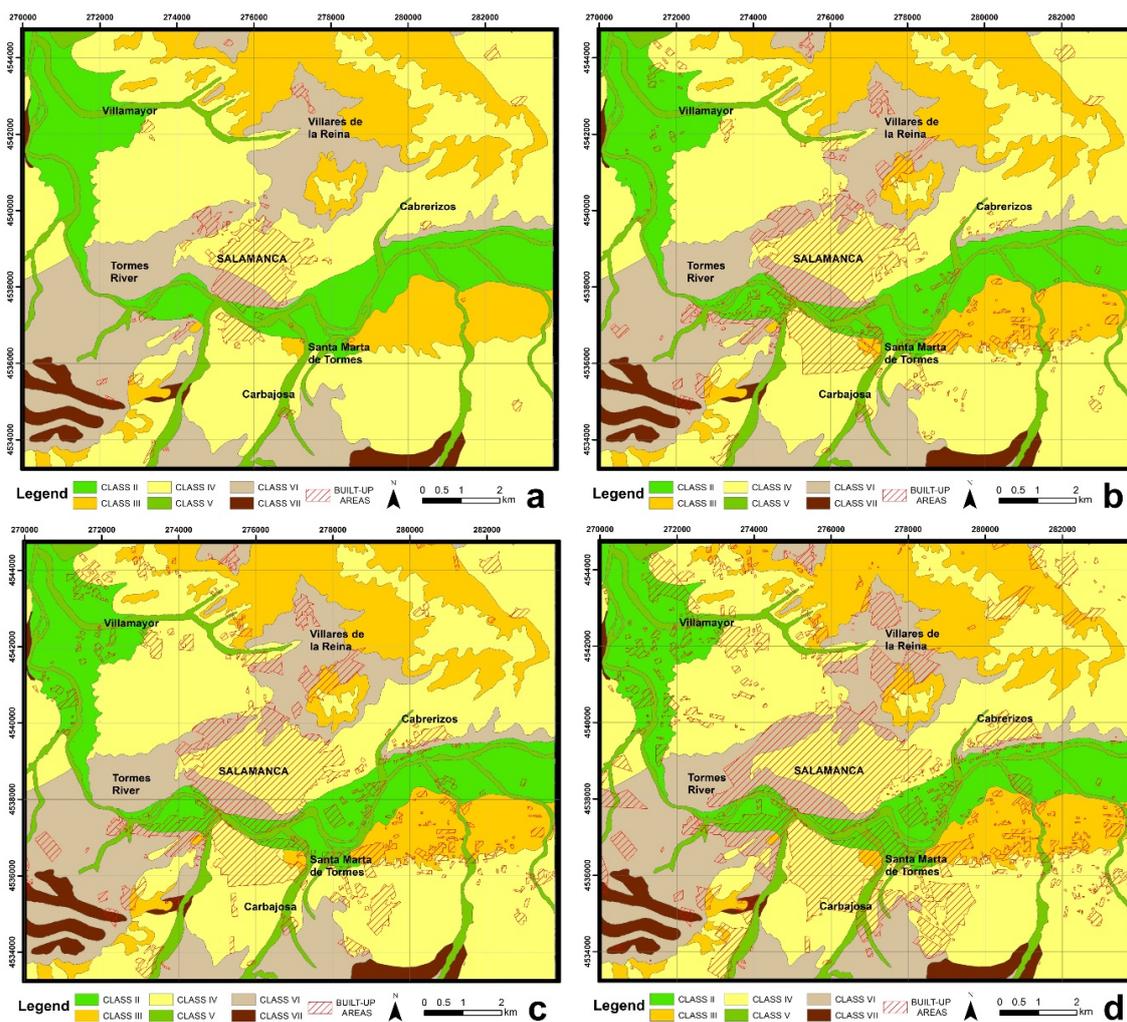
**Figure 6.** Evaluation of the restriction to urbanization in the study area using the Restrictive Areas Identification (RAI) Index.



**Figure 7.** Built-up areas evolution in spaces with restrictive conditions: (a) areas with restrictions for urbanization; (b) built up zones on restrictive areas in 1985; (c) built up spaces on restrictive areas in 1998; (d) built up areas on restrictive zones in 2018.

### 3.3. Soil Sealing, Food Production and Climate Change

Figure 8 presents the effect of urbanization on soils according to their land capability. Table 5 summarizes both the soil sealing surface in each period and the total sealed extension since the beginning of the study period according to soils land capability classes. Until 1956, 596 Ha were occupied, mainly affecting Class IV soils (Figure 8a). In the period 1956–1985, 1034 ha were built-up, of which 729 Ha had good agricultural aptitude (Figure 8b). In the next study period (1985–1998), almost 80% (455 Ha) of the new built-up area (589 Ha) corresponded to croplands (Figure 8c). On the other hand, in the period 1998–2018, 914 Ha of croplands were urbanized, out of a total of 1313 Ha (Figure 8d). In short, 3532 Ha were occupied in Salamanca and its outskirts, of which 2519 Ha were agriculturally suitable, and 426 Ha were of the most productive soils. The remaining 1013 Ha that were built correspond to soils that contain (mainly) grasslands and (hardly ever) forests.



**Figure 8.** Soil sealing according land capability: (a) until 1956; (b) up to 1985; (c) in 1998; (d) until 2018.

**Table 5.** Extension (Ha) of land capability classes affected by urbanization in the studied period.

Time	Land Capability Classes								Built up Area (Ha)
	I	II	III	IV	V	VI	VII	VIII	
Until 1956	–	18	6	400	9	163	–	–	596
1956–1985	–	128	144	454	45	257	6	–	1034
Until 1985	–	146	150	854	54	420	6	–	1630
1985–1998	–	109	43	303	22	108	4	–	589
Until 1998	–	255	193	1157	76	528	10	–	2219
1998–2018	–	171	139	604	48	340	11	–	1313
Until 2018	–	426	332	1761	124	868	21	–	3532

In relation to the affected soil types, the sealing of fluvisols (426 Ha) in meadow spaces stands out, since they are the most productive soils due to their great thickness, adequate physicochemical characteristics and water availability (Class II). In Class III, the luvisols, with good physicochemical conditions, are demarcated, these being the oldest and most developed and thick soils. Due to urban expansion, 332 Ha of luvisols were lost. Class IV soils, although they are suitable for tillage, have certain limitations. These soils are less developed and thicker than the previous ones, belonging to the cambisols, and are the soils that have had the greatest impact (1761 Ha urbanized). Class V, VI and VII

are not soils with agricultural aptitude. Class V corresponds to gleysols developed in alluvial deposits linked to water courses of small size, and its extension is scarce. They usually have different textural composition and low thickness, the clay content being an important factor in their behavior. An amount of 124 Ha of Class V was sealed, previously dedicated to wet grasslands. Class VI presents a considerable extension in the study area and groups together soils of scarce development and thickness with dry pastures presence. They are mostly regosols and cambisols of scarce development, which in the studied period, 868 Ha were occupied. Class VII soils are poorly represented in Salamanca and its surroundings. They are thin and sparsely developed soils, generally located on hard rocks associated with the mountain areas (Leptosols). Only 21 Ha built on this class have been identified where the Mediterranean forest and dry pastures are generally developed. No soils of Class I or Class VIII were identified.

Finally, SOC assessments are essential in the role of climate change mitigation. In our study area, the average organic soil carbon stock (Table 6) near the surface (0–30 cm) is 1.7 times higher in grassland lands ( $68.31 \text{ Mg C ha}^{-1}$ ) than in croplands ( $40.78 \text{ Mg C ha}^{-1}$ ), thus, a very important reduction of SOC can be expected in the upper 30 cm after land use change from grasslands to croplands. Land management is one of the most important factors that controls the concentration of SOC. There is great difference between the SOC averages of the superficial horizons of soils under grasslands (2.43%) and of the crop soils (0.89%), which shows the rapid degradation of the organic matter from grasslands when it becomes croplands. In addition, in soils with natural vegetation, all the remains are incorporated into the soil, while in the crop soils, the crops are harvested manually, with the consequent plant material being a great loss that will not return to the soil.

**Table 6.** Soil organic carbon stock statistics (SOCs) and organic carbon concentration (SOC) in different land use soils.

Carbon	Land Use	Mean	Minimum	Maximum	Standard Deviation	Kurtosis	Coef. of Variation
SOCs	Grassland	68.31	20.20	362.34	75.69	9.43	110.80
	Crop field	40.78	10.73	94.71	16.32	1.16	40.01
SOC	Grassland	2,43	0,53	7,32	1,70	1,77	69,94
	Crop field	0.89	0,25	1,72	0,37	−0,37	42,00

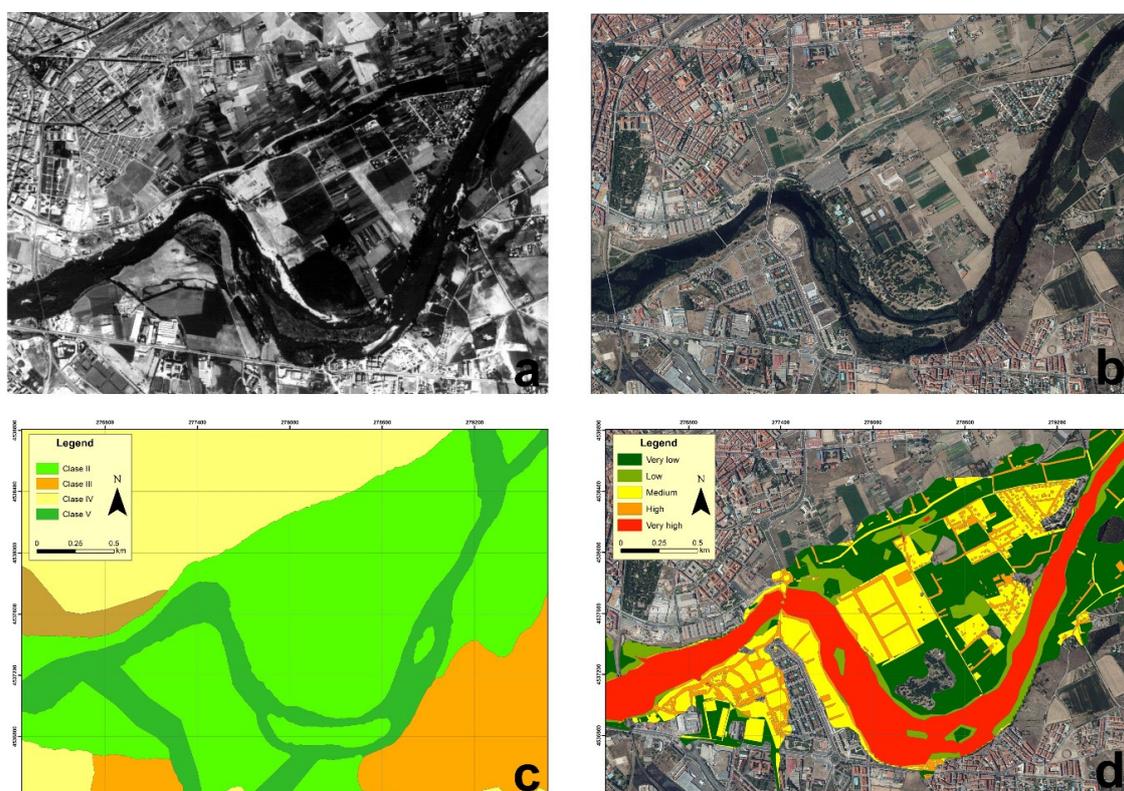
#### 4. Discussion

The analysis of the land studies evolution using aerial image processing is considered adequate and accepted for obtaining knowledge about city expansion, and is useful to carry out sustainability analyses of land cover changes. The main trend observed in this multitemporal analysis is the expansion of the urban area on croplands, in line with what has been observed in other similar studies such as the case of Tokyo, which, in addition to the sealed surface, increased from 10.3% to 23.5% [68]. Urban expansion and sealed land has also been corroborated in other places in Spain, such as Madrid, whose area increased from 15% to 24% between 1984 and 2013 [83]; Valencia, which tripled its urban area between 1956 and 2012 [84], and Cartagena (Region of Murcia), where sealed land increased by 362% in the period 1981 to 2007 [85].

The comparison between population and land cover transformations, especially up to the beginning of the twenty-first century, indicates that the urbanized area increases in line with the population dynamics. In the second decade of this century, the population stagnated, and even began to decrease slightly, which was related to regional problems. Salamanca is located in an eminently rural and agricultural–livestock region, with an aging population, and scarce and irregular implantation of the industrial fabric. This causes a loss of population on a regional scale, leaving a multitude of small villages with hardly any inhabitants, and causing their abandonment due to the lack of new professional opportunities. This rural exodus has allowed for a gradual increase in the population of the study area over the last decades, to the detriment of the rest of the province [63]. However, despite the observed standstill in the resident population since 2010, the urbanized area has grown significantly,

from 14.0% to 22.3% in the period 1998–2018, although the population has barely increased by 10,000 inhabitants. This anomaly is related to the good twenty-first century economic situation in the first decade, which caused an explosion in the construction of single-family homes, duplexes and chalets, especially in quiet areas far from the city. This demonstrates the growing dynamics that urbanization still maintains, despite its adverse effects [86].

The study area has moderate and good quality soils [87], therefore being an area of good agricultural aptitude, which explains why these soils have been cultivated for centuries, being already one of the main food sources of the Roman Empire after reaching Hispania, who considered these zones as "the granary of Spain" [88]. However, the abundance of agricultural soils should not be an excuse to promote the sealing of higher quality soils (Class II). Irregular urban expansion has been detected along the fertile plain of the river, which has caused the disappearance of the best quality soils (426 Ha). Other authors have also verified this invasion of the alluvial plains and fertile soils in other parts of Spain such as Madrid [4,89] or Castellon [90]. This is important in the current context of population growth and rapid urbanization, in which societal food production must be guaranteed. To avoid the most serious impacts of soil occupation and soil sealing, we propose to protect the high-quality soils and to guide urban development towards those soils of lower quality, as long as the opportunities to develop or redevelop the indoor of the urban area are exhausted. On the other hand, natural risk analyses were not taken into account in the city expansion processes, since up to 187 Ha were identified and built in flood zones, which was demonstrated in more detail in previous studies [80]. In short, the urban expansion has not followed rigorous sustainable criteria: the invasion of restrictive areas (with risks to the population and higher agro-environmental quality) has increased 2.5 times from 1985 to 2018. As an example, Figure 9 shows the construction of new buildings in the last few years in Salamanca-vicinity floodplains, which have occupied high-quality soils and areas with flood risk



**Figure 9.** Urban expansion by Salamanca riverside areas between 1984 (a) and 2018 (b), with high-quality agricultural soil sealing land (c) and flood risk areas invasion [80] (d).

Regarding the model, we find a part that analyzes the evolution of coverage, and another that evaluates past impacts, and that also serves to restrict future urbanization. Multitemporal evaluation has been widely used to study changes in land cover, especially using Landsat image analyses. Recently, some studies have incorporated higher resolution Sentinel images for researching the most recent changes, as more accurate results can be obtained [91,92]. In this work, we maintain Landsat images as a source of data; although its resolution is lower than Sentinel, we consider it adequate for the analysis, taking into account the extension of our study area. On the other hand, the use of multicriteria analysis is considered appropriate, as it is used and accepted as a tool in the search for urban sustainability and sustainable development in multiple studies, highlighting its ability to incorporate different scenarios for evaluation. In addition, the analysis of the impacts caused by past urbanization is considered noteworthy, as identifying the defects and impacts of the urbanization process is important to cement a more sustainable urbanization model. Finally, governments and planners in charge of urban development will be able to access this methodology of sustainable land management, although the development of more concrete and sustainable local actions is beyond the scope of this work. We encourage the implementation of these types of sustainable initiatives, which are complementary to this work, as well as the soil and SOC management as a sustainable tool for mitigating climate change.

#### *Soil Organic Carbon Stock Management and Climate Change*

The important changes in land use during the historical process of urban growth caused a significant reduction of SOC in the upper 30 cm of the soil after a change from forest or grassland to cropland. This reduction in SOC implies an average emission into the atmosphere of 1 t of carbon (3.66 t of CO<sub>2</sub>) for every 47 t of soil converted into croplands. This reduction of SOC occurs mainly by reducing biomass inputs in the soil, increasing the rates of soil erosion and accelerating the soil organic matter decomposition [93]. It was found that the soils with a very low SOC content are indicative of their extensive agricultural use that has been employed for centuries [94]. Because of this, SOC parameters are normally used as an indicator of soil quality [95] and can accumulate in the soil for decades.

In the studied area, with a semi-arid Mediterranean climate, the soils used for grassland and forests are usually limited to mountainous areas, in which the soil capacity for carbon sequestration is restricted to shallow soil profiles due to the limitation of bedrock. In addition, a reduction in rainfall would lead to a decrease in SOC in forest soils, and an increase in average annual temperature would adversely affect the SOC in cropland and pasture.

According to recent climate change forecasts, agricultural lands in the Salamanca province could act as potential carbon sinks. This is because the potential capacity for additional carbon sequestration is greater in crop soils than in grass soils, since agricultural soils are deeper and have lower carbon saturation. Therefore, it is necessary to promote agricultural techniques that favor the conservation and increase of carbon. The agricultural management practices favorable to an accumulation of organic carbon in soils are those that increase the entry of organic matter into the soil, and/or decrease the rate of degradation of organic matter.

In addition to the positive impact of carbon sequestration as a measure of mitigation and adaptation to climate change, it also improves food security. A 1 t increase in the carbon stock in degraded farmland soils can increase crop yields by 20–40 kg ha<sup>-1</sup> for wheat [96], thus, the restoration of soil-degraded farmland is key to achieving sustainable development. Several studies have shown that it is possible to restore lost organic carbon in degraded soils [97–99]. The RMPs that can favor the accumulation of organic carbon in agricultural soils in the study area include:

*Conservation tillage:* the erosion is generally reduced, the accumulation of organic matter in the soil is favored, energy saving is also associated with reduced machinery use and biological soil dynamics are favored, with an increase in soil microfauna and soil microflora.

*Mulch, covert crops and fallows with vegetation:* these are agricultural management practices that protect the soil from erosion, increase water retention capacity and provide plant residues to the soil. In addition, they decrease the soil temperature and, therefore, the rate of organic matter mineralization.

*Exogenous organic matter addition:* these must not involve risks to human or animal health, or to the environment. The addition of manure is an effective method to increase the levels of organic carbon in agricultural soils. The use of urban organic waste as a practice to increase carbon sequestration in soils is less effective than the use of manure, unless they are composted. The application of organic waste (exogenous) is recommended, as long as the limits established by environmental legislation to protect the water and soil quality are taken into account. We recommend establishing a clear distinction of this type of waste, taking their quality into account too.

## 5. Conclusions

Socioeconomic dynamics are causing an overcrowding and accelerated expansion of cities worldwide. Commonly observed problems include pollution, mobility, vulnerability to extreme phenomena and more, which affect society due to the absence of urban planning. Therefore, achieving the sustainability of cities must be a priority for governments, since the well-being of a large part of the population depends on it, as well as the fight against climate change.

Urban sustainability searches must be carried out at all levels and scales. This study provides a guiding methodology that allows for the sustainable use of the land. The environment and population protection are especially considered in this work, as they are considered key to achieving social welfare and sustainability. Planners can use this simple, low cost and adaptable tool, that combines GIS and remote sensing techniques, to: 1) identify the impacts caused by the urbanization process; and 2) establish the areas with the best conditions for future city expansion. Likewise, leaders are encouraged to design and implement complementary, concrete and ambitious actions to promote urban sustainability. However, it is recommended, whenever possible, to exhaust the possibilities of urbanization (empty and abandoned spaces or potential built-up areas) located inside the urban framework, and promote vertical growth rather than horizontal growth that consumes soil resources.

In Salamanca, land-use evolution linked to the urban expansion process shows a clear consumption of croplands that were built. The urban area has increased by 635% in the period 1956–2018, while the population has increased by 238%. The largest increase in built-up areas has occurred in recent years (coinciding with a population deceleration), which is due to the proliferation of single-family homes in areas far off the urban center. In addition, 193 urbanized Ha threatened by natural hazards were counted, as well as the sealing of 2466 Ha of croplands, of which 426 corresponded to the highest quality soils. Through multicriteria analysis, areas with restrictive conditions were identified (5960 Ha), in which future urban expansion is not recommended.

In relation to soil management, proper management of these contributions to carbon sequestration is recommended, which is why soils are currently a tool with great potential to combat climate change. A series of recommendations are proposed to increase the carbon stock in Salamanca soils, especially in agricultural soils, as they are the majority in extension, have a greater storage potential and they are the most vulnerable to carbon oxidation due to tillage work. These practices consist of reforestation of marginal arable lands, compost/biochar application, sustainable use of chemical fertilizers, conservation tillage, use of higher biomass and yield species, crop rotation and mulch, covert crops and fallows with vegetation.

We can conclude that the interaction between GIS techniques in combination with the multitemporal analysis of satellite images and the implementation of a multicriteria analysis of sustainable interest (ecological, agricultural, cultural and population protection) and soil knowledge allows us to establish the sustainability of the urban expansion from the period 1956 to 2018, finding the most suitable areas to urbanize, understanding the capacity of the land and taking into account urban dynamics and their impact on food production, as well as soil management recommendations regarding organic carbon content and climate change.

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