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Combined Remote Sensing and GIS Techniques for Studying the Large Roman Urban System Expansion during the Last Twenty Years

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Abstract

Several factors may contribute to on-going challenges for spatial planning and policy in megacities such as Rome, including rapid population shifts, poorly organized areas, and lack of data through which monitoring urban growth and land use change. This research was conducted to examine past and current effects of the urbanization process, occurred over the large Roman urban system, on the basis of multi-source and multi-temporal optical remote sensing (RS) data, collected between 1990 and 2013. These changes were then validated via Geographic Information System (GIS) techniques, in a particular procedure applied to urban land/agricultural transformations. The proposed approach, based on geo-statistical methods, was used to calculate the index of innovative space (AP Index), useful for the monitoring of the urban sprawl phenomenon. Strong evidence of urban expansion over the north-eastern quarter of the city, accompanied by environmental degradation and loss of biodiversity, is provided. Urban infill developments are expected to emerge in the south-eastern areas too, and these might increase urban pressure as well. In conclusion, RS and GIS technologies together with ancillary data can be used to assist decision makers in preparing future plans to find out appropriate solutions to urbanization encroachment.

Keywords

AP Index, GIS, GRA, Land Consumption, Megacities, Remote Sensing, Urban Sprawl

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1. Introduction

In the 1800's, only 3% of the world population lived in the cities. In the 1950's, the percentage reached around 30%. Urbanization processes are pervasive, given that, nowadays, more than half of the world population lives in cities [1]. According to studies performed by United Nations [2], this proportion might increase to over 72% by 2050. The increasing consumption of land has therefore become an unstoppable phenomenon affecting virtually all the contemporary metropolis worldwide. Policy makers face therefore unprecedented challenges with regard to governance, urban planning, and land use management because of the prevailing high dynamic growth [1]. Performing comparative studies of dynamic environments, such as in the case of a megacity, is not a trivial job, due to the fact that this involves plenty of parameters highly variable over time: shape, dispersion, compactness, density, texture, connectivity, and so on. Among these, density is the parameter commonly used to describe a type of urban environment relatively to its evolution, namely a recorded history of its growth, stagnation or decline. The urban growth process is accompanied by the modification or reduction of various portions of the city being part of a pre-existing landscape; therefore, fragmentation is the most obvious symptom of a time series that eventually leads to disorganization of an urban area. The construction of a road can be seen, at an embryonic stage, as an insignificant process: however, over the years, this may affect the land cover as well as paving the way for new urban settlements, resulting in geographic fragmentation and new structural patches spread over the area of interest [3]. In Italy, cities continue to enlarge their boundaries, even if their growth is in general accompanied by environmental degradation, drastic reduction of agricultural crops, pastures, green areas and loss of biodiversity. According to data from the Italian Institute of Statistics[1], it is possible to point out the continuing loss of the "free surface" parameter, term here used to describe fields, grasslands, forests or areas not occupied by human artifacts such as buildings, factories, urban infrastructure, etc. Unfortunately, in Italy most of the major projects of urban sprawl are planned on maps where forests, fields and natural areas are just seen as land zones not yet built. Roman suburbs are good examples of this urbanization process: they are in fact initially considered as fragmented islands, which are gradually destined to blend into the urban body, without distinction between city centre and periphery. This phenomenon can be verified through comparative studies of the complex system formed by Rome and its surroundings (previously called in fact "the Roman countryside").

2. Literature Review

The literature on urban growth and sprawl is quite extended and out of the scope of this paragraph. An in depth state of the art was recently prepared by Prof. Reid H Ewing [4]. In the context of this dissertation, efforts have been made to briefly document important aspects that mainly focus on the concept of megacity, urban expansion, their patterns, processes, and measurement/analysis. The term "mega-city" was defined for metropolitan agglomerations which concentrate more than 10 million inhabitants [5]. There are numerous large and wide cities all around the world, but in 2011, only about 25 cities reached this population level [6]. Recently, the definition of "mega-cities" has been a little bit enlarged and, at the present time, the 40 most populated cities are considered as "mega-cities", among which Rome, in Italy [7]. Renewed interest in the expansion of the large Roman urban system has developed in recent years, resulting in studies, mainly performed by the Italian National Institute of Statistics [8], the Presidency of the Council of Ministers [9], the Institute for Environmental Protection and Research (ISPRA) [10] and the European Environment Agency (EEA) in order to define potential scenarios of urban growth [11]. Application of combined remote sensing and GIS techniques in the study of urban growth/ sprawl is also big in terms of their variations. It is known that RS and GIS techniques are in fact widely used for mapping (to understand the urban pattern), monitoring (to understand the urban process), measuring (to analyze), and modeling (to simulate) the urban growth, land-use/land-cover change, and sprawl. There exist in fact dozens of metrics that might be used by urban planners in different cities spread over the world, especially in developed countries. Therefore this paper cannot embrace the totality of them. Despite this, the present research has been mainly drawn on past studies conducted by Prof. Jean-Paul Donnay [12] as well as on a similar research, recently developed in India by Dr. Basudeb Bhatta [13].

3. The Megacity of Rome and the Urban Sprawl Phenomenon

Rome, Capital of the Italian Republic and center of Christianity, is at the same time historical and modern city.

[1]Italian National Institute of Statistics (ISTAT), available at http://www.istat.it/

On one hand its monuments and artistic heritage testify to its strong historical identity. On the other hand, Rome is open as well to the future and sensitive to innovations. Historical identity and modernization are moving forward hand in hand, and this ambivalence is now the true key to urban development [14]. The urban agglomeration of Rome is one of the fastest-growing urban regions in the world, and this growth has unprecedented effects on sprawl and population dynamics. The Eternal city is in fact characterized by a large municipal territory, for which population shift towards surrounding municipalities has produced and continues to produce an impressive increase in buildings. Crossing the territory from the city centre to the outskirts, one may in fact have the perception as if it was passing through a single urban area, almost seamless. Urban sprawl, triggered by the urban development of Rome and its neighboring municipalities, can be included among the main causes of this degeneration; in particular, the urban sprawl interferes with agricultural crops, especially olive groves and vineyards. An in-depth analysis of this process is being conducted by the European Space Agency at ESRIN since twenty years. This model was initially set up and successfully tested in the areas surrounding the city of Frascati, near Rome; results of these investigations provided evidence of an urban sprawl situation that was considered critical for both rural soil conservation and for the typical Frascati DOC wine production [15]. Rome can be seen therefore as a large urban system, that is to say the final point of convergence of resources, environmental services and human activities. In 1873, the city boasted 200,000 inhabitants and only included the area within the Aurelian Walls, with the addition of the Prati di Castello. In 1909 the City Council adopted a new plan in order to move development beyond the Aurelian Walls, with the objective of providing the city with a new structure [14]. The situation in fact drastically changed in the beginning of the last century, when an entire medieval neighborhood was demolished in order to make place to the construction of the World War I memorial monument, "the Altar of the Fatherland". In any case, as it is possible to infer from **Figure 1**, on early 1920s the city of Rome was still limited to the historical centre plus some spurs built along internal principal roads.

The successive Master Plan was prepared and approved in 1931. During the Fascist era, the historical centre was object of heavy "demolitions" in order to favour the flow of traffic and isolate the monuments and archaeological areas, to the disadvantage of many historical buildings of minor importance: as an example an enormous part of the district of Borgo was demolished because the Regime required larger and straighter roads for their processions, as in the case of Via Della Conciliazione, just in front of the Basilica of San Peter. In order to accommodate thousands of people turned away from their old houses, the foundation of many new settlements were laid outside the city, mainly along the consular roads as Casilina, Prenestina or Tuscolana. In 1944, roughly 500,000 people, who were displaced from neighboring towns and villages destroyed during the war, converged in Rome. These people settled where they could; this led to an irregular increase of the mass of the population as well as of the demand for housing, thereafter evolved into various forms of unlawful buildings. A new Master Plan was approved in 1965 while the population of Rome was roughly amounting to 2,200,000. This plan privileged mainly the eastern and southern sectors of the city for new construction and identifies new industrial zones between the Tiburtina and the Prenestina [14].

As shown in **Figure 2** from ISTAT, population growth peaked in the 1980s when part of the population started to settle in the adjacent towns, looking for a more comfortable lifestyle due to the economically unsus-

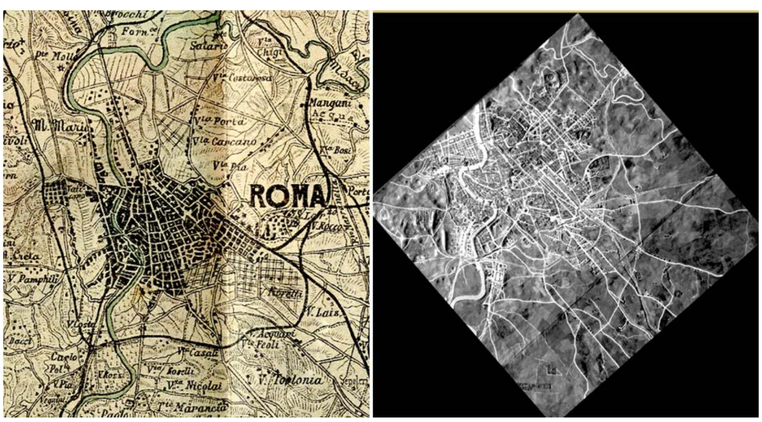

Figure 1. Treves map (1910) and rare photo of Rome city centre taken from airship in 1924 (courtesy L. Fusco).

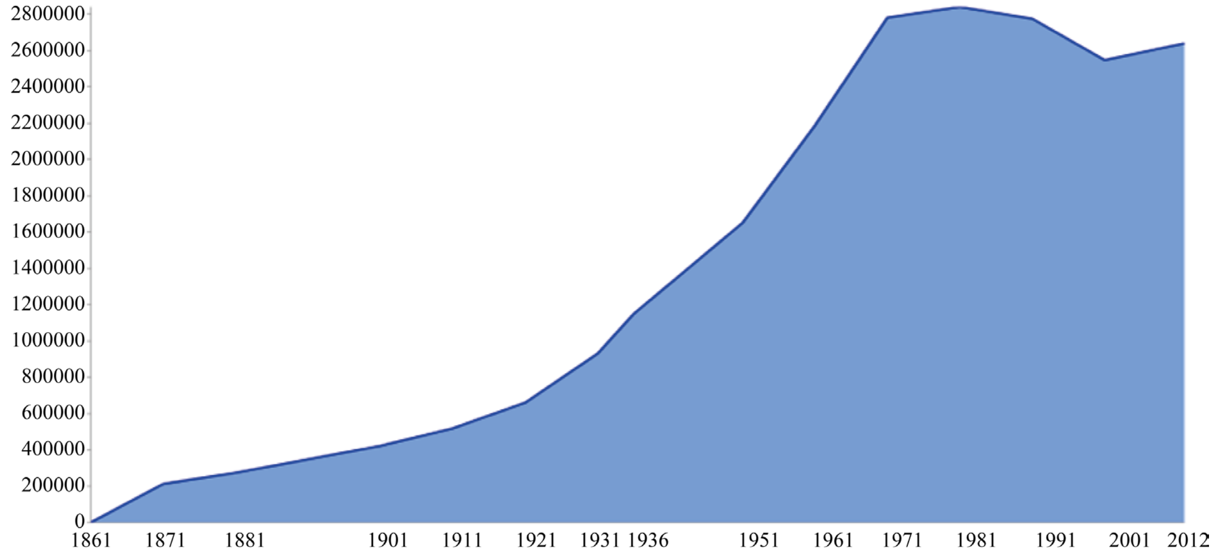

Figure 2. Demographic trend of the city of Rome from 1861 to 2012. Source: http://www.comuni-italiani.it/058/091/statistiche/popolazione.html

tainable real estate offer, mainly for those buildings closest to the city center [16]. In **Figure 3**, it is instead possible to see the Roman and regional demographic dynamics from 1971 to 2001.

However, from 1962 to 2003 the Master Plan underwent numerous variations, as result of a process, defined by distinct steps that have progressively led to its adoption by the City Council. The population of Rome is now approximately amounting to 3,000,000 people. The city, subdivided into 15 Municipalities, covers an area of 1290 Km^2 out of which 877 Km^2 (roughly 86%) are no longer buildable, defining the so-called open area of Rome, the largest in Europe. Between 2002 and 2010, the hinterland municipalities gained well about 248,000 residents, out of which 87.6% due to net migration and 13.4% for the natural balance [17]. Despite a significant attenuation in the current intensity of the phenomenon, the scenario forecast for the next decade calls for a further strengthening of the residential function of the metropolitan area, gradually spreading the effects of urban sprawl also to municipalities in the outer belt.

Several factors have contributed to the on-going challenges of spatial planning and urban policy in the area of Rome, including population shifts, less organized urban areas, and a lack of observational data to be used for monitoring urban growth and land use change. Therefore, knowledge concerning past, current, and future growth plays an important role in the decision-making process. Monitoring growth helps to develop an understanding of past trends and growth patterns; all together it is possible to retrieve useful insights into possible future developments. In this regard, significant contributions in this field have been made thanks to the technological progress of geographic information systems and remote sensing, both of which have been used to relate land use and cover change to urban growth modeling [18]. In order to support the sustainable development of Rome, this research was conducted to examine past and current urban land use changes on the basis of multi-temporal optical remote sensing and map data collected between 1990 and 2013, thereafter integrated into a multi-relational GIS database. Both GIS and Earth Observation (EO) approaches are necessary strategies for implementing appropriate actions, including a) formulating better land use policies (e.g., growth boundaries), b) responding to transportation and utility demand, c) providing infrastructure, d) identifying future development pressure points, and e) developing ex-ante visions of urbanization process implications, among others. Remote sensing data integration into GIS system allowed continuity of the measurements performed, otherwise not possible when using only cartographic maps [19]. Measures of urban classes are actually based on the urbanized areas, namely those areas no longer agricultural but largely transformed with buildings, services and various infrastructures that, over time, have drastically changed the appearance of the primitive landscape. The urban growth phenomenon can be measured trough the analysis of remote sensing data integrated into multi-relational GIS systems; this allows a quantitative study of the dynamic model of the urban structure as well as of the physiology of strictly related factors, such as the economic, social and political ones, which shape the landscape, transforming it from natural to man-made.

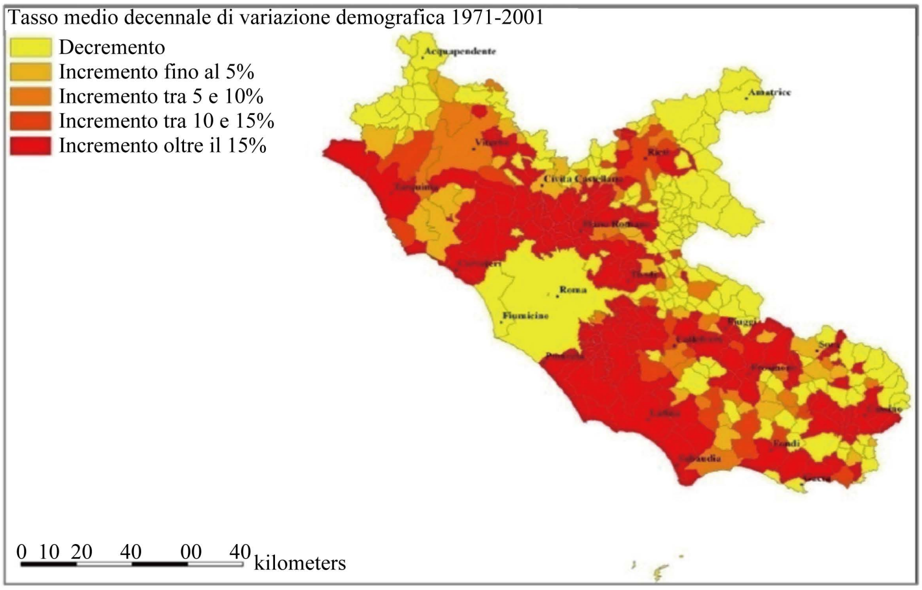

Figure 3. Rome and regional demographic dynamics from 1971 to 2001 (CRESME).

4. Study Area

Natural landscape and urban development both have determined the urban structure of Rome. The present analysis is based on the continuation of our past study, carried out in the mid-1990s at the European Space Agency in ESRIN[2], in collaboration with the Italian National Institute of Urban Planning[3], and conducted in view of the extension of the future Metropolitan area [20]. Digitized maps were superimposed to classified satellite images, acquired within a predefined time window (from 1900 to 1996) (see **Figure 4**), then integrated into a multi-relational GIS database. The city of Rome is characterized by a large Municipal Territory, for which population shift towards surrounding municipalities has produced and continues to produce an impressive increase in buildings. As shown in **Figure 5**, The area of interest was included into the Great Ring Road (GRA), which encloses an area of approximately 345 km^2. Outcomes showed how, between 1960 and 1980, the city of Rome drastically increased within the belt of the GRA (**Table 1**).

The urban growth phenomenon in the area of Rome has been well rendered since this early analysis, despite some inaccuracies that occurred during the surface classification performed via Landsat satellite data, mainly due to the low ground pixel resolution.

5. Materials

Multi-temporal SPOT-4/5 images, which have been then integrated and processed with additional pictures from aircraft and other spacecraft missions, such as Kompsat-2, as well as validated against both panchromatic and color ortho-photos (see the list of available sensors in **Table 2**).

As outlined in **Table 3**, a wide range of proprietary software programs were used in this research for accomplishing different tasks. For remote sensing image analysis, processing, mosaicking and manipulation the following tools were employed: (a) ERDAS Imagine[4], b) ENVI service pack[5].

For GIS statistical analysis, digitalization, measurement tasks, identification and rendering of surface features, as well as soil high resolution mapping and detailed site characterization for potential urbanized areas, the Arc GIS 9.3[6] software was used.

[2]European Space Research Institute, more info at http://www.esa.int/About_Us/ESRIN
[3]INU, Italian National Institute of Urban Planning, available at http://www.inu.it/
[4]ERDAS Imagine, Intergraph, available at http://www.intergraph.com/
[5]ENVI 5 Service Pack 3, Exelis, available at http://www.exelisvis.com
[6]Arc GIS 9.3, ESRI, available at http://www.esri.com/software/arcgis

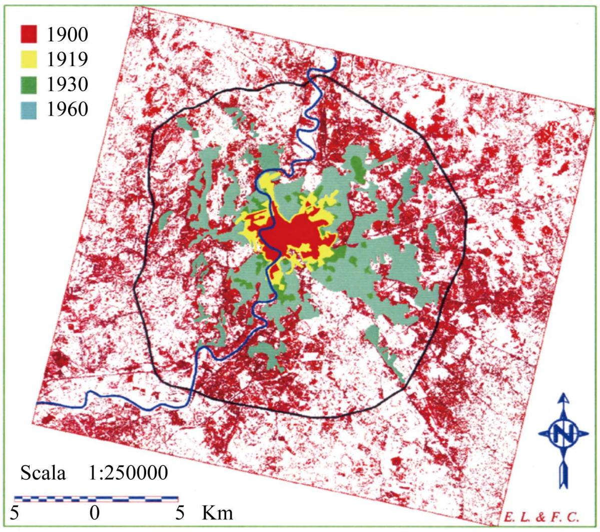

Figure 4. Increase of the urban area extension in Rome within the time range: 1900-1960. Results were validated against evidence from one supervised classified Landsat TM image, acquired in 1996.

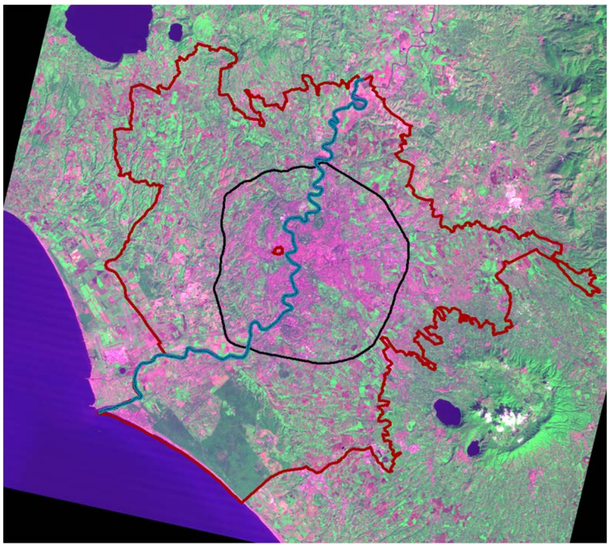

Figure 5. Boundaries of the study area: (a) in red the district of Rome (Landsat TM), (b) in black the area included within the ring road GRA.

Table 1. The urban growth phenomenon in the area of Rome, from 1900 to 1996.

Tipology	Year	Area (ha)	% of GRA
Map	1900	1186	3.44
Map	1919	1952	5.66
Map	1930	2305	6.68
Map	1960	9348	27.08
Image	1986	21515	62.33
Image	1996	21538	62.45

Table 2. Mission, sensors and products type.

Mission	Sensor	Product type	Resolution	Year
SPOT-4	HRVIR	MS	6 m	2002
SPOT-5	HRG	MS	2.5 m	2006
SPOT-5	HRG	MS	2.5 m	2011
Kompsat-2	MSC	MS + PAN	1 m	2013
Aerial Ortophoto			50 cm	2000

Table 3. Software packages.

Name of the software	Version	Developed by	Description
ERDAS imagine	11.0.2	INTERGRAPH	Geospatial image processing/analysis
ENVI	5.0	EXELISVIS	Geospatial image processing/analysis
Arc GIS	9.3	ESRI	GIS-Terrain Model Mapping

6. Methodology

It is known that land consumption represents an essential indicator of the sustainability of urban ecosystems as well as an efficient quantification of sprawl. Monitoring land consumption using remote sensing is instrumental to understand the contemporary process of urbanization on both global and local scale [21]. As a result of this research, still in development, a multi-relational GIS platform was created to observe the urban sprawl phenomenon over Rome. The main purpose is to continue studying and analyzing the process of urban sprawl in a greater representative sample of populated metropolitan area, namely the one outside the GRA but yet within the boundaries of the city of Rome. The methodology involved image processing, classification, measurement and interpretation of the available data collections. Data were gathered by ESA, NASA and other available sources (Volo Italia[7], Regione Lazio[8], Comune di Roma[9]). Each mission used its own unique suite of instruments to monitor the territory and a wealth of interesting properties of the area of interest was gathered from their combined results. Processing techniques were used to get each image from its original format into a projected map and consequently vectorialized in order to obtain a GIS compatible format (.shp files). A GIS multi-relational database was built and integrated with the available remotely sensed data, as well as ortho-photo and topographic maps. For the integration of SPOT mission data, a UTM-ED1950/33N coordinate system has been used. The GIS System was used for handling maps of different kinds in several different layers, where each layer holds data about a particular kind of feature. Each feature was linked to a position on the graphical image on a map and a record in an attribute table.

A workspace has been therefore created for scientific management and orientated thematic information. The base layer contains information on the features identified in the selected area of interest (vegetated, urbanized, and so on). The basic recorded attributes were "type" and "area" essential to define the type of urban areas (layer of buildings), in order to analyze the density in that area. The work steps can be summarized in the following main aspects:

- Optical images processing: geo-referencing and geometric correction;
- Definition of the Areas of Interest (AOIs) and subsets (image cropping);
- Supervised classification according to the Corine Land Cover (CLC)-like simplified model;
- Vectorialization of surface values and grid alignment;
- Urban growth analysis trough the Kernel Density Estimation (KDE) function;
- GIS API index application, modelization and multi-temporal correlation coefficient application;
- Interpretation and validation against very high resolution imagery and photogrammetry.

Remote sensing is a powerful tool available to the scientist [22], as it mainly enables a direct comparison of

[7]Istituto Geografico Militare, IGM, catalogue available at http://www.igmi.org/voli/
[8]Regione Lazio, available at http://www.regione.lazio.it/
[9]Comune di Roma Capitale, available at http://www.comune.roma.it/PCR/do/jpsite/Site/home

different areas of interest across the surface of the city, allowing visual interpretation and validation for urban growth analysis. Images detected by spacecraft sensors contain in fact a great deal of information about urbanization, input required for the analysis of almost any past and future acquired dataset. Images from SPOT-4/5 data, radiometrically and geometrically corrected, were resampled through the nearest-neighbour technique and UTM ED-1950/33N projection was applied. The difference in resolution between the images SPOT-4, acquired in 2002, and SPOT-5, acquired respectively in 2006 and 2011, was resolved, at the end of the entire process, by integrating the files in a grid of mesh 100 × 100 m² or into squares of 1 ha of surface area. Ad-hoc corrections were applied for improving SPOT data spectral discrimination of different classes but with same radiance values. Supervised maximum likelihood classification allowed to calculate class means evenly distributed in the subset and, then, to iteratively cluster the remaining pixels, using minimum distance techniques. Twenty iterations were run during the supervised classification, while the used change threshold value was set to the default value of 2. This number means that, when the percentage of pixels that change during an iteration is less than the threshold value itself, the classification process ends. A spatial subset of each image has been then created against the area of interest, namely the interior of GRA (see **Figure 6**). A supervised classification was performed, in order to categorize pixels, into initial seventeenth classes, thereafter merged into four main urban classes, corresponding to a recognized field "value", with the output value ranging from "low" to "very high", as displayed with color codes in **Figure 7**. Subsequently, the raster file was converted into vector format, maintaining the value of these 4 classes in the table attributes. In **Figure 8**, it is possible to infer the urban area extension of the city of Rome from 2002 to 2011. In **Table 4**, the urban growth values are compared in respect to the area of the GRA and percentage are shown as well.

Following vectorialization of the urbanized classes, precise values of the evolution of the populated areas were computed. Trough a "raster to point" conversion, the centroid of the polygon was extracted from each cell. The Kernel density function (KDE) has been duly applied to these "centroids" [23] and a grid file was obtained for estimating the statistical values of the density function.

The resulting changes in the urban density were computed through a specific index in order to measure the spatial profile of each land use class in a certain fixed area [24]. List of AP Index values for the years 2002-2011

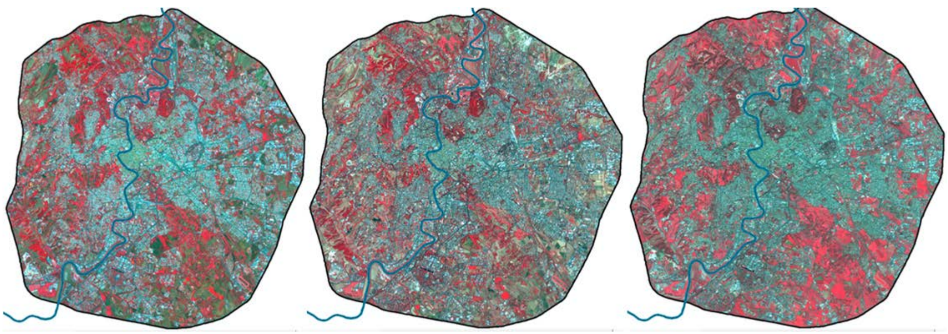

Figure 6. SPOT images cut to show the inner part within of the GRA: SPOT-4 2002, SPOT-5 2006 and SPOT-5 2011.

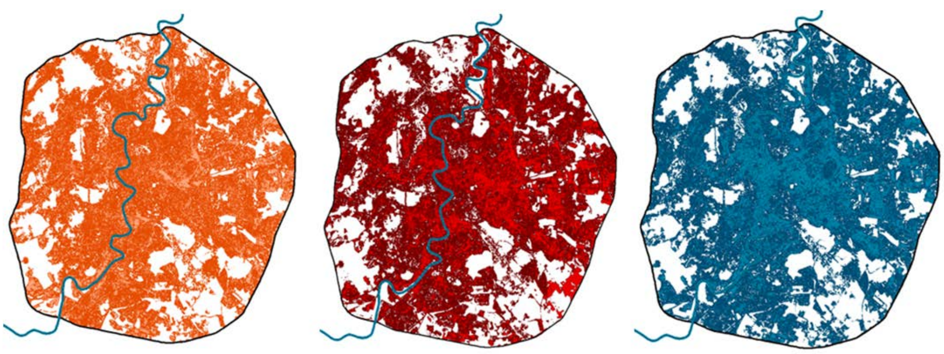

Figure 7. Variation on the extension of the Roman urban area from 2002 to 2011.

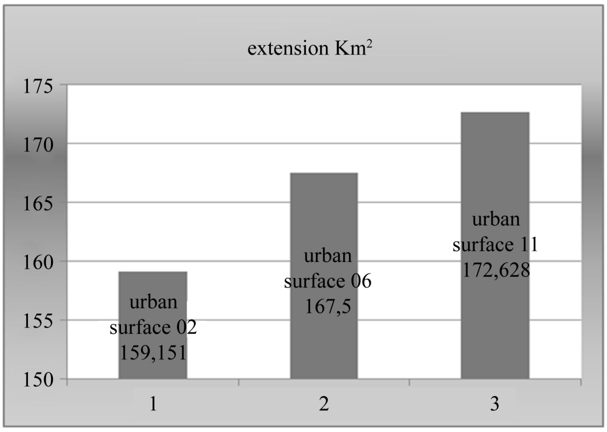

Figure 8. City of Rome: urban area extension in Km^2 from 2002 to 2011.

Table 4. Urban growth in km^2 from 2002 to 2011.

Year	2002	2006	2011
Urban surf	159.151	167.5	172.628
GRA surf km²	345.2	345.2	345.2
%	46.104	48.523	50.008

is outlined in **Table 5**, while density variations of the urban growth and corresponding AP index values, are shown respectively in **Figure 9** and **Figure 10**.

7. Measuring Sprawl: The API Index

Urban growth is a critical driver of environmental problems as it may cause the loss of informal open space and the fragmentation of wildlife habitats. Urban growth can take place either in a radial direction around a city core or linearly along the highways. The latter is dispersed urban development and is often referred to as sprawl. According to recent literature, the notion of sprawl is often coupled with a series of measurable indicators such as density gradients and sprawl indices. In order to timely and accurately assess future scenarios and related impacts, research organizations may therefore put forward different indicators depending on the physical parameter to be then modeled. Nevertheless, it is worth mentioning that indicators represent only a simple "sign" of a possible effect on the environment; they are in fact not a measure of the effect itself. If badly chosen, they can lead to a misleading interpretation of the real consequences that can be produced at the end of the process. Also, indexes tend to describe both the spatial and the functional structure of the system components. But since an index may involve more than one aspect of this organization, this might further result in a loss of relationship between the measure and the specific system component. In order to define a better match between the values calculated from an index and the spatial configuration, typical of a dynamic system, has been necessary to develop a new specific index for the phenomenon of urban sprawl that we wanted to investigate: the AP index. The AP index allows the measurement of the spatial profile of each land use class in a fixed area. The spatial profile is evaluated in terms of spatial pattern of each land use and spatial relationships among different land uses [25]. The AP Index formula is:

$$\mathrm{API}_{xi} = \frac{S_x \cdot (C_i / C_t)}{S_t} \quad (1)$$

and the overall density value for a specific land use *x*:

$$\mathrm{API}_{i} = \sum_x \frac{S_x \cdot (C_i / C_t)}{S_t} \quad (2)$$

Table 5. AP Index values for the years 2002-2011.

Density Val.	API Index		
	2011	2006	2002
Very Low	0.182	0.188	0.165
Low	0.181	0.174	0.209
Medium	0.208	0.207	0.243
High	0.224	0.228	0.235
Very High	0.208	0.202	0.150
Total	1.004	1.000	1.002

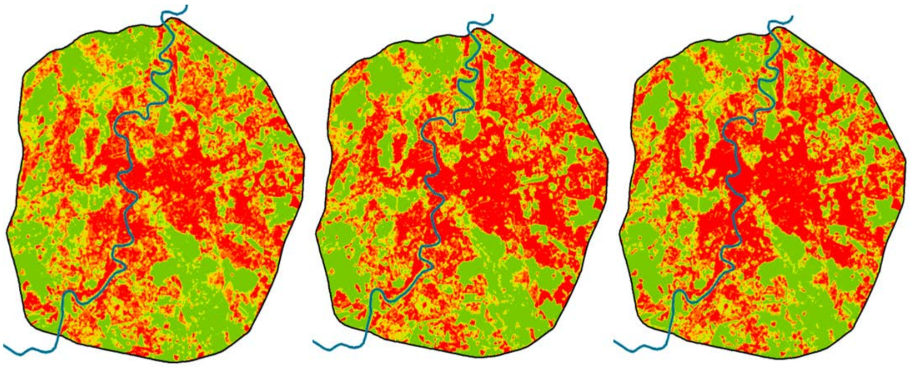

Figure 9. Density variation (min green, max red) of the urban growth from 2002 to 2011.

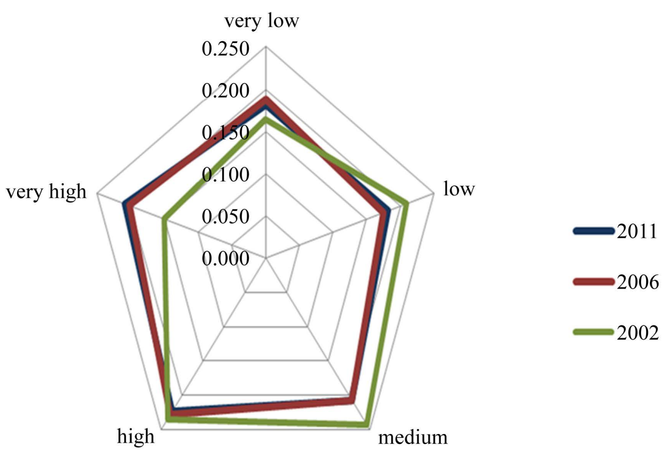

Figure 10. Urban density variations (AP Index values) from 2002 to 2011.

where:

API_{xi} = Area Profile Index for the density class i and the land use x.

S_x = Total area for the specific land use (x).

C_i = Number of cells in density class i.

C_t = Total area cells.

S_t = Total municipal area.

Equation (2) was defined in order to produce a quantitative descriptive summary of the spatial arrangement of the different land uses, which allows to easily understand the environmental framework of the territory. Basically the AP index operates over selected areas of interest, generating a summary of the environmental state of each of them, namely assessing their profile with the following objectives:

1) Calculate the size of the elements in the analysis (agricultural, urban extensions, etc.);
2) Analyze qualitative and quantitative levels of "compromise" of the components involved;
3) Assess the evolution of these components to control the phenomenon;
4) Articulate appropriate actions for a better land use planning;
5) Predict the environmental impact through forecasting modeling.

8. Validation of Results

A logical model was adopted to evaluate the AP Index. This model is based on measuring spatial relationships among the density distribution of each land use and on the comparison of each distribution with the total amount of each specific land use area [25]. In this work, the API index relates density values at different times calculated from 2002, 2006 and 2011 image data respectively, by using a 100 × 100 m^2 grid in order to make coherent values at different pixel resolutions (SPOT-4, SPOT-5) and by then analyzing results by applying the Pearson correlation coefficient between API 2002 and API 2011 (see **Table 6**).

Following that and as shown in **Figure 11**, the universal Cokriging interpolator was used for validating autocorrelation between values throughout the predefined time window, as well as their fitting to the semi-variogram model (see **Figure 12**). In order to validate results on the structure of the concerning area of interest, interpolation values have been superimposed to a Kompast-2 image acquired in 2013, focusing on what happened along the predefined time window over both the NE and SE quarters. As it can be inferred from **Figure 13** and **Figure 14**, free spaces within the GRA have been "built", causing a consequent increase of the population density.

Table 6. Pearson correlation coefficient, applied to the AP Index (API2002-API2011).

	X	Y	X^2	Y^2	X × Y
	AP02	AP11	$(AP02)^2$	$(AP11)^2$	AP02 × AP11
1	0.15	0.182	0.0225	0.033124	0.0273
2	0.165	0.181	0.027225	0.032761	0.029865
3	0.209	0.208	0.043681	0.043264	0.043472
4	0.235	0.224	0.055225	0.050176	0.05264
5	0.243	0.208	0.059049	0.043264	0.050544
Sum	1.002	1.003	0.20768	0.202589	0.203821

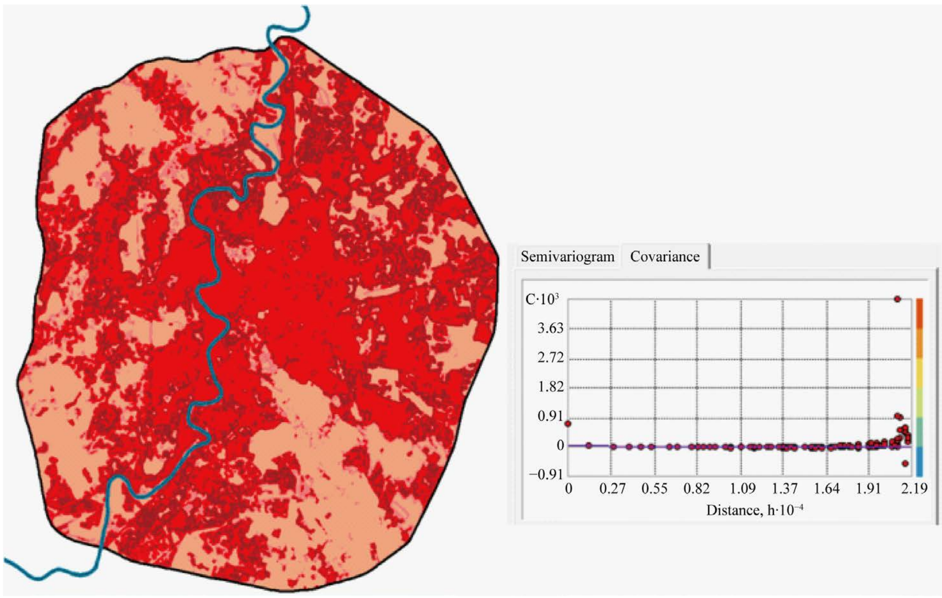

Figure 11. CoKriging results against API index values in 2002 and 2011, plus subset over the NE quarter.

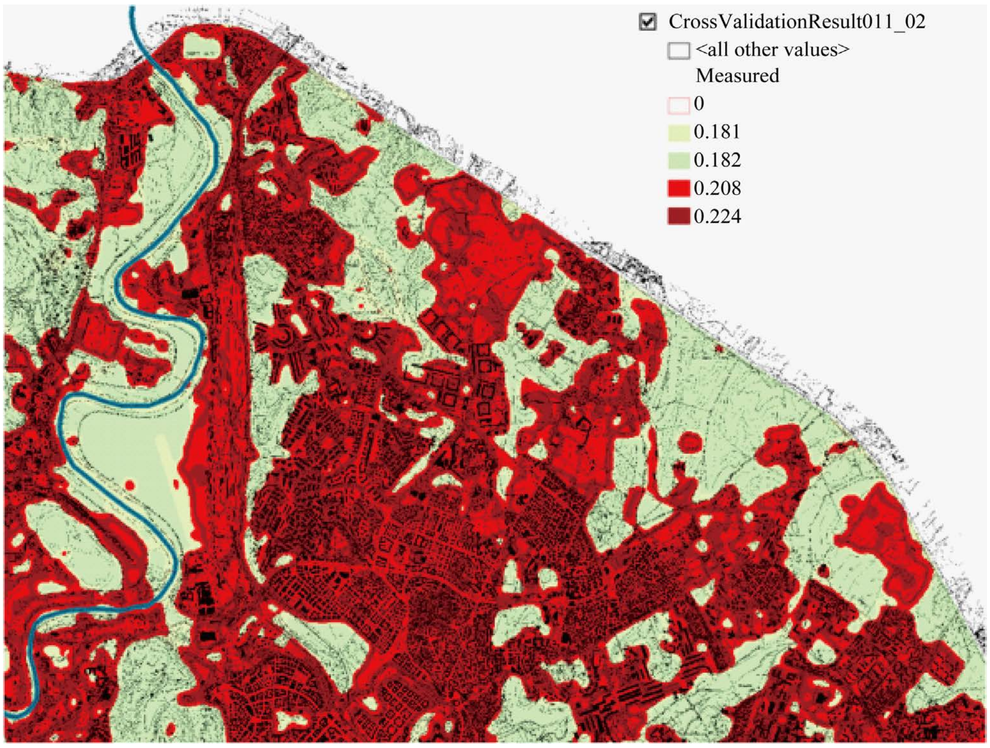

Figure 12. CoKriging results against AP index values in 2002 and 2011, particular of the NE quarter area including the 1999 edification map overlay.

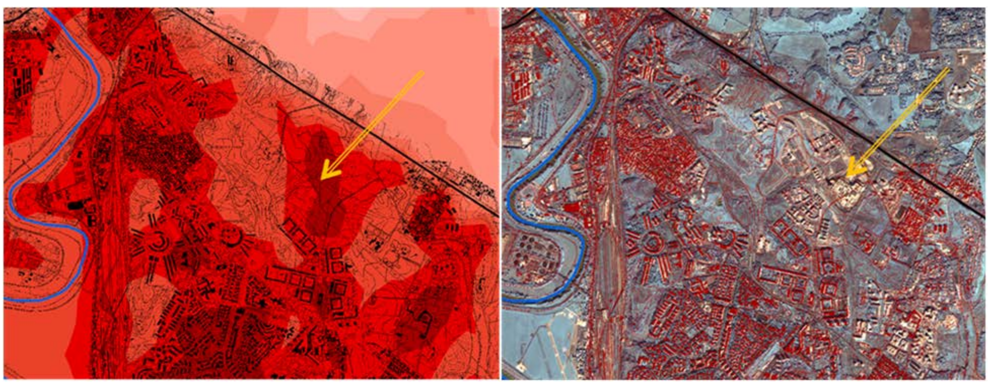

Figure 13. AP index density variation, due to new urban settlement in the north-eastern quarter as validated against Kompsat-2 imagery, acquired in 2013.

9. Discussion

The applied methodology is based on the inclusion of information derived from multi-source and multi-temporal satellite imagery into a GIS database [26], for the cartographic update of a fast evolving situation related to the expansion of the Roman large urban area. In this context, RS applications, already described in the literature, have been used in a particular geo-statistic procedure already applied to agricultural analysis and territorial transformations [25].

It can be noted that this approach can be easily applied to other research disciplines, where different variables have to be compared. In this particular case, urban areas derived from a classification procedure have been processed in density classes and analyzed through the AP index. The latter provided values for applying interpolations, such as the CoKriging, where the unknown value of the density of a point is computed from the weighted mean of known values generated by the AP index. Results indicate that for the timeframe 2002-2011,

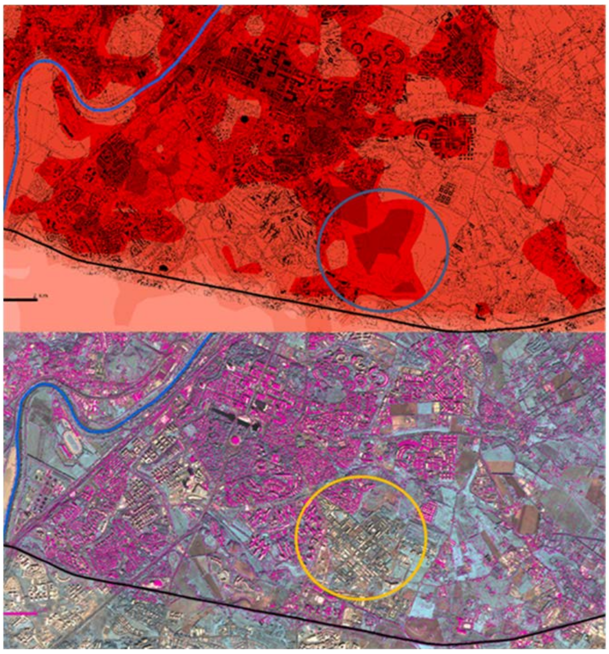

Figure 14. AP index density variation, due to new urban settlement in the south-eastern quarter, as validated against Kompsat-2 imagery, acquired in 2013.

the land use classes were likely to turn into built-up areas. This can be also confirmed from the ISTAT data: in the last years, the demographic growth trend, after a sudden fall (−8.2), is actually growing from 2001, even if not much (+3.6). However, the analysis of super-imposed multi temporal satellite images against a Regional Technical Map (CTR) edited in 1990 and one aero-photogrammetric map of Rome acquired in 2000 shows that the demographic phenomenon has not been always accompanied by a decrease or a standstill of buildings. Actually, the latter seems to keep increasing in number, filling empty spaces within the GRA; in the last decade, this trend is appearing also outside the GRA, where the urbanization of neighboring communes tends to fill free space and make them join one another. Whilst a comparison was performed between the 1990 and 2000 urban extension maps, a progressive building extension in time can be observed as well. This is confirmed also by the positive value of the Pearson's correlation coefficient (or Pearson Product Moment Correlation), applied respectively to the AP indexes in 2002 and in 2011. The Pearson's correlation coefficient between two variables is defined as the covariance of the two variables (in our case AP02-AP11).divided by the product of their standard deviations. Commonly represented by the letter *r*, the correlation coefficient ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between AP02 and AP11 perfectly, with all data points lying on a line for which AP11 increases as AP02 increases. A value of 0 implies that there is no linear correlation between the variables. The equation of the Pearson's correlation coefficient applied to our case study is:

$$r = \frac{n\left(\sum \mathrm{AP02}\,AP11\right) - \left(\sum \mathrm{AP02}\right)\left(\sum \mathrm{AP11}\right)}{\sqrt{\left[n\sum \mathrm{AP02}^2 - \left(\sum \mathrm{AP02}\right)^2\right]\left[n\sum \mathrm{AP11}^2 - \left(\sum \mathrm{AP11}\right)^2\right]}} \quad (3)$$

Thus, according to Equation (3), we have obtained a positive value close to 1: $r = 0.91281$.

Moreover, focusing on the analysis of the Kompsat-2 image, it is possible to identify new buildings replacing agricultural areas spread over some specific areas in the NE and SE quarters. It can be concluded that the general urbanization trend is still growing within the study area (internal to GRA). In particular, the constant increase in the urban density process is currently filling up the remaining gaps left by the sprawl phenomena previously occurred. Our analysis demonstrates that the integration of GIS, remote sensing, and urban modeling offers an enhanced understanding of the future and trends that megacities, such as Rome, will face [27]. Future extension of this research will be dedicated to the evaluation of urban growth over a larger area of interest as well as of different planning scenarios on land use dynamics. Moreover, to clarify whether the predicted urban growth patterns are specific to Rome, this approach should be empirically replicated and requires further comparative studies. Therefore, our relevant findings should advise policy makers, urban planners and land use management organizations. This will help them in preparation for the expansion of urban living, and inform them of the extent of growth that can be expected, in order that sustainable policy interventions (e.g., imposing zoning regulations, establishing growth boundaries/limits) can be applied in the management of inevitable urbanization processes.

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