

MONITORING SOIL EROSION BY RASTER IMAGES: FROM AERIAL PHOTOGRAPHS TO DRONE TAKEN PICTURES

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Abstract

With the aim of understanding the evolution of soil erosion in an ecologically degraded area in southeast Madrid (Spain), an analysis is conducted on a series of aerial photographs, multi-temporal satellite images and high resolution photographs taken from a drone. This natural space has been selected as a pilot project for monitoring soil erosion in recently urbanized areas built on clastic sediments and soils. This characteristic landscape is mainly covered by gullies and is subject to high surface run-off. The evolution of soil erosion varies significantly depending on anthropic influences and vegetation cover. Soils are highly pervious and classified as regosols and arenosols, mixed with luvisols and cambisols where Mediterranean vegetation is present. Recent urbanization has increased the erosion of sandy materials. A better understanding of the soil loss processes will be useful in land use and urban planning.

Keywords: *Aerial photographs, Spot, Landsat, UAV, remote sensing, degradation soils.*

1. INTRODUCTION

The study area is located in the Community of Madrid (Spain), in the Regional Park of the Middle Guadarrama River Basin (*Parque Regional del curso medio del río Guadarrama*), in an area degraded by natural processes and human action. We use field work, aerial photography, and both satellite and UAV (Unmanned Aerial Vehicle) images to analyse degradation processes and changes in recent decades. The development of UAVs makes it possible to do high spatial resolution remote sensing.

The aim of this paper is to analyse a series of historical photographs and satellite images and compare them with current photos taken by a drone equipped with an infrared and visible light camera to study the soil degradation produced by the presence of gullies. Aerial photography and satellite images are important sources of relevant information for studying the dynamics and evolution of soil use processes and for programming initiatives to mitigate the geological risks linked to intensely anthropized areas. It is only by understanding our past and analysing how changes have affected the natural environment that we can avoid its destruction and the risk that this implies for all living beings. Many research projects have used remote sensing to analyse and measure soil degradation, (Dwivedi et al, 1997; Mathieu

et al. 1997 and 2007; Blum, 1998; Haboudane et al. 2002; Wu, 2004; King et al. 2005; Pérez and García, 2005 and 2013; Begueira, 2006; Carpintero et al. 2007; Liberti et al. 2009; García et al. 2014 and 2016; Mokarram et al. 2016; Vishwakarma et al. 2016; Yengoh, 2016, etc.) as this technique uses digital processing to provide multitemporal and multispectral monitoring of erosive processes to enhance the visualization of the results of erosion. This in turn enables implementation of soil protection measures. (Van Camp et al. 2004; Gardi. et al. 2011; Prokop et al. 2011).

2. STUDY AREA

For this paper, a case study area was selected in central Spain, in the southeast of the Madrid Autonomous Community. The centre of the 837 ha study area is located at N 40°13'56'' latitude and W 3°56'17'' longitude, with an altitude that ranges from 568 m to 635 m. The climate is Mediterranean and is characterized by a four-month summer drought (June to September), an average annual rainfall of 450 mm and an average annual temperature of 14.9° C. The main characteristic of the precipitation is its temporal and spatial irregularity, with monthly rainfall reaching a high of 199.8 mm (November 1997) and a 24-hour maximum of 79.4 mm (24 June 1995). Monthly rainfall varies from 60 mm during the wettest month to 11 mm in the driest, with an average of 16.2 days per year with thunderstorms and 58.8 days annual precipitation ≥ 1 mm. The average monthly temperature ranges from 6.0° C in January to 25.6° C in July.

In hydrological terms this area forms part of the middle reach of the Guadarrama River, which flows through tertiary sediments of arkosic sands with some gravel and clay layers. As you move from the river's source in the granitic sierra to its lower reaches, the grain size of the sands diminishes and the amount of clay increases. The river channel is confined within a gently sloping valley flanked by remnants of multiple terraces; gravels predominate in the highest of these, gradually becoming increasingly sandy downstream. In the lower reaches the valley broadens out and becomes flatter, so that the outlines of the terraces are difficult to distinguish. Here the slope contributions and remobilization of material by lateral fans are especially important and are essential for the channel supply during flash floods. The flood plain is not well defined and in the lowest reach has a maximum width of 1 km, (Garzón and Alonso, 1996).

Two features condition the flood risk: in this river the morphological and sedimentological limits between the high water channel and the flood plain are not clearly defined and the sandy banks are very unstable, facilitating remobilization. Another significant effect is the subsurface bank erosion process resulting from the sandy composition of the banks and intercalated sandy material, and also from the elimination of protective vegetation. The result is the formation on the banks of gullies that reach tens of meters in length, where various housing developments have been built, (Sanz et al. 2014).

The soils are mainly regosols and arenosols, (Monturiol and Alcalá, 1990), with the occasional presence of luvisols, anthrosols and cambisols, (Pérez and García, 2016). These soils are highly permeable and have been subjected to increased soil sealing in recent years, because of urban expansion in Madrid.

The study area is one of the few spaces to the south of Madrid which conserves the potential Mediterranean forest vegetation, formed by a dense arboreal stratum of *Quercus* with abundant scrub undergrowth, (*Cistus salvifolius*, *Cistus alvidus*, *Retama sphaerocarpa*, *Phyllirea angustifolia*, *Thymus Zygis*, *Thymus mastichina*, *Rosmarinus officinalis*, *Daphne guidium*, *Crataegus monogyna*, etc.), especially where erosion processes (natural degradation by gullyng or anthropic degradation from soil sealing) have not occurred. Groups of *Populus*

x canadiensis, *Salix fragilis*, *Salix atrocinerea* and *Salix purpurea* are found in some areas on the banks of the Guadarrama River (Figure 1).

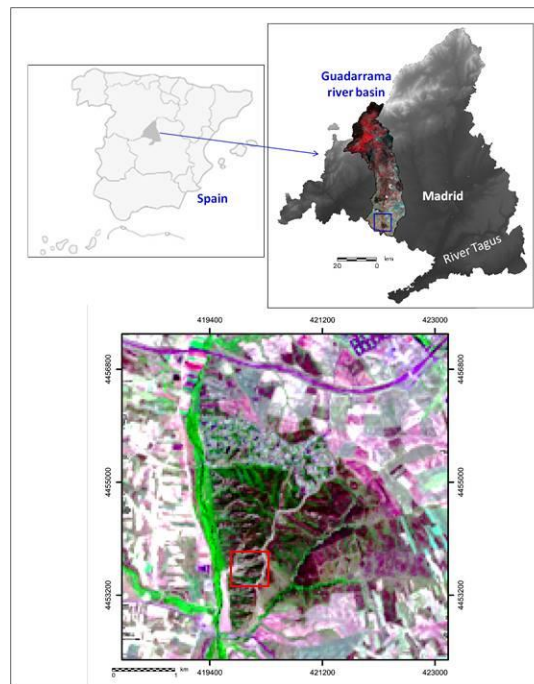


Figure 1. Study area and detail of Landsat 8 image: 7-4-2 (R-G-B), 06-06-2013. The red square marks the largest gully area.

3. MATERIAL AND METHODS

The monitoring and measurement of soil degradation in the southern part of Madrid has been carried out with a range of raster images from the last sixty years. A selection of historic aerial photographs taken on different dates and scales was also used, as well as Landsat and Spot satellite images. In the part of the study area where the most gullies have formed (Figure 2), a drone (Unmanned Aerial Vehicle) was also used to obtain very high spatial resolution images, (0.03 m).

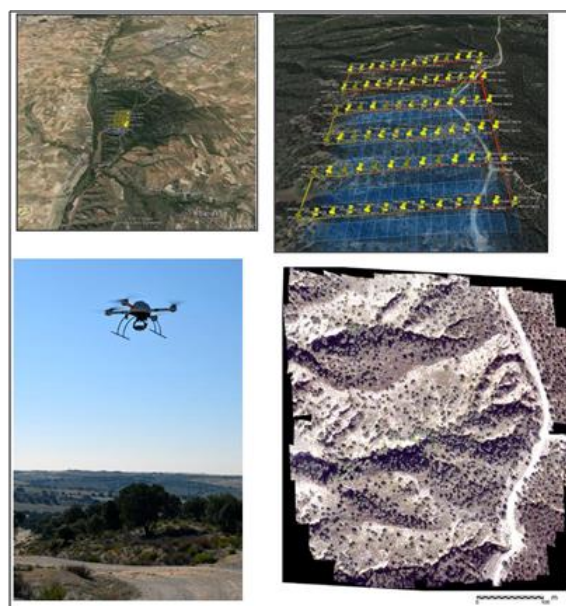


Figure 2. UAV flight plan and image obtained in the visible spectrum.

Table 1 shows the dates and main characteristics of the raster information used. Figure 3 shows the study phases.

Table 1. Raster images selection: aerial photographs, satellite images and UAV image.

Raster images	Date	Spatial resolution/Scale	Spectral resolution
Aerial Photograph	1956	1:25,000	Panchromatic
Aerial Photograph	1961-1967	1:30,000	Panchromatic
Landsat 8 images	06/06/2013	15 m 30 m	Panchromatic Blue, Green, Red, NIR, 2 SWIR
Spot 5 images	08/09/2013	2.5 m 10 m/20 m	Panchromatic Green, Red, NIR/1 SWIR
UAV	12/03/2015	0.03 m	Natural colour (R-G-B) Multispectral (G-R-NIR)

Raster images were geo-referenced to Universal Transverse Mercator UTM coordinates (grid zone 30T) and Datum ETRS89, and all of them were processed with Erdas Imagine-2015 software. Also, the Landsat and Spot images were processed carrying out different spectral enhancements (band combinations, tasseled-cap and principal components), radiometric enhancement (histogram equalization) and spatial enhancements (3x3 convolution filter and resolution merging of panchromatic and multispectral images).

To understand the soil characteristics in the study area, different samples were selected to cover the edaphic range, from the most fertile soils on the river flood plain with the lowest slopes and the greatest vegetation cover, to the most intensely degraded soils. We collected samples of the soil surface horizon and analysed them in the laboratory. The measurements taken were texture (Robinson's pipette international method), pH (paste saturated with water and KCl), organic material (Walkley and Black method), carbonates (Bernard calcimeter) and electrical conductivity (aqueous soil extract and 1:1 soil/water ratio), to define the properties of the soils affected by sealing. Four analyses of each sample were performed to obtain a mean.

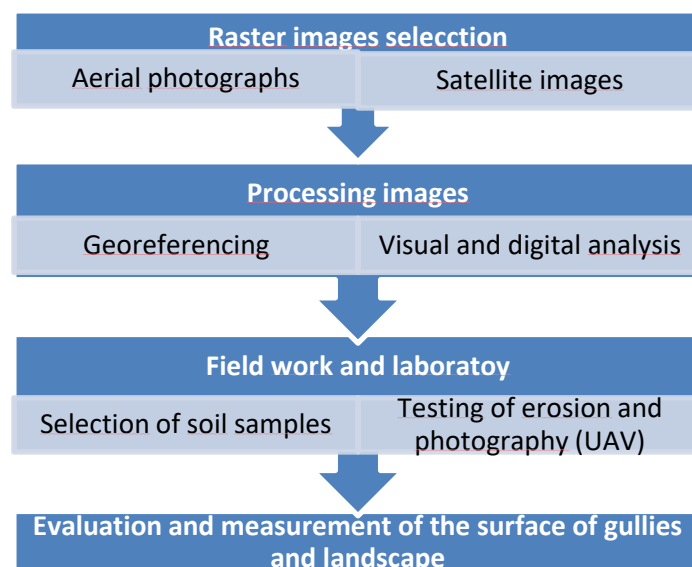


Figure 3. Methodology flow chart.

The raster images were analysed and the information obtained was contrasted with the ground truth. Some images were then trimmed to coincide with the UAV image showing the most extensive surface area of degraded soils. Supervised classifications were then performed using a minimum distance parametric rule. Four categories of state soil conservation or soil occupation were selected: bare soil, forest 1 (woodland), forest 2 (shrubby - herbaceous) and shadows (cast by the trees), although this class was finally included with forest 1.

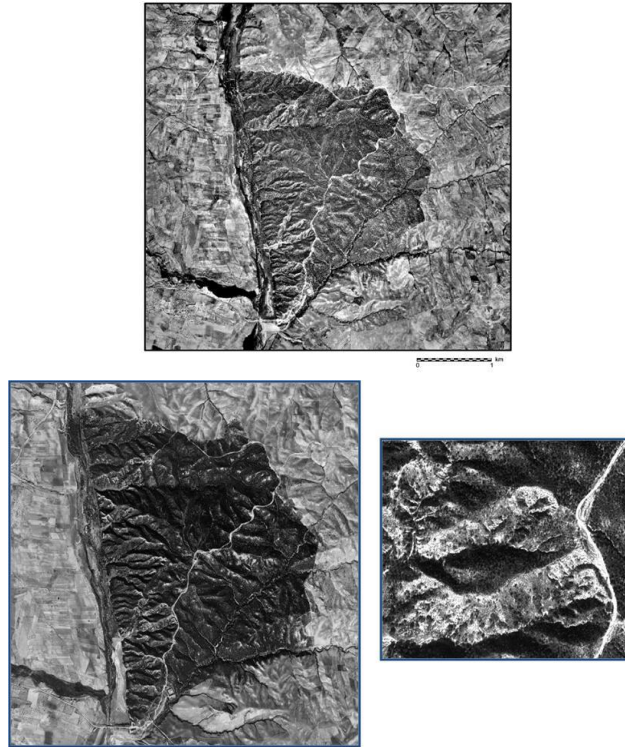
A confusion matrix was used to check the accuracy of the classifications, contrasting the results with the existing maps on both dates and with the ground truth data verified in May 2016. Although the most recent orthophotos of Madrid (Madrid Community, 2011; Scale 1:5000) permit high precision visual interpretation confirming the field data, 50 random sampling points were chosen and their accuracy was checked.

Finally, the classified images from 1956 and 2015 were used to obtain the surface areas of bare soil and the most stable areas with various vegetation strata.

4. RESULTS AND DISCUSSION

The high spatial resolution of conventional aerial photography may seem suitable for analysing soil degradation processes, but the lack of multispectral data and the low temporal resolution make it less important for thematic mapping. However, this type of photography is still essential for geomorphological or small scale vegetation studies and can also be used as a reference source or to validate semi-automatic mapping from the past. This case study uses aerial photographs taken from planes and a UAV for detailed studies, but sun-synchronous orbit satellites were selected as support for smaller scale images. Thus, recent images from Landsat and Spot satellites are analysed here with multiple spectral channels to facilitate the detection and measurement of the erosion processes. It is important to note here that visual identification of the gullied materials is significantly conditioned by the spatial and spectral resolution of the sensor used. The Landsat satellite has higher spectral resolution and the Spot satellite greater spatial resolution and, therefore, both images are used to extract the maximum possible information on the evolution of the terrain.

Panchromatic aerial photos from the 1950s and 1960s provide information on the level of conservation of this natural area in the south of Madrid and the almost complete absence of urban development during those years. In these, a contrast can be observed between the stabilized soil covered by vegetation (dark tones) and the eroded soils with gully formation (light colours). Nevertheless, sectors with high forest density, the largest gullies and drivers' roads can already be identified here. Figure 4 shows a detail of the sector with the most gullies.



Source: www.madrid.org/cartografia.

Figure 4. Aerial photograph 1956 (up) and 1961-67 (down) in the study area.

Although the 2013 30m resolution Landsat-8 image has some limitations, it does have the advantage of providing high spectral resolution, with seven visible and infrared channels that can discriminate between vegetation, sealed soil and gullies after spectral enhancements. With all the processing, the best identification of erosive processes was obtained from spectral enhancement using principal component analysis and tasseled-cap transformation. Principal components analysis is based on summarizing a large number of variables into a smaller group, taking the variance matrix into account, with hardly any loss of information. The variables are the different sensor bands and this analysis is used to obtain a new image, in which the first few components will represent almost the entire range of variability. In Figure 5 the principal components image (left) shows the urban development in individual plots and gardens to the north of the nature area, clearly shown in purple tones, with the gullies in orange. The tasseled-cap image (right) shows the same area with the gullies in orange and the urban development in purple.

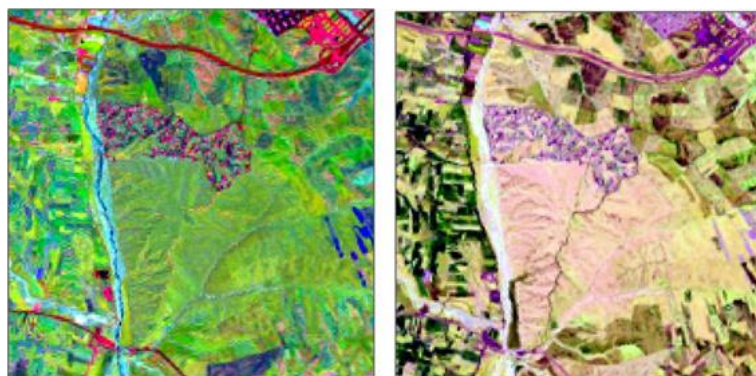


Figure 5. Landsat 8 Image, Principal components (left) and tasseled-cap (right).

The tasseled-cap function reduces sensor bands to three new bands representing the brightness or albedo (reflectivity of all bands), green (relationship between visible and near infrared channels) and humidity (considering the mid-infrared). Figure 5 (right) also highlights sealed soils (in purple), and identifies the forest surface area (pink) and gullies in black.

The Spo-5 satellite with higher spatial resolution allows a clearer visual identification of the ground features. It was also processed with a series of spatial enhancements using convolution filtering (3x3 high pass filter) and resolution merge to obtain excellent results. Thus, the resolution merge function improved the level of detail in the final image and the multispectral image was merged with the panchromatic satellite image. This discriminates clearly between urban developments with open building, riverbank vegetation, the densest forest areas, scrubland or open woodland, drovers' roads and the most intensely degraded soils (rills, gullies and ravines with no vegetation cover), Figure 6.

The impact of urban development on the increased soil erosion near large urban nuclei has been studied by many authors (Gover and Poesen, 1986; Poesen and Govers, 1986; Ramos et al. 2000; Zhanga et al. 2003; García and Pérez, 2007 and 2011; Plata et al. 2009; Scalenghe and Ajmone, 2009; Siebelec et al. 2010; Valera et al. 2011 and 2013; Barbero et al., 2013; Xiao et al. 2013).

The image obtained using convolution filtering (3x3 High Pass) facilitates the detection of linear features, (gullies in white, Figure 6).

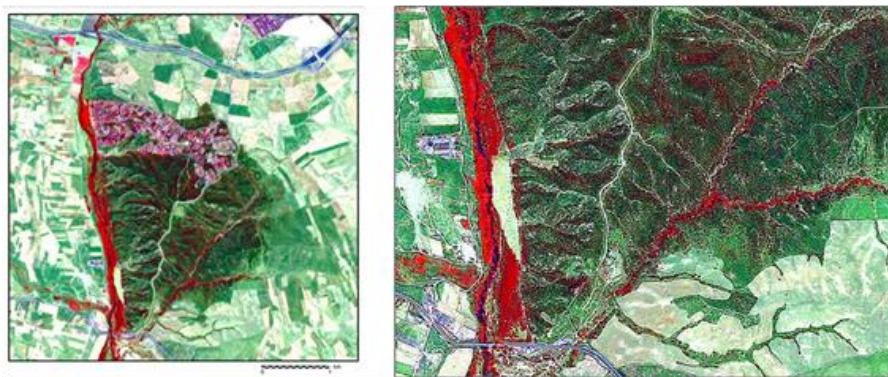


Figure 6. Spot 5 Image, 3-2-1 (R-G-B). 08-09-2013. Resolution merge (left) and 3x3 high pass filter (right).

Once the study area had been analysed, a small sector (17.4 ha, 2.1 % of study area) with the most important erosive processes was selected for a UAV flight to compare the image obtained with the photographs from 1956 and the satellite images. Using the photographs with the highest spatial resolution a classification was made to differentiate eroded areas from areas which present more stable vegetation

The high spatial resolution of the UAV image allows vegetation cover (trees and shrubs) to be identified in detail. It is also possible to map the surface of the badlands and the depth of each ravine. In the future these data will make it possible to measure soil loss more accurately.

Multitemporal analysis of the main gullies highlights the increase in bare soil to the detriment of shrubby and herbaceous vegetation. These bare soils underwent important erosive processes from 1956-2015. In contrast, in those areas where a dense arboreal vegetation of *Quercus ilex* already existed, the stabilization is confirmed or has even increased, with mature, dense, stable forest growth which impedes gully evolution.

The presence of drainage pipes at some gully heads evidences the anthropic cause of the erosion, which is very rapid in sandy sediments. In the nearby housing developments built on these fragile sediments the regular watering of garden areas has facilitated rapid soil loss.

Planting Mediterranean species in these gardens would be much less demanding in terms of water and more viable considering the local climatic conditions, (Figure 7).

In other soils developed on sandy sediments, similar to SW Madrid, changes in the hydrological cycles and increased surface runoff due to soil sealing have led to an increase in gully-formation processes (Assouline and Mualem, 2006; Jacobson, 2011; Jakab et al. 2013).



Figure 7. Photographs showing the erosion of sandy sediments Guadarrama Basin, 04-15-2016.

To see how these erosive processes can affect the soil, four profiles were selected for physical and chemical analysis (Table 2). With these tests the soil was confirmed to be sandy loam. These soils are poor in clay and organic matter and their structure is unstable, favouring erosion processes. They are permeable, neutral or slightly acid, with few carbonates and very few salts. Although these soils are not particularly fertile their loss also implies reduced water infiltration and greater surface run-off. The destruction of the vegetation cover accelerates this erosion.

Table 2. Analytical data and classification soils

Sample	Gravel %	Coarse Sand %	Fine Sand %	Silt %	Clay %	pH (H ₂ O)	pH (KCl)	O.M. %	Carbonates %	E.C. dS/m	Soils
1	34.78	47.5	28.45	6	18.05	6.23	5.08	1.37	1.03	0.23	Regosol
2	34.40	16.7	52.62	10.02	20.65	6.65	5.73	2.69	0.93	0.38	Fluvisol
3	16.02	34.2	45.52	6.85	13.43	6.40	5.14	1.32	0.99	0.11	Cambisol
4	27.86	31.4	43.67	9	15.93	7.51	6.74	6.56	1.25	0.55	Anthrosol

Finally, a supervised classification was carried out using the minimum distance rule with the two images obtained from the 1956 aerial photos and the UAV. The aim was to measure the surface areas with vegetation and with degraded soil and analyse the changes between these two dates, (Figure 8 y Table 3).

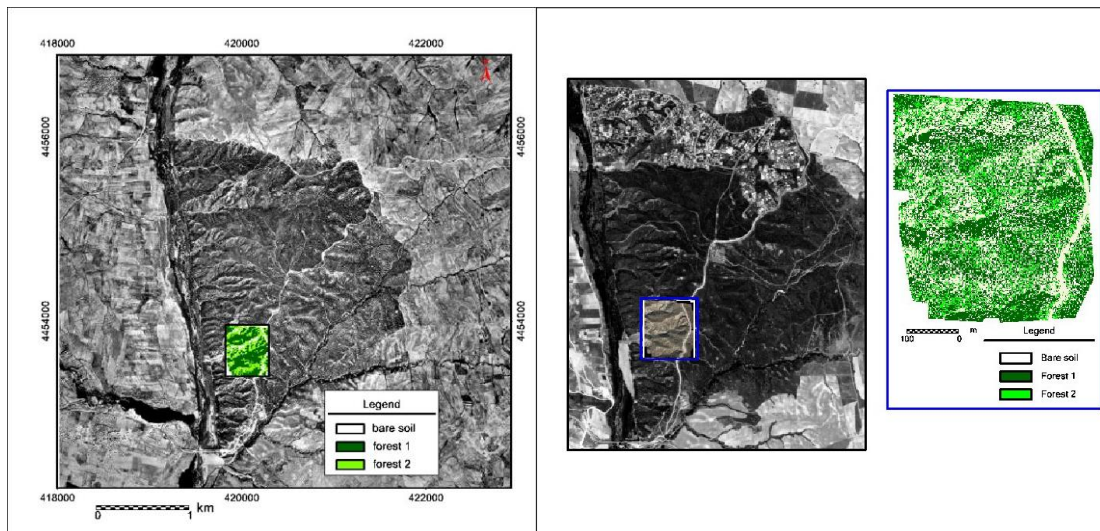


Figure 8. Land cover classification: aerial photograph-1956 (left), and UAV-2013 and localization in Spot image (right).

Three classes were established: bare soil, dense woodland, and scattered woodland and/or scrubland. A fourth preliminary class, corresponding to the shaded area, was combined with the forest area from the information contributed by the UAV multispectral image. This multitemporal analysis confirms that the percentage of bare soil increased considerably over those sixty years, to the detriment of the areas with more scattered or less developed vegetation. However, areas with dense or highly developed vegetation remained stable.

The presence of dense Mediterranean vegetation woodland thus halts the degradation processes which would otherwise been greater in areas where hydric erosion, anthropic action and the presence of highly permeable soils lead to the formation of deep gullies causing rapid soil loss.

Table 3. Supervised classification

Classes	Aerial Photograph	UAV images
	1956	2015
Bare soil (%)	12.00	28.87
Forest 1 (%)	52.35	50.63
Forest 2 (%)	35.65	20.50
<i>Total (%)</i>	<i>100</i>	<i>100</i>

The landscape of this area is characteristically eroded by gullies, which evolve in different ways depending on anthropic activity. The area known as “*Las Cárcavas*”, on the left bank of the river at the southern edge of the Community and protected within the area of the regional Park (*Parque Regional del curso medio del río Guadarrama*), has remained almost unchanged over the last 60 years and has sectors where vegetation density is even greater, which contributes to river bank stability. Conversely, in areas where intensive soil sealing has occurred as a result of urban development, the erosive process has intensified. Earth moving required to construct the road network and buildings, in addition to increased surface water from irrigation have produced significant degradation of Mediterranean woodland and sediment loss. An example of this can be seen in the *Cotorredondo* housing development, where building started in the 1970s on poorly compacted sandy material and which now presents very important erosion problems, (Sanz et al., 2014).

5. CONCLUSIONS

The study area in general shows that arboreal vegetation has recovered between the 1950s and 2015, although at specific points there are problems of erosion affecting the stability of the Neogene materials, vegetation mass and soils. This erosion has been heightened by urban development on sandy materials and by increased surface runoff originating from irrigation or artificial drainage with above-ground outlets.

Remote sensing is extremely useful for measuring degraded soils. A comparison of images from different dates enables the intensity and evolution of the process to be analysed. Furthermore, merging images with different spectral and spatial resolutions gives good results.

The availability of raster images with increasingly higher spatial resolutions allows territorial processes to be analysed from scales that range from the medium level (30 meters for the Landsat images and 10/5 meters for Spot images) down to the highly detailed (3 cm of the UAV images).

The Landsat and Spot images with several infrared channels provide valuable ground information that cannot be obtained with high spatial resolution images that only capture visible channels.

The images analysed between the 1960s and 2015 show a general recovery of the vegetation in certain places. However in areas that have been subject to sealing or badland processes, soil erosion has increased, both in built-up areas and ravines.

These land-monitoring techniques should be incorporated into the tools used by the relevant local authorities.

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