Using Archival Aerial Imagery to Study Landscape Properties and Dynamics

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Abstract

Current advances in computer vision and photogrammetry allow extraction of high-resolution 3D topographic models and orthophotomosaics from digital images. Together, these allow for a much improved characterization of landscape properties and their evolution compared to older, more traditional photogrammetric methods. But can we benefit from some of these advances to use historical information such as archival aerial imagery to extend the temporal scales at which landscapes can be observed, analysed and understood?

In this chapter, we provide some examples to demonstrate how archival aerial imagery can be treated digitally to extract the information needed to study landscape forms at multiple temporal scales. First, we provide a general section highlighting the opportunities provided by archival information and how coupling historical with contemporary datasets allows for an improved understanding of landscape evolution. Second, we explain how we can integrate archival aerial imagery with geographic information systems (GIS) to allow analysis of landscape features of interest. To illustrate the value of this approach, we present a case study analysis of landscape dynamics; this case study uses archival imagery to assess land use evolution related to afforestation and land abandonment and assess multi-temporal topographic changes related to human disturbance. Specific methodological workflows to treat and analyse archival aerial imagery in order to extract information, together with a tutorial, datasets and required software, are provided as part of the chapter.

Keywords

Archival aerial imagery · GIS · Landscape · Structure from Motion (SfM) · Landscape properties and changes

7.1 Introduction

7.1.1 Context

New platforms, sensors, software and algorithms have revolutionised the temporal and spatial scales at which geographical information can be acquired. An example of this is the use of Structure from Motion Photogrammetry (SfM) that uses ground-based images or those taken by unmanned aerial vehicles (UAVs) or other platforms (e.g. Westoby et al. 2012; James and Robson 2012; Smith et al. 2015). SfM, together with Multi-View Stereo (MVS) algorithms, allows extraction of high-resolution 3D topographic models together with orthophotomosaics, which can be analysed to understand landscape evolution. We use the term SfM photogrammetry to refer to this. These advances provide a new paradigm, reflecting (a) 'speed' (photographs can be quickly acquired, i.e. less time involved on data collection), (b) 'cost' (the access to these techniques is relatively cheap compared with other that provide similar data) and (c) 'resolution' (we can

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survey large spatial areas on multiple occasions, providing repeated and detailed information that can be used to study changes).

The application of SfM photogrammetry to archival aerial imagery, together with the application of methodologies based on GIS and remote sensing approaches, offers a wide range of possibilities to study changes in landscape properties and topography through time. On the one hand, orthophotomosaics can be post-processed by the application of digital image classification for land use mapping; on the other hand, Digital Elevation Models can be compared for the estimation of topographic changes. The study of land use changes (including topographic and planimetric) is an obvious application of these methods.

7.1.2 Contents

The chapter aims to provide non-expert teachers, lecturers and students with guidance on spatial analysis using geographic information systems (GIS). It provides basic knowledge, guidance and materials to extract and analyse spatial information obtained from historical archival aerial imagery through Open Source GIS. Prior knowledge of GIS-based spatial analysis tools is not necessary, since all details are provided. The information provided can be used to characterise landscape properties and to understand long-term landscape changes, specifically (a) the evolution of land uses due to afforestation and land abandonment and (b) multi-temporal topographic changes related to human disturbance.

The chapter is divided into four main sections. First, a broad introduction to the opportunities that SfM photogrammetry applied to archival aerial imagery is presented. This section includes an overview of the methods ('workflow') used to assess land use and topographic changes through the analysis of geographic information derived from the application of SfM photogrammetry to archival aerial photographs. This overview is mainly theoretical. The second section includes a case study from which readers and end-users can learn about and are then able to apply these methods. The case study provides details of materials and methods, along with the main results and a brief discussion. Some of these results were presented by Llena et al. (2018, 2019). The third section provides some final considerations and take-home messages. This is followed by a detailed tutorial along with the data used in the chapter (Sect. 7.4); supplementary materials are also provided. Tutorial also includes a series of key questions designed to stimulate thought. The answers to these are provided in the study case section; the questions help ensure that the learning outcomes of the chapter are attained.

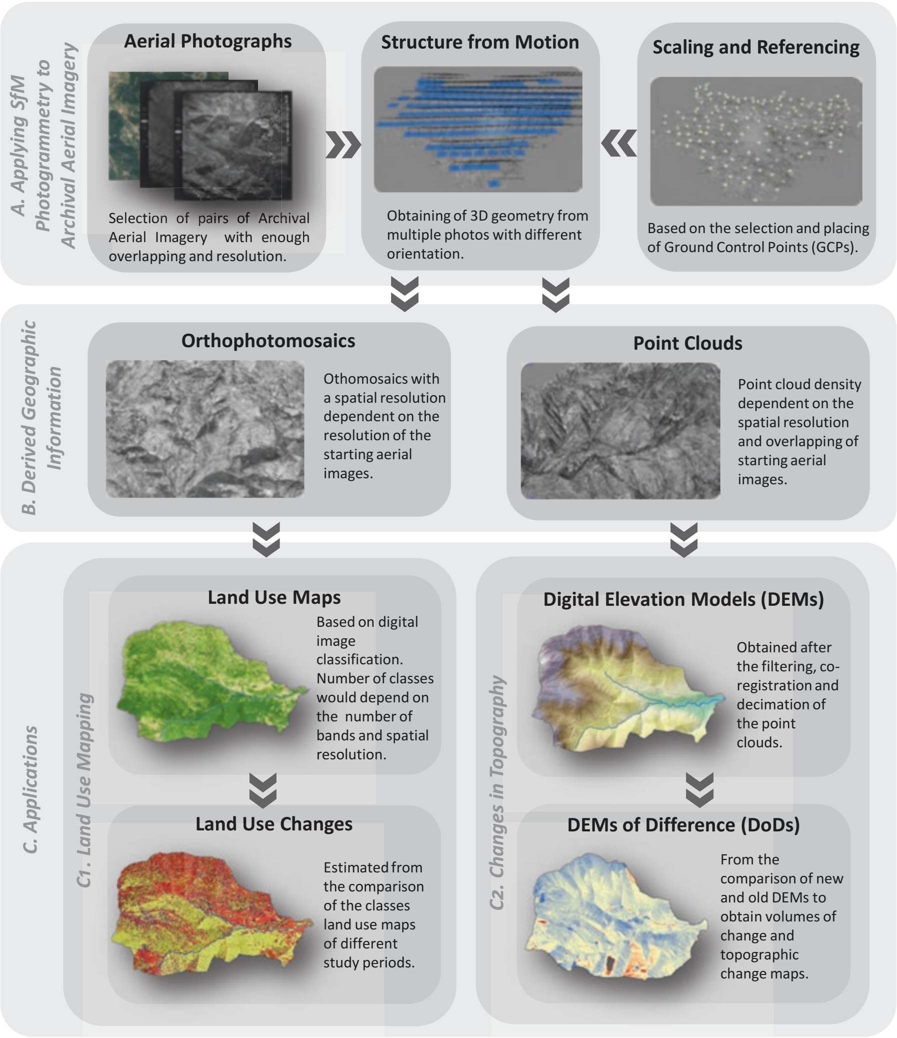
7.2 Applying SFM Photogrammetry on Archival Aerial Imagery

7.2.1 Opportunities

SfM photogrammetry allows extraction of 3D information and orthophotomosaics from multiple photographs. Extraction of 3D information is possible because each photograph is taken, looking at the scene or object of interest from a different position. Despite a wide range of SfM photogrammetric software being available to process images, most share a common methodological approach. This approach can be applied to archival aerial imagery, but it is necessary to follow a specific workflow. The main steps of this workflow are summarized and presented in Fig. 7.1. They are also described in greater detail by Llena et al. (2018). The first step consists in image alignment, which is achieved by the software searching for common points visible in several images. Then, the 3D geometry of the scene is estimated, including the coordinates of the common points, along with the position of the camera (i.e. extrinsic calibration) and the internal parameters of the camera (i.e. intrinsic calibration; Ullman 1979). The use of historical aerial photographs presents two main issues that may affect data accuracy and precision: (a) the overlap between photographs and (b) the quality of the image (Micheletti et al. 2015; Bakker and Lane 2017; Llena et al. 2018). In historical photographs, the quality of the image is often compromised during its storage or during the scanning process, leading to the loss of image quality (e.g. blurred areas, presence of artefacts), and a consequent increase in errors in the alignment process and, consequently, final 3D products. Through the alignment process, a first low-density point cloud is obtained, which must be georeferenced and scaled. The georeferencing and scaling process consists of the geometric and geographic correction of the sparse point cloud by the use of Ground Control Points (i.e. GCPs). The selection of GCPs is based on the location of coincident points from the photographs in potentially unchanged locations (e.g. road crossings, field boundaries) compared with available georeferenced information. It is important to avoid the selection of GCPs in elements with complex or irregular geometries since these irregularities may decrease the accuracy of the GCPs and introduce significant errors in the final point cloud.

The last step is the acquisition of derived products or geographic information. Here we refer to (a) point clouds and (b) orthophotomosaics. Once the sparse point cloud is georeferenced in a known coordinate system, the next step is to apply different algorithms (e.g. MVS) to increase the density of the point cloud by at least two orders of magnitude, obtaining a definitive dense cloud. Additionally, through the orthorectification process, a single orthophoto-

Fig. 7.1 Summary of the workflow followed to obtain orthophotomosaics and point clouds through the application of SfM photogrammetry (**a** and **b**). (**c**) Examples of application: land use mapping and changes in topography



mosaic is obtained, and this is corrected geographically and geometrically, thanks to the spatial information provided in the preliminary steps. In this process, a colour correction is also performed in the boundary zones between photographs by homogenising the histograms of the adjacent pairs to obtain the final mosaic.

The application of SfM photogrammetry opens the door to a multitude of applications, both from the scientific and learning point of view. Once users are familiar with the software, orthophotomosaics can be obtained through a fast, automatic and easy, although blind, process. In general, better-quality products are obtained (e.g. lower georeferencing errors, orthorectified images) relative to standard methods of image georeferencing available in GIS. Point clouds offer a wide range of possibilities to characterise landforms and study changes in landscape properties and topography through time. This is important, especially from the point of view of historical analysis, since it allows the reconstruction of landscapes at various points in the past in both two (orthophotomosaics) and three (point clouds) dimensions; this means that we can look at landforms in a 4D dimensional way.

7.2.2 Image Classification: Land Use Mapping

7.2.2.1 Image Classification: General Explanation

Images are built as a mosaic of pixels or cells. A pixel represents the smallest area in a landscape that contains data. Images with large pixels provide less detail, while small pixels mean more detail is visible but require more computational time during image processing. The size of the pixels determines the spatial resolution of the image. For instance, an image with a pixel of 2 × 2 m indicates that the real area covered by the pixel is 4 m^2.

Images can have one band or multiple bands. One band means that each pixel is characterised by a single value. Multiple spectral bands, however, produce multiple values for each pixel, yielding more information for each one.

Digital image classification consists of the transformation of the values of each of the pixels into categorical values, based on some predetermined classification (Fig. 7.1).

But what exactly do the numerical values contained in a pixel represent? The spectral response captured in an image (in each pixel) depends on the sensor. Additionally, the type of sensor determines the number of bands the image can have. For instance, ordinary colour images have three bands, registering the response of the electromagnetic energy across three wavelength bands (red, green and blue (RGB)) in the visible spectrum. The combination of values for these three bands is what provides the colour we see the objects represented in pixels across an image. More complex sensors capture more bands, corresponding to different wavelengths along the electromagnetic spectrum. Therefore, the principle of image classification is one of using the different response of the bands to different objects to be able to identify them.

The definition of the categories used in the classification can be done in one of two ways, referred to as supervised and unsupervised classification. The supervised method implies a previous knowledge of the area and appropriate categories. The identification of samples (control points or polygons mainly) for each category is required. The software calculates the digital values in each category based on the sample values. Once the pixel values are segregated by category, differences between categories are computed (different statistical methods can be applied), and the rules that come from this computation allow each pixel to be assigned to a category. The unsupervised method uses automatic searches to find clusters of pixels with homogeneous values within the image; the user simply sets a total number of categories to be used. Thus, if, for example, the user is interested in identifying four landcover categories in the whole image, the software, based on the pixel values, finds the four groups can be best statistically differentiated. In this method, no prior knowledge of the study area is required, and the work of the user is more focused on the labelling and reclassification of the resulting groups than on providing input information to the clustering algorithm. See Chuvieco (2016) for full details of digital image classification procedures.

7.2.2.2 Image Classification: What for?

One of the most widespread applications of the digital classification of images is obtaining land uses maps (e.g. Foerster et al. 2014; Haliuc et al. 2018). Change and evolution of land uses and their causes (e.g. rural abandonment, forest fire) can be analysed and quantified based on multi-temporal land use maps. Likewise, image classification can be used to analyse other planimetric changes such as the evolution of the active channel width in fluvial systems (e.g. Batalla et al. 2018), glacier evolution (e.g. Marochov et al. 2020) or evolution of water masses (e.g. Torres-Batlló et al. 2020). The increasing frequency of satellite missions, along with the freely and easily downloadable data (downloaded from several official web servers; e.g. ESA-SENTINEL-2, European Space Agency) represents a great advance from the user accessibility point of view. Analysis is facilitated further by the availability of Open Source GIS (e.g. QGIS) to post-process and interrogate images, providing great opportunities for classroom learning.

7.2.3 Landscape Evolution: Changes in Topography

Three-dimension point clouds derived from SfM photogrammetry need to be post-processed in order to extract reliable spatial information. The first step is to filter the points by eliminating data that do not belong to the ground surface (e.g. buildings, vegetation), as well as other possible outliers that may create noise. The objective of this process is to obtain a model of the ground, representing the topographic elevation of the terrain, that allows comparison with other models of the same characteristics without the presence of other elements (such as vegetation) that may contribute uncertainty. The comparison between different point clouds is possible, thanks to the georeferencing process in the same reference system; however, residual misalignments can remain, and it therefore becomes essential to carry out a co-registration between the historical point cloud and reference point cloud by the pairing of stable areas (see Cucchiaro et al. 2020, for more details).

In order to analyse the spatial distribution of topographic changes and at the same time be able to obtain volumetric changes, filtered point clouds are transformed into continuous digital models in a raster format (i.e. digital image divided in pixels where each pixel represents the ground elevation). Therefore, interpolation is required to transform dense clouds into pixels representing Digital Elevation Models (DEM); i.e. each of the pixels of the raster file represents one value of terrain elevation. Landscape changes can be analysed if DEMs are obtained for different points in time (i.e. multi-temporal DEMs). A DEM of Difference (DoDs) is obtained from the comparison of DEMs from two different time periods (Fig. 7.1; e.g. Brasington et al. 2000; Lane et al. 2003; Williams 2012; Vericat et al. 2017). A DoD is a model representing changes in elevation (i.e. each pixel represents a positive or negative value, indicating elevation gain or loss). A DoD (a) provides the spatial distribution of elevation gain and loss that in a landscape, translated into maps of erosion and deposition, and (b) by the integration of these values through their area, allows computation of the volumes of materials eroded or deposited.

As mentioned above, in the case of archival aerial imagery, the overlap between photographs and the quality of the images may affect data accuracy and precision of the final products derived through SfM photogrammetry. The interaction of the magnitude of real changes in the landscape of interest and errors in the final products determines the limits of detection and the accuracy of this approach. If the magnitude of the changes is higher than the total error of the DoD, results will help in identifying zones of potential change, although absolute differences may be subjected to uncertainty. As long as these limitations are recognised, the method provides a way of obtaining spatial information from historical periods for which only archival aerial photographs are available and in turn provides a wide range of possibilities for the study of historical landscape changes. Several authors have recently used this approach to study topographical changes in fluvial geomorphology (e.g. Llena et al. 2020), mass-wasting processes (e.g. Leenman and Tunnicliffe 2018), glacial dynamics (e.g. Mertes et al. 2017; Midgley and Tonkin 2017) and coastal erosion dynamics (e.g. Carvalho et al. 2021).

7.3 Study Case: The Fiscal Catchment

7.3.1 Study Area

The Fiscal River catchment (16 km^2) is located in the middle part of the Ara River catchment (715 km^2) in the southern Pyrenees, NE Iberian Peninsula (Fig. 7.2). This is a mountain catchment with an altitude ranging between 749 m a.s.l. at the outlet and 1927 m a.s.l. in the headwaters. Like most mountain catchments in the Pyrenees, the Fiscal has suffered from anthropic disturbances that have affected its sedimentary dynamics, especially in the second half of the twentieth century due to major changes in land use (Beguería 2006; Garcia-Ruiz 2010). Other localized disturbances have also modified the transfer of water and sediments through Pyrenean catchments in general. For instance, gravel mining and channel embankments have a direct impact on river corridors, while the construction of large infrastructures such as roads or the extraction of sediments in open pit quarries modifies the topography of hillslopes; all of these change have a direct impact on sediment connectivity (e.g. Tague and Band 2001; Llena et al. 2019). The Fiscal catchment experienced a significant increase in forest cover and concomitant loss of meadow and bare surfaces during the second half of the twentieth century due to land abandonment (e.g. see (i) in Fig. 7.2). Furthermore, during the beginning of the twentieth century, a new road (5 km long and 20 m wide) was built crossing the river in the central part of the catchment (see (ii) in Fig. 7.2). Construction of this road induced important changes on the hillslopes and the movement of large amounts of material, modifying the natural drainage

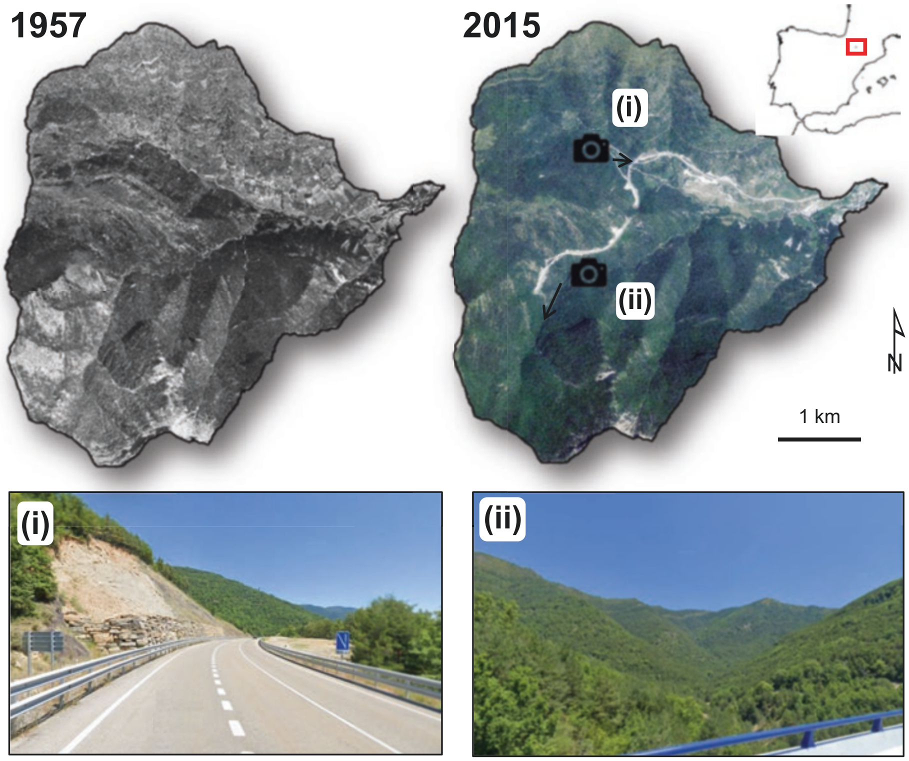


Fig. 7.2 Orthophotomosaics of the Fiscal catchment for 1957 and 2015. The red square in the Iberian Peninsula indicates the location of the catchment. (i) View of the road constructed in the central part of the catchment. (ii) View of a forested part of the catchment. Clear differences can be observed by comparing 1957 and 2015 conditions. The 1957 orthophotomosaic was obtained following the workflow presented in Fig. 7.1 and Sect. 7.2

network. All these changes make the Fiscal as an excellent case study for this chapter.

7.3.2 Objectives, Materials and Methods

7.3.2.1 Objective

The objective of this case study is the characterization of land use and terrain (topography) across the catchment in 2 years (1957 and 2015) in order to evaluate the impact of land abandonment and the construction of a road. Land abandonment has modified landcover in this catchment, while changes in topography resulted from road construction. The following text provides an overview of the datasets and analytical methods, with full details on how to apply these methods explained in detail in the supplementary materials section in the form of a tutorial; the supplementary material includes links to the datasets and the software.

7.3.2.2 Datasets: Archival Aerial Imagery

The 1957 dataset represents the landscape before the change or disturbance, while the 2015 dataset represents the landscape affected by the change. Each dataset consists of (a) an orthophotomosaic of 1 m resolution and (b) a DEM with a spatial resolution of 10 m. The methods followed to obtain these datasets were different for each year. In the case of 1957, the orthophotomosaic and the DEM were elaborated by the application of SfM photogrammetry to archival aerial imagery obtained from the Spanish National Centre of Geographic Information (CNIG) (see Sect. 7.2 and Fig. 7.1 for more details about the specific workflow). The 2015 dataset, however, consists of an orthophotomosaic and DEM provided by the Spanish National Centre of Geographic Information (CNIG). Both were obtained in the background of the National Aerial Orthophoto Program in Spain (PNOA) – the orthophotomosaic in 2015 and DEM in 2010.

7.3.2.3 Data Analysis

Land Use Changes

Land use maps were obtained through the application of an unsupervised image classification. The classification used the K-means clustering method, applied using QGIS 3.2. This determines the differences between classes in order to classify each pixel of the image as belonging to one of the classes. Orthophotomosaics were initially classified into ten classes (i.e. ten clusters in this method). Due to the limited spectral response of the 1957 panchromatic aerial photos, the ten classes were then grouped into three broader ones (bare earth, forest, meadow) based on photointerpretation. Classes were maintained for both years in order to be able to compare the land use maps. These classes permit analysis of the general evolution of land use, mainly dominated by afforestation. Once the classification had been carried out, it was possible to calculate the absolute and percentage area of each class for each year. These results provide insights into land use at two different points in time ('two snapshots', two maps) and the evolution of these uses over time ('comparing snapshots', one map showing changes).

Topographic Changes

Topographic changes were analysed by comparison of the 1957 and 2015 DEMs through a DEM of Difference (DoD), providing a gross estimate of the changes within the area affected by the construction of the road. A minimum level of detection (minLoD) was set in order to distinguish those cells in which the topographic change might be uncertain from those where the change is considered real (i.e. DoD > minLoD). This is a common practice in order to segregate the values of the DoD considered real from those that may be noise or uncertain change (e.g. Wheaton et al. 2010). The minLoD of a DoD can be assessed by propagation of the errors of each DEM being compared. This propagation can be computed in a 'simple' way (the root square of the sum of the square of the errors) or more sophisticated ways (see Wheaton et al. 2010 for more details). Anderson (2019) has recently presented an interesting discussion about the use of these minLoD for thresholding DoDs. In the Fiscal case study, a simple minLod of 2 m was applied, based on previously calculated errors (Llena et al. 2018). Therefore, those cells in which estimated changes are greater than 2 m (either in the positive or negative direction) are considered 'real', while changes less than 2 m (i.e. within the interval −2 to +2 m) are considered uncertain, potentially resulting from errors in the computation of the DEMs rather than being real topographic change. The DoD was calculated by the application of the GCD 7 software (Standalone), which allow change detection analyses and error thresholding. Results can be displayed in an Open Source GIS such as QGIS.

7.3.3 Main Results and Discussion

7.3.3.1 Land Use Changes

Land use maps of the Fiscal catchment showed a clear trend towards afforestation during the 58 years of the study period (Fig. 7.3). Forest cover increased from 57% of the total surface in 1957 to 68% in 2015. In contrast, bare surfaces suffered an important decrease, from 23% to 9% in 2015, while meadow increased slightly from 20% in 1957 to 23% in 2015. Afforestation mainly occurred on terraced slopes that were abandoned (see (i) and (ii) in Fig. 7.3) and in formerly active sedimentary areas that were stabilised by vegetation either in the upper parts of the catchment (i.e. erosional features, see (iii) and (iv) in Fig. 7.3) or in the valley bottom (i.e. the active floodplain, see (i) and (ii) in Fig. 7.3). Only areas

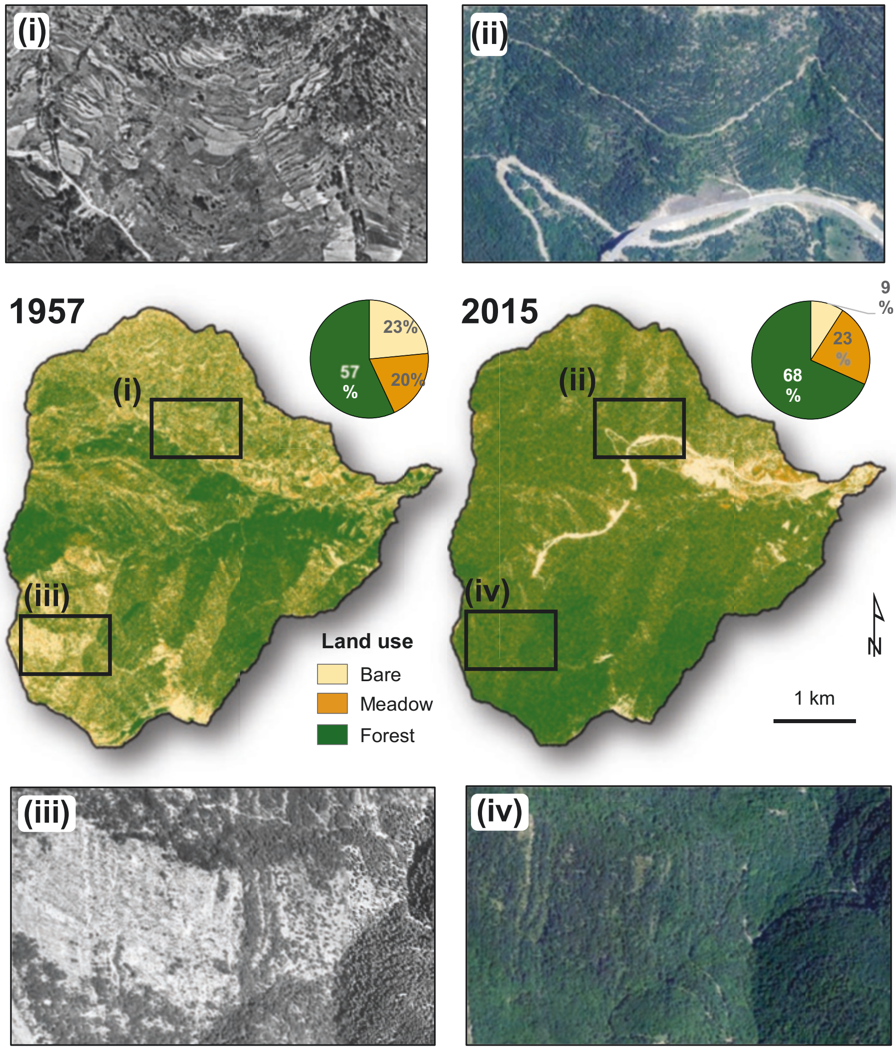


Fig. 7.3 Land use maps of the Fiscal catchment in 1957 and 2015. Pie charts represent the percentage of each land use (i.e. bare, meadow and forest). (i–iv) provide some examples of catchment areas that have suffered land use changes, as discussed in the text

directly affected by the road construction works experienced an increase in bare areas, with corresponding decrease in either forest or meadow.

The increase of forest during the second half of the twentieth century observed in the Fiscal catchment is representative of many Mediterranean mountain catchments. Several studies proved that afforestation is mainly driven by a combination of crop abandonment and decreasing grazing (e.g. García-Ruiz et al. 1996; Gallart and Llorens 2003; García-Ruiz and Lana-Renault 2011), along with climate change (e.g. López-Moreno et al. 2011; Macklin et al. 2012; Buendia et al. 2015; Zabalza-Martinez et al. 2019). The rapid increase of forest on abandoned terraced landscapes can be explained by the stability of these areas and their favourable soil properties. Terrace abandonment followed by strong scrub or meadow regeneration in humid areas improves soil quality and creates effective protection against soil erosion, ultimately favouring afforestation (e.g. Lana-Renault et al. 2014; Lizaga et al. 2019; Nadal-Romero et al. 2021).

7.3.3.2 Topographic Changes

The construction of the road involved engineering works with significant land movement along the routeway (Fig. 7.4). Since 'erosion' and 'sedimentation' resulting from the road construction were anthropogenic rather than the result of natural processes, we use the terms 'extraction' and 'deposition' respectively to represent the topographic changes in the Fiscal catchment. Mean depth of the sediment extracted as result of road construction during the period 1957–2015 was around −10.1 m, and the average depth of deposition was around 7.6 m. This yields a net change in elevation of −2.4 m. Twenty-one percent of the affected area by the works had values below the minLoD. Of the remaining area, sediment extraction dominated (70%), with deposition less important (30%). These respective changes were mainly due to the

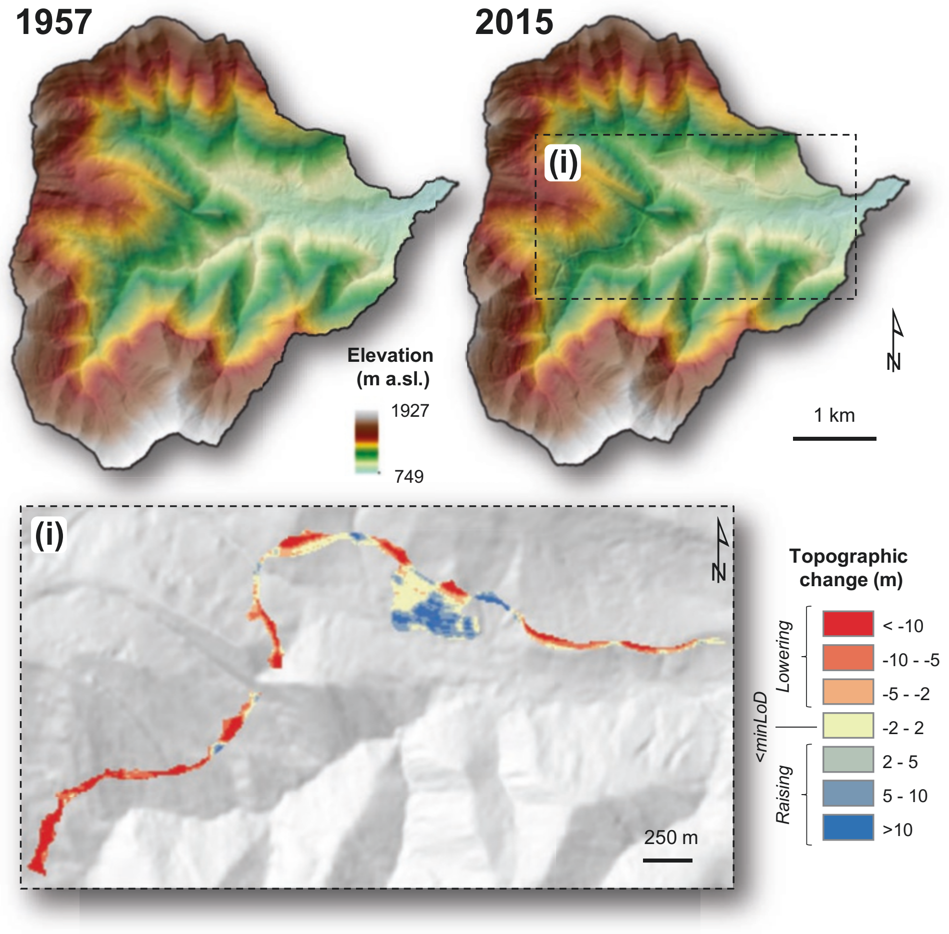


Fig. 7.4 Digital Elevation Models (DEM) of the Fiscal catchment in 1957 and 2015. The zoom-in (i) shows the associated DEM of Difference (DoD) representing the topographic changes

excavation of material from hillslopes and the infilling of depressions or deep channels (see (i) in Fig. 7.4). Analysis of the DoD shows that 1,457,277 m^3 of material was extracted from the area affected by the road construction during the execution of the works, while 637,543 m^3 of material was deposited. In terms of the total sediment budget, there was a net extraction of −819,734 m^3 of material. Net budget without taking into account the minLoD was −826,176 m^3, which only represented 1% of change.

Topographic changes caused by road construction influence the overall sediment transfer in two ways: (i) by inducing erosion downslope of the road and (ii) by capturing sediment coming from above the road and delivering it downstream. Due to the induced effects on flow paths and, consequently, on runoff, topographic changes due to roads may have a localised effect on connectivity (e.g. Wemple et al. 2001; Kalantari et al. 2017). The road artificially cut the drainage network, producing a localised increase in potential connectivity in the upslope area and a decrease in connectivity downslope. Therefore, the morphological variation due to road construction may lead to an increase of erosional processes uphill, triggering localised landslides in some instances (e.g. Persichillo et al. 2018; Llena et al. 2019).

7.4 Final Considerations, Conclusions and Tutorial

This chapter has provided a method for the post-processing of archival aerial imagery to allow the study of long-term landscape properties and dynamics, including both land use and topographic changes. It set out the basic workflow to estimate land use and topographic changes through the analysis of geographic information derived from the application of SfM photogrammetry to archival aerial photographs. The case study of the Fiscal catchment showed the insights that this workflow can produce. The supplementary material section provides a detailed tutorial based on this case study. The take-home messages of this chapter are as follows.

The application of SfM photogrammetry to archival aerial imagery allows the extraction of orthophotomosaics and point clouds. Although orthophotomosaics can be directly analysed, point clouds require filtering and regularisation in order to compute Digital Elevation Models (DEM).

Orthophotomosaics and DEMs can be analysed using GIS-based algorithms.

A single orthophotomosaic or DEM allows landscape characterization (the study of its properties), while multi-temporal datasets allow study of the evolution and dynamics (landscape change).

Digital image classification allows, among other applications, production of land use maps. From comparison of maps from different points in time, it is possible to analyse the evolution of uses, including both the spatial distribution of changes and quantitative changes in different land uses (the percentage change in each use).

The comparison of DEMs permits analysis of topographic changes through time. As with land use, this includes analysis of the spatial distribution of changes and quantitative estimates of change expressed in terms of total gain and loss of elevation and corresponding volumes.

The case study presented here shows that the Fiscal catchment has undergone afforestation processes during the period 1957–2015. The observed 11% increase in forest is mainly due to the abandonment of rural, mountain areas.

The construction of a road in the central part of the catchment during the beginning of the twentieth century caused important local topographic changes, with these having potential effects on sediment transfer and connectivity.

Application of the methods explained in this chapter allows the extraction of the geographic information needed for assessment of changes in the landscape through time and, in turn, assessment of their causes.

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