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Agricultural land abandonment linked to pipe collapse and gully development: Reconstruction from archival SfM and LiDAR datasets

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ABSTRACT

Land use and land cover changes such as agricultural land abandonment along with soil erosion are perceived to be important factors that add to land degradation worldwide. In this study, we used aerial imagery, archival-Structure from Motion (SfM) reconstruction and airborne-LiDAR surveys to reconstruct land abandonment along with pipe collapse and gully development in a semi-arid Mediterranean catchment area of the Ebro Valley (Spain) during 1957–2021. Agricultural land dynamics were analysed from the study of planform changes to field crops. Land degradation associated to pipe collapse and gully development was inferred from the geomorphic change detection deduced from the comparison of topographic models obtained from archival-SfM and LiDAR datasets. Through spatial correlation analysis, we identified that higher, steeper, and more hydrologically connected field crop areas were the first to be abandoned. Additionally, the extent of pipe collapses and gullying processes was significantly correlated with the degree of land abandonment over the duration of the study period. Our findings reveal that approximately 20 % of agricultural lands within the study area were abandoned during said study period, with up to 15 % of the abandoned area directly impacted by pipe collapse and gullying processes. Erosion rates associated with these processes within the catchment, implied erosion areas of 3.9 ha and 1.5 ha for the period 1977–2009 and 2009–2021, ranging between 120 Mg/ha yr^{-1} and 203.2 Mg/ha yr^{-1}, respectively. Our study highlights that abandonment in said area is predominantly conditioned by land degradation resulting from pipe collapses and gully development. The recognition and protection of piping and gully affected areas as geodiversity sites is presented as an alternative at a local level to mitigate the economic impacts of soil degradation. Understanding the effects that pipe collapse and gully development have on arable lands over long-term study periods (i.e., >50 years) is essential in order to shed light on the interconnected factors influencing land productivity and agricultural sustainability. This ultimately guides us to make informed policy decisions that mitigate these detrimental effects.

1. Introduction

Soil degradation is considered one of the most important global environmental concerns, as soils play a crucial role in fulfilling essential ecosystem functions, including process regulation: water regulation and production (e.g., Keesstra et al., 2021), carbon storage (e.g., Lal, 2004), and supporting biodiversity (e.g., Thornes, 1985; Pimentel, 2006). Additionally, soils serve as the very foundation that provide ecosystem services (Adhikari and Hartemink, 2016) and resources upon which human activities are developed (Koppitke et al., 2019). Soil erosion, which includes subsurface erosion, represents a significant global challenge in land degradation (Poesen, 2018; Quinton and Fiener, 2024), with water being one of the major driving forces (besides wind) behind soil erosion (Borrelli et al., 2020). Up to now most research on water soil erosion has focused on sheet and rill erosion, whereas gully erosion has received less attention (Poesen et al., 2003; Borrelli et al., 2020, 2022; Bernatek-Jakiel and Nadal-Romero, 2022), and soil piping is even often omitted in soil studies (García-Ruiz et al., 2017; Bernatek-Jakiel and Poesen, 2018). This may occur because, in most landscapes, gully channels and soil pipes occupy small areas (gullies less than 1–5 %). As for soil piping, it is one of the most difficult erosion processes to study due to its subsurface nature. However, gully erosion may

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contribute to overall soil loss and sediment production at the catchment scale, often more than 5 %, and occasionally up to 80 % in dry environments (Poesen et al., 2003), whereas piping erosion may contribute to the total catchment sediment yield from 15 % up to 90 % (Bernatek-Jakiel and Poesen, 2018).

Piping leads to the formation of subsurface linear pipes in soils and unconsolidated or poorly consolidated sediments (Gutiérrez et al., 1988; Boucher, 1990; Faulkner et al., 2004). This phenomenon results from the combination of different environmental factors such as soil characteristics, topography, local hydraulic gradient, and climatic conditions. It is often associated with the physical and chemical properties of the soil, including the presence of expansive clays such as illite or kaolinite, high SAR (Sodium Adsorption Ratio) values, or elevated levels of exchangeable sodium (Bryan and Yair, 1982; Gutiérrez et al., 1997). Additionally, it is also necessary to consider factors that allow waterflow and infiltrations, such as the presence of crevices or cracks in the soil (Harvey, 2004). The progression of piping through an area involves the development of a network of subsurface pipes that may collapse due to the weight of the overlying sediment, generating collapses that vary in size and form. Piping plays a critical role in landscape evolution by primarily initiating and transforming gully networks, and as such, it is significantly associated with gully erosion. It represents a significant soil erosion hazard that may cause notable and detrimental effects, including the destruction of engineering structures (Singh, 1996; Richards and Reddy, 2007; Nadal-Romero et al., 2011), the loss of pastures (Verachtert et al., 2011; Bernatek-Jakiel et al., 2017), and croplands (García-Ruiz et al., 1997; Romero-Díaz et al., 2007; Pereyra et al., 2020).

Studying piping erosion still poses a challenge when it comes to quantifying its scale. Some authors (Holden et al., 2002; Bernatek-Jakiel and Kondracka, 2016) have pointed out that the results of surface studies may underestimate, at times up to 50 %, the extent of pipe networks real impact, meaning that there is still no satisfactory method to calculate the real extent of pipe networks that may allow for the creation of reliable prediction models. As a consequence, piping is considered one of the most difficult geomorphological processes to analyse and quantify (Faulkner, 2013). Some attempts have been made to study the complexity of underground piping systems using non-destructive methods, as for example geophysics techniques (e.g., Holden et al., 2002; Got et al., 2014; Bernatek-Jakiel and Kondracka, 2016, 2022; Kariminejad et al., 2023). Despite this fact, these are challenging methods, and the interpretation of derived results must always be accompanied by the surface indicators of piping (Bernatek-Jakiel and Kondracka, 2016). For this reason, soil piping has mainly been studied using pipe collapse as surface indicators of this subsurface process. Mapping pipe collapses still represents the most common field method of pipe detection, both mapped in the field and with the use of orthophotos (e.g., Verachtert et al., 2011; Wilson et al., 2015). Together with aerial optical information, the advances in High-Resolution Topography over the last two decades (Tarolli, 2014; Passalacqua et al., 2015) provide new opportunities for the multi-temporal study of earth-surface dynamics and geomorphic processes, such as piping and gully erosion.

Land degradation is a particularly pressing problem in regions with contrasting climates under strong anthropic pressure, as is the case of the Mediterranean regions. Here, intense precipitations occurring over short periods of time, together with steep topography, the abundance of easily weathered rock outcrops and scarce vegetation cover, constitute an ideal space for the development of erosion processes and the formation of badlands (Nadal-Romero et al., 2007; García-Ruiz and López-Bermúdez, 2009). In the context of Global Change, climate variations and Land Use Land Cover (LULC) changes are deeply interrelated with land degradation processes (e.g., piping and gullying) as one of the main triggers for agricultural abandonment. The use and extension of agricultural fields have changed significantly over the centuries in the Mediterranean region, and one of the most important changes was the sudden abandonment of arable land during the 20th century. In general, abandonment is considered a global issue with special prevalence in developed countries due to a wide variety of reasons (Lasanta et al., 2021): (i) the migration of the rural population to urban areas and the aging of the remaining population (Ruiz-Sinoga and Martínez-Murillo, 2009; Kosmas et al., 2002, Meléndez-Pastor et al., 2014); (ii) the mechanization of agricultural operations leading to the abandonment of smaller fields (Lasanta, 1988; Nagendra et al., 2003; Onega-López et al., 2010); (iii) low productivity due to a lack of soil fertility (Duarte et al., 2008), (iv) high market competitiveness (García-Ruiz et al., 2015; Van Leeuwen et al., 2019); and (v) the impact of the Common Agricultural Policy (PAC) which, between 1989 and 2008, encouraged farmers to abandon their agricultural land, either temporarily or permanently (Boellstorff and Benito, 2005; Alonso-Sarría et al., 2016). The abandonment of cultivated fields has also been identified as a significant contributing factor to soil degradation, constituting a complex process which is dependent on various factors such as climate, topography, and the history of Land Use and Land Cover (Lasanta et al., 2019; Rodrigo-Comino et al., 2018).

Available information is limited, but it has been demonstrated that the agricultural abandonment in the Mediterranean basins has recently extended to semi-arid areas. This shift can be attributed to the low productivity of unirrigated crops, as well as salinization and soil deterioration (Cerdà et al., 2018; Ferreira et al., 2022). This is the case for agricultural areas affected by gullying and piping processes. These processes pose a threat to land productivity, agricultural sustainability, soil nutrient levels and carbon cycles, while also potentially destabilizing socio-economic conditions, particularly in agricultural lands (Poesen et al., 2003; Bernatek-Jakiel and Poesen, 2018). As aforementioned, piping and gullying processes have a direct effect on land degradation, which together with the change of the agricultural management model (Lasanta et al., 2021), are major triggers for agricultural land abandonment. As recently stated by Quinton and Fiener (2024), there are still some challenges relating to the study of soil erosion processes. Among other things, they conclude that understanding the interaction between different processes and how they interrelate across spatial and temporal scales still requires research attention. This may be extrapolated to the interactions between gullying, piping processes and LULC changes. Several studies quantified soil degradation and agricultural abandonment in Mediterranean areas due to LULC changes (e.g., Bakker et al., 2005; García Ruiz, 2010; Weissteiner et al., 2011; Rodrigo-Comino et al., 2018), as well as the impact of gullying and piping erosion on agricultural lands worldwide (e.g., Pereyra et al., 2020; Chen et al., 2022; Tichavský et al., 2023). Despite this, to date there are very few studies (e.g., Bernatek-Jakiel and Jakiel, 2021) that integrate both driving forces and their impact on agricultural abandonment over a sufficient time span to establish a cause-and-effect relationships between these variables. Such research is crucial for understanding the intricate dynamics that lead to the loss of arable land. They may shed light on the interconnected factors influencing land productivity and agricultural sustainability, ultimately guiding informed policy decisions to mitigate these detrimental effects.

The main aim of this paper is to analyse the effects of piping and gully erosion on agricultural land abandonment in a semiarid Mediterranean area in a context of LULC changes, including the change of the agricultural management model. The detailed objectives of this study are: (i) to quantify planimetric changes in the study area related to the reduction and expansion of agricultural areas; (ii) to calculate volumetric changes due to erosion (soil losses) and sedimentation processes associated to pipe collapse and gully erosion; and (iii) to identify the morphometric driving forces related to agricultural abandonment in the study area. This leads to the following research hypothesis: agricultural abandonment in the study area is mainly conditioned by land degradation that has occurred due to pipe collapses and gully development.

The novelty of this study lies in the combination of methods used to analyse the evolution of agricultural land abandonment related to pipe collapse and gully dynamics and development in the long term, i.e., from 1957 to 2021. This was possible through the analysis of aerial imagery, available since the 1950 s, using archival-SfM, and airborne-LiDAR surveys of a semi-arid Mediterranean basin located in the Ebro Valley (NE Spain).

2. Study area: The Barreiro catchment and Aguarales

The study basin (124 ha) covers the upper part of the Barreiro catchment, which is located in the Ebro Basin (NE of the Iberian Peninsula; Fig. 1A), with altitudes ranging from 460 to 625 m a.s.l. The bedrock is composed of mudstones with interbedded tabular sandstone layers, deposited in alluvial fan environments primarily affected by sheet flooding. The laterally extensive sandstone beds form the cap rock of mesas and stepped structural surfaces (Bernatek-Jakiel et al., 2019). The valleys within the catchment area are largely filled by thick, massive and planar-bedded cohesive clayey silts, reaching a thickness of up to 8 m (Ferrer et al., 2017; Carreras, 2023). The top of this Holocene valley fill, deeply dissected by the Barreiro Creek and currently featuring active gullies, forms extensive and gently sloping aggradation terraces. Several other studies carried out in similar catchments of the central Ebro Valley (e.g., Constante et al., 2011; Peña-Monné et al., 2023) have demonstrated that sediment accumulation is a consequence of land cover changes, human-related fires, stockbreeding and cultivation since Neolithic times, and particularly during the Bronze and Iron Ages, until the end of the Roman Period. Afterwards, several incision and aggradation short periods led to the development of two terrace levels, as has been observed in the Barreiro catchment (Fig. 1B). Erosion processes have become strikingly relevant in this region, reaching its maximum development where Barreiro Creek and tributaries dissect the Holocene sediments valleys, which are rich in clay minerals, favouring soil erosion (including piping and gullying processes) and the development of badlands. The southern part of the valley fill displays a dramatic network of interrelated pipes, pinnacles and gullies, giving it the name Aguarales de Valpalmas. Los Aguarales exhibits a ruin-like landscape with prominent vertical slopes and pyramidal structures as a result of piping processes that can reach several meters in depth (i.e., >5 m). Renowned for its geological and geomorphological significance, this area was named as a Site of Geological Interest by the Aragón Government in 2015 (Fig. 1C).

From a climatological point of view, this is a semiarid area with an average annual precipitation of 526 mm, where precipitation is concentrated in short periods, mainly in spring and fall. The average annual temperature is 13 °C, which is equivalent to a continental Mediterranean climate (2005–2023 register at the R29-CHE meteorological station located 7 km from the study area).

The hillslopes display Rendzina Litosols, whereas Calcic-Rendzina Cambisols prevail in the footslopes (CNIG, 2007). Agriculture plays an important role in the area, which is dominated by unirrigated cereal crops. The life cycle of these crops implies a lack of soil protection over long periods of time, facilitating its deterioration and the infiltration of rainwater. Agricultural lands cover 25 % of the catchment area, 73 % are covered by shrublands, dominated by *Rosmarinus officinalis* and *Thymus vulgaris* (Ferrer et al., 2017), and 2 % are bare badlands.

3. Materials and methods

3.1. Archival aerial SfM and LiDAR datasets: Ortho photomosaics and point clouds

This work encompasses a study period of 64 years, covering five different study years: 1957, 1977, 1997, 2009 and 2021. The selection of the study years was determined by the availability and type of the datasets. Two types of data were obtained and analysed: orhthophotomosaics and point clouds. The former were obtained directly from the

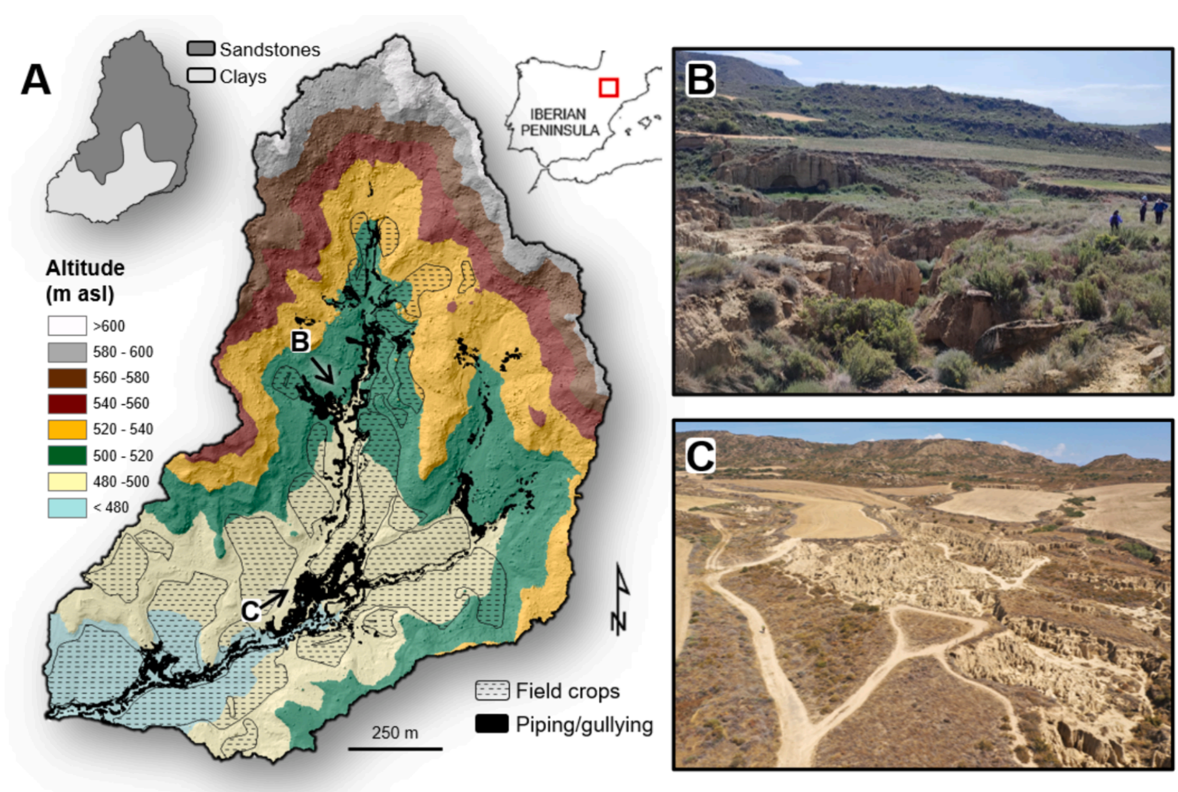

Fig. 1. Digital Elevation Model (DEM) of the study catchment together with field crops and piping/gullying affected areas marked within the context of the Iberian Peninsula. Note that field crops and piping extent correspond to year 2021. A. Main outcropping rocks in the study area. B. Landscape overview of an area affected by piping and gully erosion processes in the upper part of the catchment (Photo: M. Llena). C. Oblique aerial view of Aguarales de Valpalmas, a geomorph site located in the lower part of the study area (Photo: J. I. López-Moreno).

Table 1
Characteristics of archival aerial imagery and derived spatial datasets. Note: All data were obtained from the Spanish National Centre of Geographic Information (CNIG).

Year	Resolution (m)	Bands	Source	Point cloud density (pts m^{-2})	Error (m)
1957	0.50	Panchromatic	Americano Serie B	–	–
1977	0.30	Panchromatic	Interministerial	3.18	0.68
1997	1.00	Panchromatic	Olistat	–	–
2009	0.50	RGB	PNOA	0.75	0.35
2021	0.25	RGB	PNOA	1.25	0.25

Spanish National Centre of Geographic Information (CNIG) for all the study years, except for 1977 (Table 1). The latter orthophoto was obtained from the processing through historical-Structure from Motion (SfM) technique of the archival-aerial paired imagery (see Llena et al., 2018, and Llena and Vericat, 2023 for further details of this technique).

Additionally, point clouds were obtained for the 1977, 2009 and 2021 study years. 2009- and 2021-point clouds were obtained from the airborne-LiDAR surveys of the PNOA (CNIG), which have a spatial resolution of 0.75 and 1.25 points m^{-2} and an estimated root mean square error (RMSE) of 0.35 and 0.25 m respectively, obtained by comparing it to a validation dataset. A 1977-point cloud was obtained from the SfM processing of archival imagery available for this year, which results in a dataset with a resolution of 3.18 points m^{-2} and RMSE of 0.68 m (Table 1). Despite LiDAR datasets (2009, 2021) which were already classified thanks to the multiple-return classification, all the point clouds (1977, 2009, 2021) were filtered out, removing vegetation and noise points by using the classified LiDAR values together with the application of the Statistical Outlier Filter (SOR) algorithm (i.e., SOR) implemented in the software Cloud Compare v2.12.4 (Girardeau-Montaut, 2019).

Finally, Digital Elevation Models (DEM) of 1x1 m were obtained for the three study years (1977, 2009, 2021) after the decimation and regularization by means of the ToPCAT algorithm (Brasington et al., 2012). ToPCAT allows for the interrogation and analysis of observations within each grid cell. The minimum elevation within each grid was used to represent the ground elevation within each cell, while the detrended standard deviation was used as a proxy for surface roughness (e.g., Brasington et al., 2012; Vericat et al., 2014; Llena et al., 2020).

3.2. Mapping the evolution of field crops and their degradation

Field crops were manually mapped for each study year based on orthophotomaps and DEM-derived hillshade rasters, when available. Polygons were systematically mapped at the same scale (i.e., 1:1,500) for all the study years to avoid inconsistencies related to the spatial resolution. Despite this, a mapping uncertainty value of $\pm$ 1 m was assigned to digitalized polygons and their corresponding derived areas of change. Regarding the dynamics of agricultural land areas, their evolution over the study period was analysed by comparing consecutive field crop areas. Three classes of changes, all of which include agricultural and non-agricultural areas, were identified: (i) expansion, (ii) reduction, and (iii) no change (Fig. 2A).

Geomorphic changes were estimated by DEM of Difference (DoD) analysis performed on sequential DEMs obtained for the 1977, 2009 and 2021 study years (i.e., 1977–2009 and 2009–2021 DoDs). The uncertainty surrounding each DEM was associated with the point cloud errors (Table 1), then propagated to the DoD (Wheaton et al., 2010). A critical t-value, using an 80 % confidence interval, was then applied to these error surfaces to calculate the minimum level of detection (minLoD). Accordingly, DoD cells with absolute values below the minLoD were ruled out of the computation of the so-called threshold DoD. From these results it was possible to deduce erosion (degradation) and deposition (aggradation) processes (Fig. 2B). To minimize uncertainties, DoD maps were masked to the spatial extent occupied by field crops and areas affected by pipe collapse and gullying processes.

Identifying pipe collapse and gullying areas was achieved through a combination of image classification, slope analysis, and roughness assessment (e.g., Avcıoğlu et al., 2022). Initially, Unsupervised Image Classification based on ISO Clusters was employed to distinguish three classes of vegetation cover: bare areas, grass, and shrubs. On the one hand, grass (mainly composed by *Gramineae* and *Leguminae* species) refers to plants with a short life cycle that may appear in unstable areas such as those affected by piping collapses. On the other hand, shrubs (mainly made up of *Rosmarinus officinalis* and *Thymus vulgaris*) denotes woody and perennial plants with long life that are usually developed in more stable areas. Subsequently, slope and roughness of bare and grassy areas were used to delineate pipe collapses and gullying areas, using threshold values of 30° and 0.2 m, respectively. These thresholds were established based on the values extracted from expert mapping derived from a combination of high-resolution DEMs and orthophotomosaics, which were then validated by field work observations in approximately 1 ha (i.e., 14 %) of the piping/gullying affected area, and located between the 480–500 m asl elevation range (Fig. 1A). This classification approach enables a focused analysis of degradation processes concerning pipe collapse and gully erosion, isolating geomorphic changes within these areas, and examining their interaction with agricultural fields (Fig. 2C). It is worth mentioning that piping erosion primarily occurs underground, therefore, it poses certain challenges to the direct measurement of its magnitude. In this context, erosion rates attributed to piping and gullying processes, refer to the geomorphic changes resulting from pipe collapse, usually followed by rill and gully erosion processes. These rates serve as proxies for measuring piping erosion processes. We are aware that rill and gully erosion processes may also occur in areas that are not affected by pipe collapse. In the study area it is almost impossible to separate pipe collapse and gully erosion processes, as both of these processes occur simultaneously.

In order to better understand the relationship between pipe collapse and gullying erosion processes on croplands and its abandonment, the area and number of field crops affected by these processes were analysed as well as the area and the number of field crops abandoned.

3.3. Data analysis

The degree of agricultural abandonment within the study catchment over the chosen period was spatially represented using the occupation frequency of field crops. This was analysed using the variation of the field crops' positions in probability terms. The layers occupied by field crops in each survey were intersected, assigning a high frequency (i.e., 100 %) to areas consistently classified as field crops in all surveys. Probability decreased proportionally for pixels not consistently classified as occupied by an active field crop, indicating a lower probability (e.g., 25 %) and suggesting a short period of agricultural use, indicative of high abandonment.

To understand the main factors influencing the changes in agricultural fields, the interrelationships between these changes and potential triggers were analysed. Pearson's linear correlation testing was conducted across the polygons representing areal changes, comparing the occupation frequency of agricultural lands with morphometric characteristics (altitude, slope, and hydrological connectivity) and pipe collapse and gullying areas. Hydrological connectivity was modelled

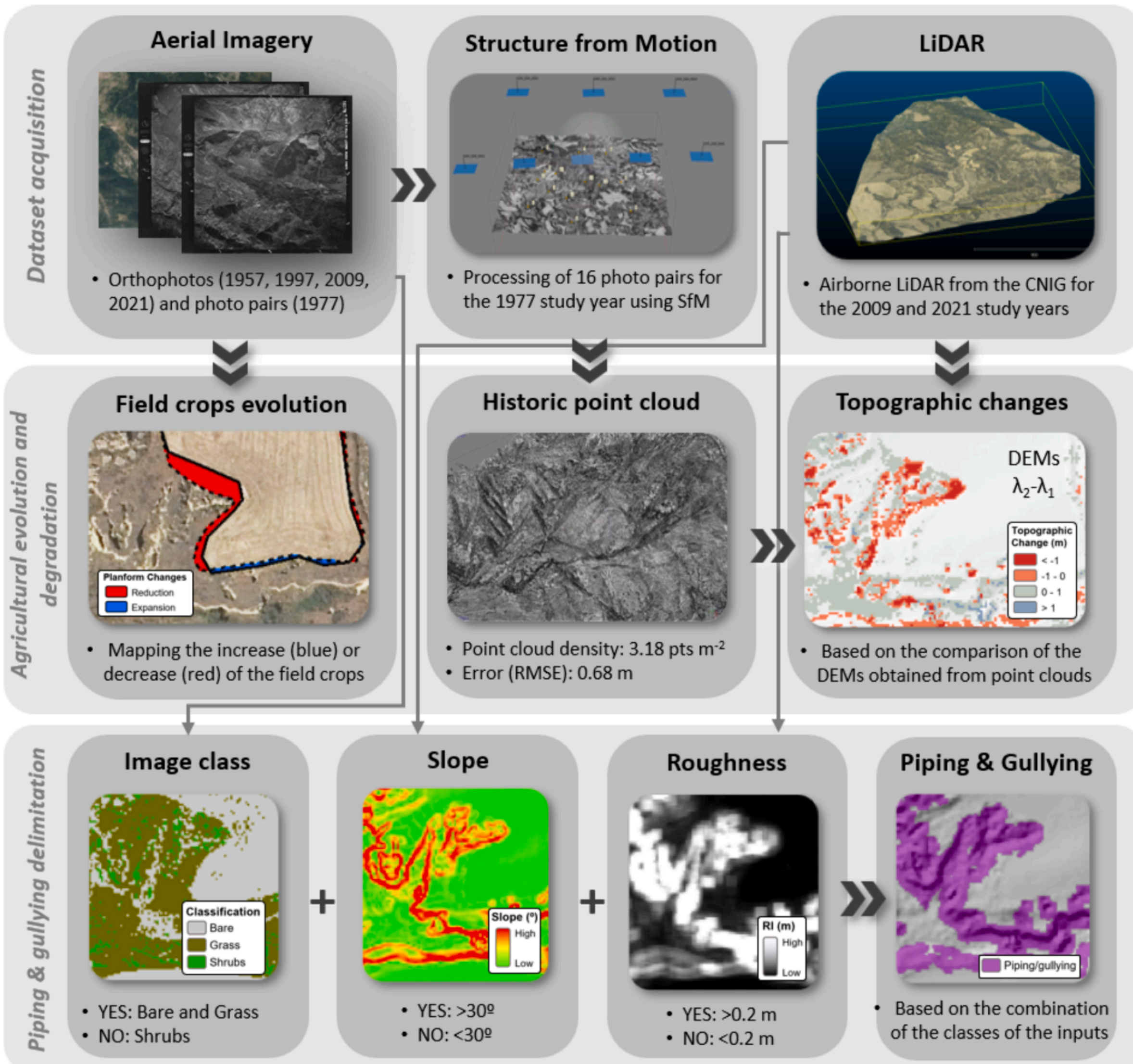

Fig. 2. Flow chart summarizing the entire methodological procedure, from the spatial datasets obtained from LiDAR and archival aerial imagery, agricultural evolution and degradation, and procedure to delimit pipe collapse and gullying processes from spatial inputs (i.e., Non-Supervised Classification, Slope, and Roughness).

using the Connectivity Index (IC) developed by Cavalli et al. (2013), based on the work of Borselli et al. (2008). The Index of Sediment Connectivity (IC) was computed using SedInConnect 2.3 (Crema and Cavalli, 2018).

4. Results

4.1. *Agricultural lands dynamics*

Table 2 represents the areas of agricultural fields for each study year, while Fig. 3A shows the distribution of these fields and Fig. 3B represents all fields overlapped within the study catchment. Overall, field crops underwent a net decrease in area during the study period, with the variations between years attributed to the dynamics of both a real reduction and expansion (Fig. 3 and Table 3). The loss of agricultural lands was particularly striking from 1957 to 1977, when a total of 4.86 ha of croplands were abandoned (i.e., 14 % of the entire agricultural land). The remaining periods did not show such a large reduction, although in all cases, the balance was negative: 0.32 ha were lost from 1977 to 1997 (i.e., 1 % of the entire agricultural land); 0.64 ha from 1997 to 2009 (i.e., 2 % of the entire agricultural land), and finally, 1.13 ha from 2009 to 2021 (i.e., 4 % of the entire agricultural land). Ultimately, when comparing the situation of agricultural lands during the entire study period (1957 and 2021), a loss of 6.96 ha of agricultural land was observed. Considering that the initial situation in 1957 was 35.20 ha, this loss represents up to 21 % of the initial surface area (Table 3). The number of field crops (Fig. 3B) also exhibited a negative trend, even steeper than the reduction of agricultural land area. From 1957 to 1977, the number of fields was drastically reduced from 66 to 35. Subsequently, between 1977 and 1997, it further decreased to 26

Table 2
Number (n) and size (total and mean area in ha) of the active field crops during the study years.

Year	Field crops		
	Total area (ha)	(n)	Mean area (ha)
1957	35.2	66	0.5
1977	30.4	35	0.9
1997	30.0	26	1.2
2009	29.4	26	1.1
2021	28.2	25	1.1

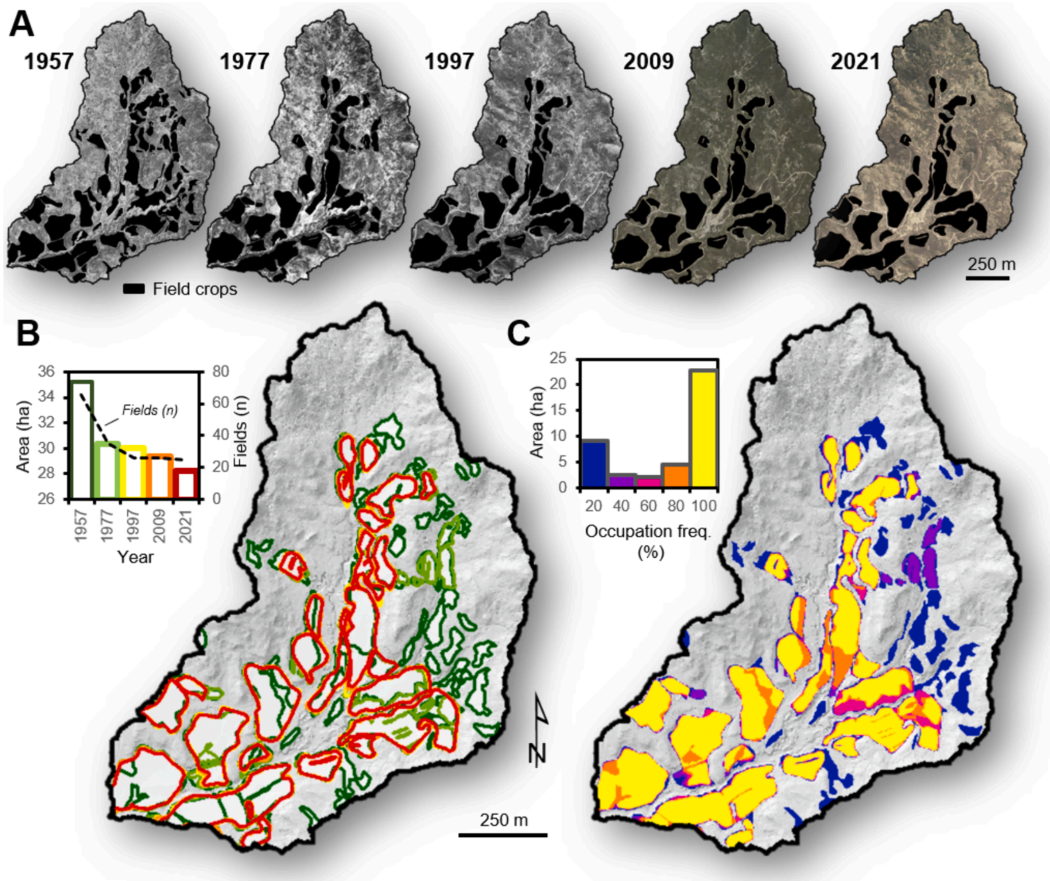

Fig. 3. A. Field crop polygons for each study year B. Overlapped field crop polygons for all the study years together with an associated area (colour bars) and number of field crops per year (dotted black line). C. Map of percentage of occupation frequency of the field crops throughout the entire study period (i.e., 100% of occupation time means that this area has been occupied by field crops throughout all of the study years).

Table 3
Planform changes of field crop including expansion, reduction, total change and net change.

Period	Reduction			Expansion			Total Change			Net Change		
	Absolute (ha)	%	Relative (ha/year)	Absolute (ha)	%	Relative (ha/year)	Absolute (ha)	%	Relative (ha/year)	Absolute (ha)	%	Relative (ha/year)
1957–1977	9.09	26	0.45	4.23	12	0.21	13.33	38	0.67	−4.86	14	−0.24
1977–1997	2.82	9	0.14	2.50	8	0.12	5.32	18	0.27	−0.32	1	−0.02
1997–2009	1.17	4	0.10	0.53	2	0.04	1.70	6	0.14	−0.64	2	−0.05
2009–2021	1.44	5	0.12	0.32	1	0.03	1.76	6	0.15	−1.13	4	−0.09

and remained relatively stable until 2021, with 25 field crops. The mean size of agricultural fields is a direct consequence of the area and number of fields. The mean size experienced a constant increase between 1957 and 1997, growing from 0.53 to 1.15 ha. After 1997, the mean size remained stable, i.e., 1.13 ha.

The occupation frequency (%) of agricultural lands throughout the study period in the entire catchment (Fig. 3C) did not exhibit a clear trend. Agricultural lands that remained active throughout all the study years occupy the most extensive area (22.74 ha), followed by those active during 20 % (9.12 ha), 80 % (4.63 ha), 40 % (2.58 ha), and 60 % (2.19 ha) of the study period. In terms of distribution, the agricultural lands that were consistently maintained are relatively large and they are located in the lower and flatter zones of the study area.

The analysis of planform changes in agricultural lands during the different study periods provides insights into the dynamics of field crops (Table 3 and Fig. 4). When planform changes are categorized by sign (i.e., reduction or expansion), the period 1957–1977 stands out with the highest values of change, both in absolute and relative terms. During this time span, the largest expansion of agricultural lands of the entire study period took place (4.23 ha), predominantly concentrated in the lower and more accessible areas of the catchment. As inferred from the 1957 aerial imagery, these areas were previously highly affected by pipe collapses and gullying processes. The reduction during this period had a larger magnitude (9.09 ha) than expansion, resulting in a clear negative net change (−4.86 ha). The main reduction during 1957–1977 was attributed to the abandonment of small field crops, mostly located in the upper and steeper parts of the study catchment (e.g., Fig. 4C). Even though, during 1977–1997, the second-largest reduction and expansion of agricultural lands occurred (2.82 and 2.50 ha respectively), the similar magnitudes of these changes resulted in the smallest net change of the entire study period (0.32 ha). The main reduction areas observed in this period corresponded to the abandoned fields in the highermost part of the catchment, along with a reduction of field size in the rest of the catchment, especially those in contact with areas affected by pipe collapse and gully erosion. Similarly to 1957–1977, expansion areas corresponded to the increase of field crops in the lower parts of the study

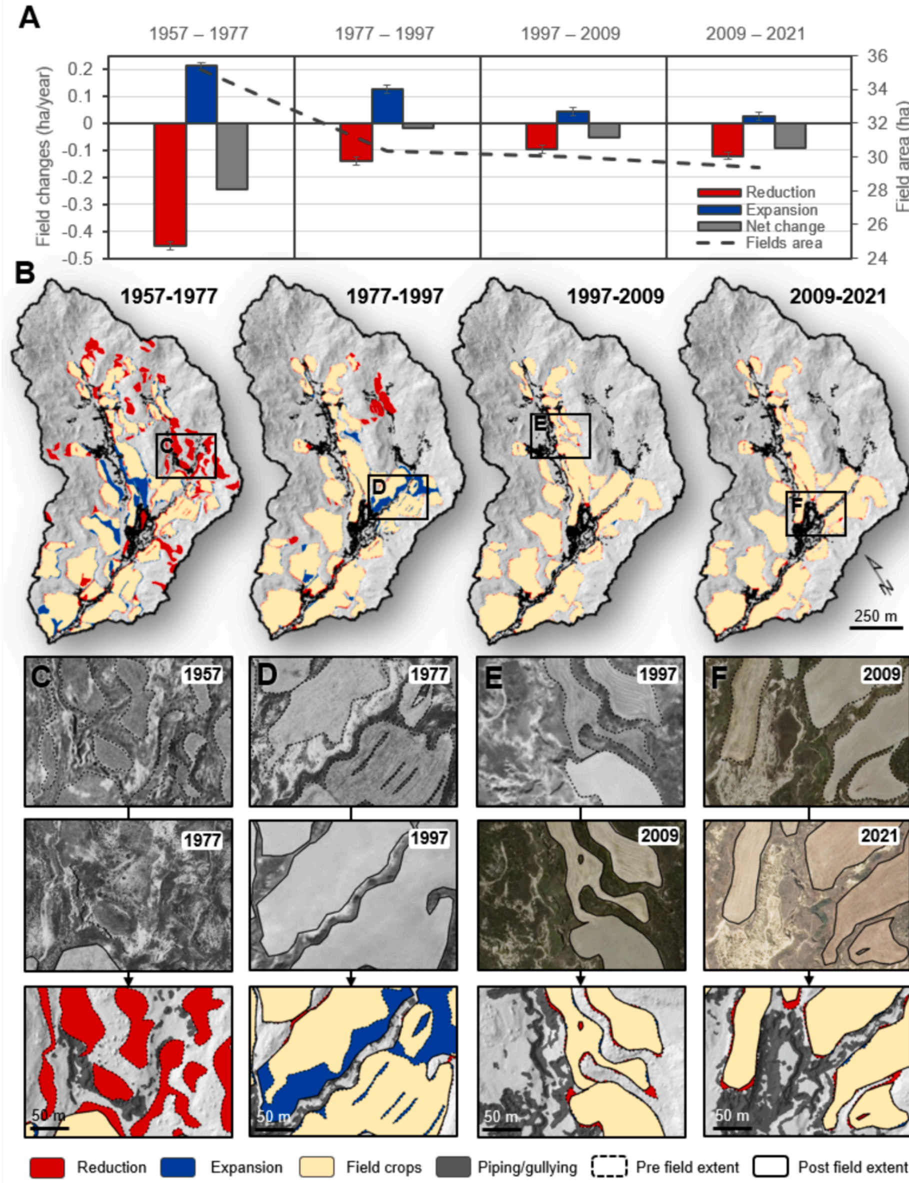

Fig. 4. A. Planform evolution of field crops during the different study periods together with field crops area. B. Spatial evolution of planform changes within the entire study area together with zooms of four selected examples (C, D, E, F) for each study period.

area (e.g., Fig. 4D) driven by: i) regained and stabilized areas from zones previously affected by pipe collapse and gullying; and ii) parcel concentration of crop fields, gaining space from previously non-agricultural areas (e.g., shrublands). Periods 1997–2009 and 2009–2021 exhibited a similar evolution in terms of agricultural land dynamics. In both periods, the reduction of agricultural lands was limited to the direct effects of pipe collapse and gullying processes (e.g., Fig. 4E and Fig. 4F), continually eroding crop fields. Timid efforts to recover these areas represent a slight expansion of agricultural lands (0.53 and 0.32 ha respectively), which was insufficient to compensate the reduction caused by pipe collapse and gully erosion. Consequently, the net changes were negative in both periods (−0.64 and −1.13 ha respectively; Table 3).

4.2. Soil degradation due to pipe collapse and gully development inferred from topographic changes

Collectively, within the pipe collapses and gullying areas, the area occupied by topographic changes above the minLoD (i.e., median value of 0.59 m) accounts for ~37 % and ~21 % (i.e., 27.04 and 15.45 ha) from 1977 to 2009 and 2009–2021 periods, respectively. 64 % and 63 %

Table 4
Absolute and relative volume changes within piping and gullying areas, segmented into erosion, sedimentation, total change, and net change.

Period	Erosion		Sedimentation		Total Change		Net Change	
	Absolute (10^4 m^3)	Relative (10^4 m^3 ha^{-1})	Absolute (10^4 m^3)	Relative (10^4 m^3 ha^{-1})	Absolute (10^4 m^3)	Relative (10^4 m^3 ha^{-1})	Absolute (10^4 m^3)	Relative (10^4 m^3 ha^{-1})
1977–2009	3.462	0.015	1.695	0.002	5.157	0.017	−1.767	−0.013
2009–2021	1.409	0.010	0.496	0.002	1.905	0.012	−0.913	−0.007

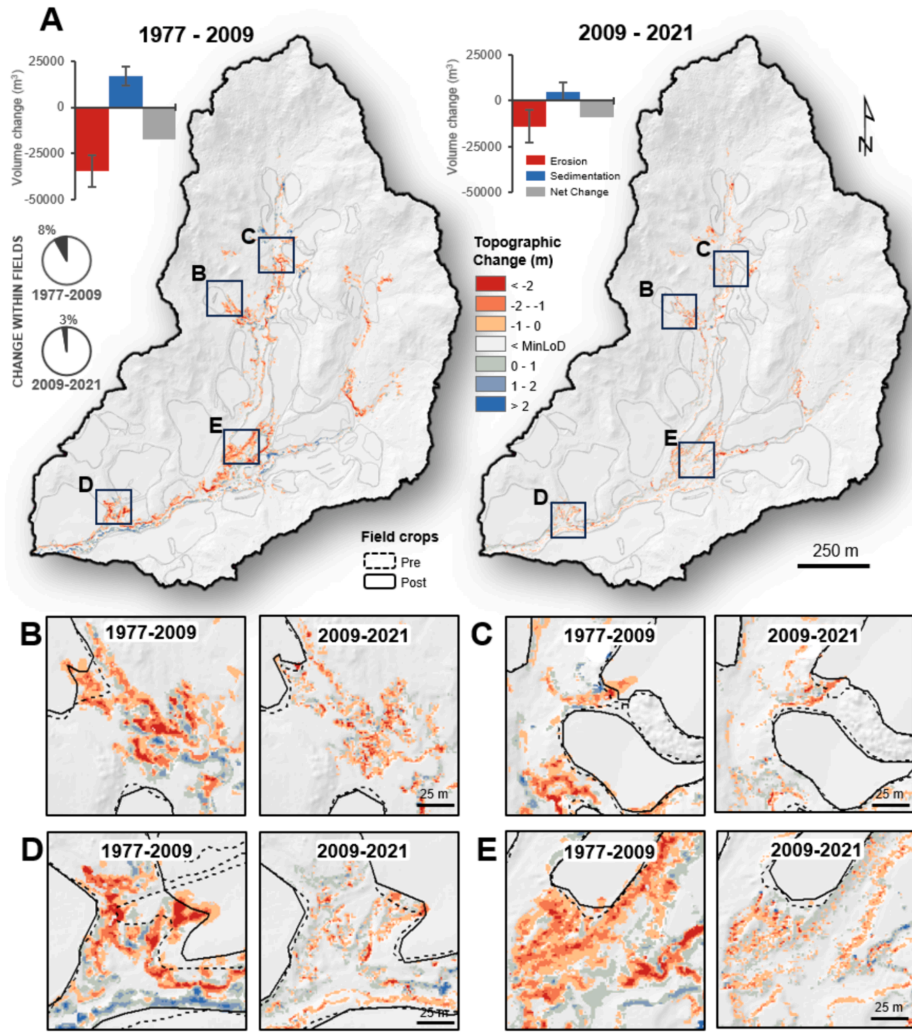

Fig. 5. A. DoD (i.e., DEMs of Difference) maps within areas affected by pipe collapse and gully erosion along with field crops polygons, overall volumetric change budget (i.e., bar charts), and the percentage of total change within agricultural lands (i.e., pie charts) for each study period with available topographic data (i.e., 1977–2009 and 2009–2021). Panels B–E detail zoomed-in areas of DoDs within the study catchment for both study periods, showing examples of land degradation associated with pipe collapses and gullying processes.

of these areas are associated with erosion (i.e., topographic degradation) and the remaining 36 % and 37 % with sedimentation (i.e., topographic aggradation) processes. In volumetric terms (Table 4 and Fig. 5)., erosion (3.462 and 1.409 · 10^4 m^3) dominates sedimentation (1.695 and 0.496 · 10^4 m^3) in both periods, yielding a net negative balance of −1.767 and −0.913 · 10^4 m^3, respectively (Table 4 and Fig. 5). When volumetric changes are standardized by area, topographic changes exhibit similar values in terms of erosion (0.015 and 0.010 · 10^4 m^3) and sedimentation (0.002 and 0.002 · 10^4 m^3) in both study periods (Table 4). This indicates that the magnitude of geomorphic changes associated with pipe collapses and gullying processes follows a constant volume of change throughout the study period with available topographic data (i.e., 1977–2021).

Topographic changes within the pipe collapse and gullying areas follow a clustered spatial distribution in terms of altitude for both the 1977–2009 and 2009–2021 study periods. The primary pipe collapse and gullying processes occur between 480 and 520 m a.s.l., where there are expansive clay outcrops due to upstream hydrological erosion in the zones with the greatest flow accumulation (Fig. 5). Within these areas, the main mechanisms responsible for geomorphic changes were associated with pipe collapse and headward erosion. Collapsing pipes were manifested as both isolated failures of pipe roofing within the lateral layers, and as wall collapses of large packages of these strata due to undercutting caused by piping (e.g., Fig. 6A). These vertical collapses may appear secondary to rotational and planar slides (e.g., Fig. 6D), exceeding 2 m of erosion (e.g., Fig. 5E), and occasionally up to 5 m. In most cases, after pipe collapse, headward erosion occurs due to knickpoint migration (e.g., Fig. 5D and Fig. 6B), which can exceed 3 m of erosion at certain points. As a consequence of these processes, a chaotic landscape emerges, characterized by collapsing pipes, gullies, and rills, which are often separated by isolated pinnacles (e.g., Fig. 6B and Fig. 6C). It is worth mentioning that, following erosion processes caused by either mass wasting or water flow, aggradation may occur due to the deposition of these eroded materials, which could potentially be rapidly removed after a significant rainfall event.

The volume change associated with pipe collapse and gully erosion within the agricultural areas accounts for only 8 % and 3 % of the total change volume associated with these processes throughout the entire study catchment, respectively (Fig. 5). Despite this, when normalized by a surface of field crops, pipe collapses and gully erosion processes are responsible for a net degradation of −0.41 and −0.09 · 10^4 m^3/ha (Table 4), representing −0.013 and −0.007 · 10^4 m^3/ha/year (−127 and −75 m^3/ha/year), respectively.

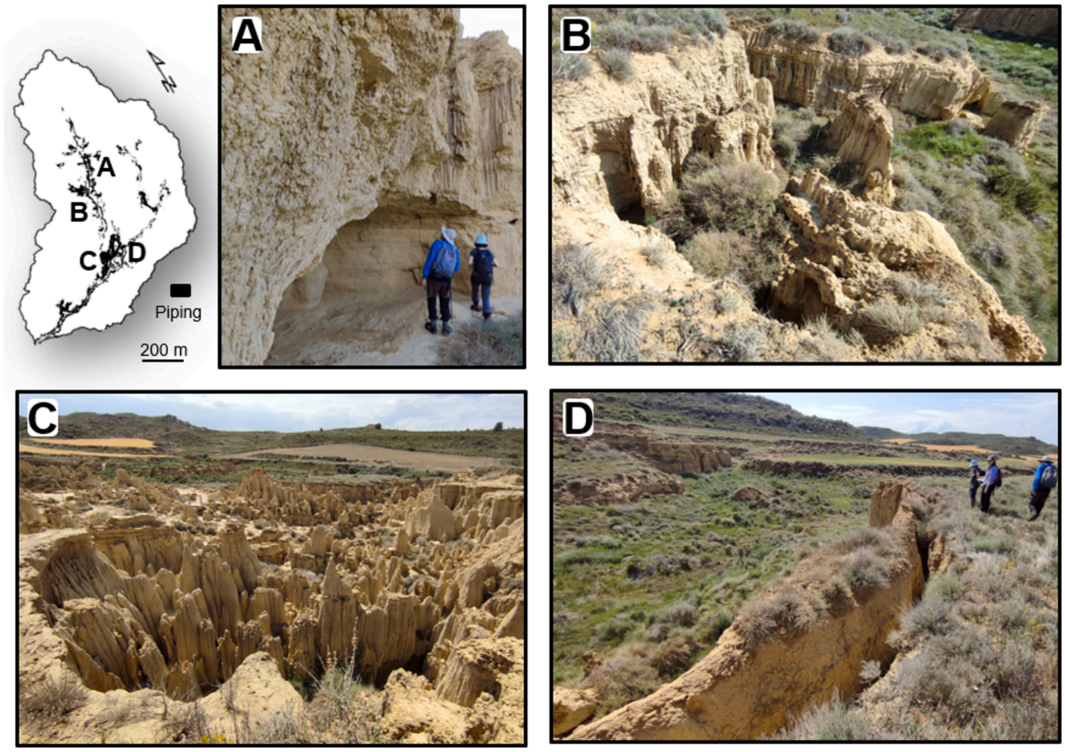

Fig. 6. Field work photos showing some examples of soil degradation resulting from piping and gullying processes within the study area. A. Undercutting of sediment strata walls caused by piping. B. Headward migration and planar slides resulting from pipe collapse and upstream erosion. C. Piping landscape characterized by gullies and rills separated by isolated pinnacles. D. Top view of a planar slide triggered by piping undercutting at the border of the highest terrace. The two terrace levels represented in the catchment can be observed (Photos: M. Llena).

4.3. Morphometric drivers of agricultural abandonment

As stated in Section 4.1. Agricultural land dynamics, agricultural land abandonment is related to some morphometric characteristics of the landscape. When considering occupation frequency of field crops throughout the entire study period, we observe high linear correlations between this and elevation, slope, hydrological connectivity, and pipe collapse and gullying areas. The occupation frequency of agricultural lands decreases as the median elevation, slope, connectivity (IC), and piping/gullying surface of fields crops increase (Fig. 7).

The impact of pipe collapses and gullying processes on agricultural fields is evident. Fig. 8 displays, for each study period, the relation between piping/gullying areas and both i) the affected agricultural surface (Fig. 8A); and ii) agricultural abandonment (Fig. 8B). The percentage of the total cropland area affected by pipe collapses and gullying processes clearly tends to decrease over the study period, from almost 4 % of the area affected in 1957 to 0.2 % in 2021. The number of active agricultural fields follows the same downward trend, decreasing from 66 % to 26 % between 1957 and 1997, and then remaining relatively stable until 2021, when it slightly decreased to 25 %. When analysing the impact of piping/gullying within abandoned areas, a clear increase in the areas affected by piping/gullying can be observed between 1957 and 2009, rising from 10 % to 15 %, respectively. However, during the period 2009–2021, there was a slight decrease to 12 %. On the contrary, the number of abandoned field crops showed a dramatic decrease, from 31 % in 1957–1977 to there being no abandoned field crops in 1977–1997. Then, from 2009 to 2021 one single field crop was abandoned (Fig. 8B).

5. Discussion

5.1. Rural abandonment vs land degradation

Mediterranean mountain areas and semi-arid environments make up the regions with the largest number of abandoned lands, where soil degradation processes are most pronounced. In semi-arid areas, land abandonment has occurred due to the low productivity of rain-fed fields on steep hillslopes, irregular rainfall patterns, frequent heavy rainfall events, and poor, shallow soils. De Baets et al. (2013) identified areas of land abandonment in Sierra de los Filabres (SE Spain), where the percentage of cropland decreased from 70 % of the total studied area in 1957 to 3 % in 2007. Boix-Fayos et al. (2007) estimated that rain-fed agriculture decreased by approximately 25 % in the La Rogativa catchment (SE, Spain) from 1956 to 1981, and by around 45 % from 1956 to 1997. The connectivity between agricultural areas also decreased during this period, resulting in highly disconnected agricultural patches. Similarly, Nainggolan et al. (2012) analysed land abandonment processes over 50 years in Torrealvilla (SE Spain) noting that cereal cultivation occupied about 26 % of the area in 1956, which had then decreased to 17 % by 2018. In this case, expansion was observed between 1956 and 1986 due to an increase in irrigated areas or the expansion of tree cultivation.

Outwith the Iberian Peninsula, other rain-fed agricultural areas followed a similar abandonment trend during the 20th century (e.g., Queiroz et al., 2014; Lasanta et al., 2017; Levers et al., 2018). For instance, Petanidou et al. (2008) reported a reduction of around 30 % in cultivated land and 35 % in animal units during the second half of the 20th century on the Nisyros Island (Greece), while Sluiter and de Jong

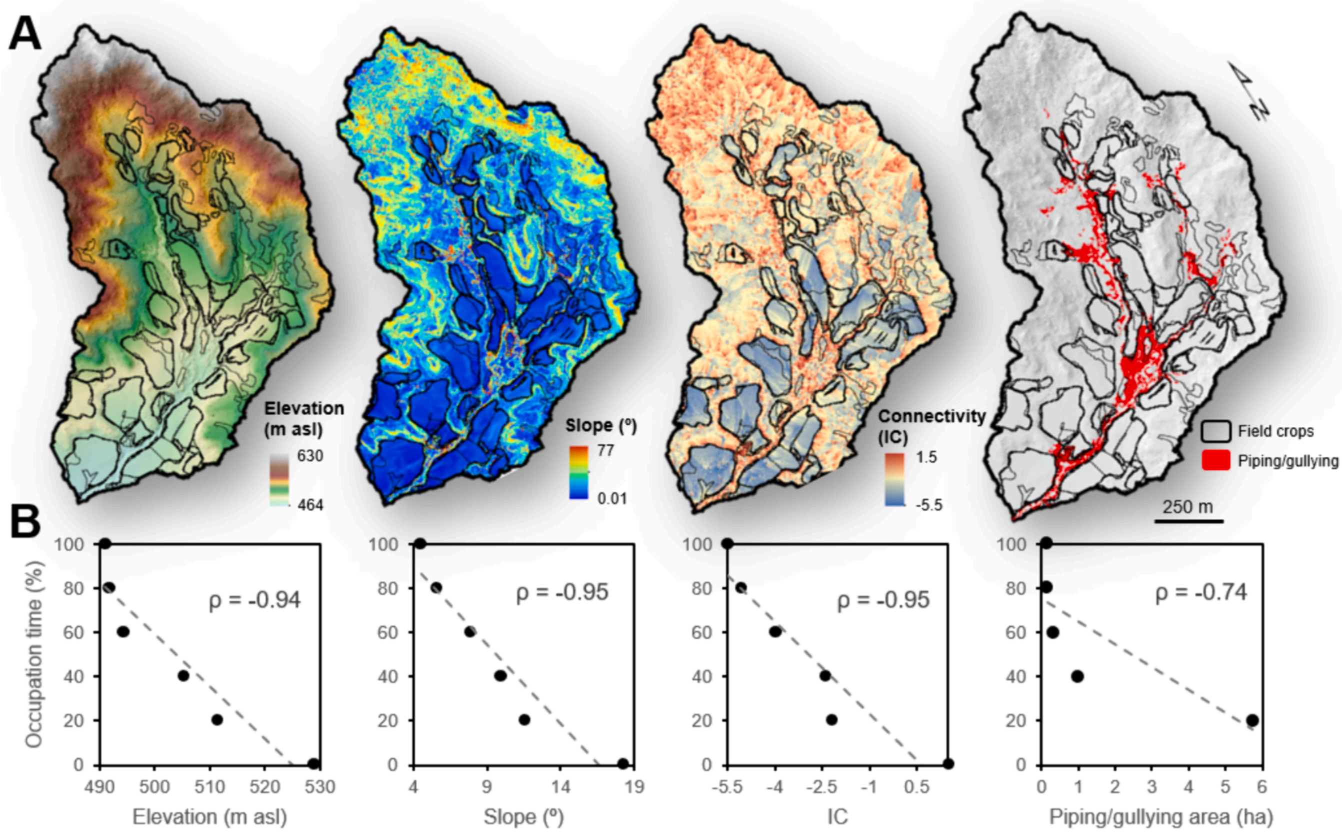

Fig. 7. A. Maps of Elevation (DEM), Slope, Hydrological Connectivity (IC index) and piping/gullying areas (marked in red) overlapped with field crop polygons (marked as polygons with black contour) for all the study years. B. Scatter plots as a function of map variables (A) and occupation frequency (%) of field crops during the entire study period. ρ values indicate Pearson's linear correlation coefficients. Note that each point refers to the mean value of the map variable within each occupation polygon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

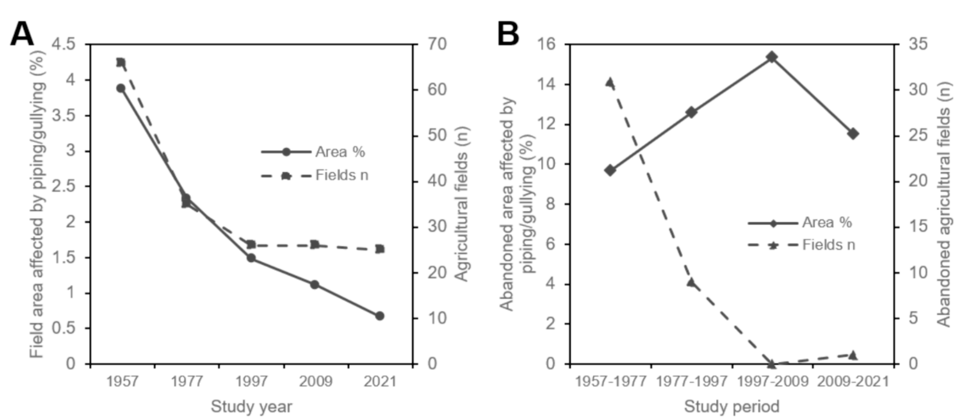

Fig. 8. A. Percentage offield crop area affected by pipe collapses and gullying processes (primary vertical axis) together with the number of agricultural fields per each study year (secondary vertical axis). B. Percentage of abandoned area affected by pipe collapse and gullying processes (primary vertical axis) together with the number of abandoned agricultural fields per each study period (secondary vertical axis).

(2007) documented land abandonment of around 40 % in an area within Mediterranean France. In the present study, the most extensive period of abandonment was recorded from 1957 to 1977 (i.e., 14 % reduction), coinciding with the main abandonment period in other mountainous and semi-arid Mediterranean areas. Throughout the entire study period (1957–2020), around 20 % of cultivated land has been abandoned. However, the mean size of cultivated fields has likely increased due to the expansion of cultivation activities in more favourable locations and a slight concentration of land (see Fig. 4). This trend aligns with observations in other rain-fed Mediterranean areas throughout the second half of the 20th century (e.g., Esgalhado et al., 2021; Heider et al., 2021), indicating a significant increase in land concentration driven by historical reforms and socio-economic transformations in agricultural practices.

Previous research has demonstrated that abandoned fields in semi-arid areas are highly vulnerable to soil erosion processes (i.e. Lesschen et al., 2008). In these regions, land abandonment exacerbates soil cracking, facilitates infiltration channels, increases subsurface runoff and erosion, and leads to the formation of complex gully networks. Soil degradation may also be linked to grazing livestock on these abandoned fields. Piping erosion, particularly in arid and semi-arid regions, is recognized as a significant cause of land degradation. While piping in semi-arid cultivated landscapes is generally perceived as a consequence of land abandonment in piping-prone settings (e.g., Romero-Díaz et al., 2007), pipe formation may precede the cessation of cultivation. This can ultimately lead to land abandonment due to maintenance issues and irreversible soil degradation (see Fig. 4, Fig. 5 and Fig. 7). In cereal fields, such as those cultivated in the study catchment, small and incipient pipes are typically destroyed by annual ploughing. Despite this fact, in some cases, agricultural practices enhance gully and pipe formation in fields due to movement of the surface layer of the soil, which, in turn, exposes the bedrock formed by dispersive clays. This becomes weathered and undergoes erosion processes due to piping and gullying (e.g., Linares et al., 2002; Faulkner et al., 2003). In any case, pipe collapses increased over time, causing farmers to be forced to reduce the size of their fields (see Fig. 9A and Fig. 9B). Moreover, large pipe collapse started to be transformed by other surface erosional processes, which often results in the formation of large gullies. Similarly, agricultural fields not directly impacted by pipe collapses experience indirect effects when their access, such as roads, is affected by pipe collapse (see Fig. 9C). After land abandonment, pipe collapse and subsequent surface erosion processes, like gully erosion, accelerate, resulting in larger pipe collapse and gullies on abandoned fields, rendering them more likely to remain permanently abandoned (see Fig. 9D). Consequently, land abandonment exacerbates piping processes, gully development and overall land degradation.

Soil susceptibility to pipe formation depends not only on soil characteristics but also on the history of soil management and land use and land cover practices. However, few studies have examined the relationship and evolution of soil pipes with land use history. Holden (2006) concluded that land management was the most important control regarding soil pipe distribution in peatlands (UK). The spatial distribution of pipes in the study catchment was not uniform, as pipe collapse is concentrated in flat alluvial plains, close to the banks (i.e.., gully and valley banks). As stated by Liu et al. (2021) in their extensive review, initiation position of gully erosion occurs along shallow drainage ways (rills), adjacent to incised streams and gullies at the edge of fields, or where subsurface soil pipes have collapsed. Similar results regarding piping distribution have been reported worldwide, with most subsurface studies focusing on abandoned lands located in low and moderate gradient landscapes (Romero-Díaz et al., 2007; Moreno-de-las-Heras et al., 2019; Chen et al., 2022). For instance, Zhang and Wilson (2013) noted the irregular distribution of pipe collapse, with slope gradients being less than 1° for 92 % of the collapses, and less than 2° for 99 %. Similarly, Pereyra et al. (2020) identified pipe collapse in agricultural fields with slope gradients between 1 % and 3 %. Kariminejad et al. (2019) indicated that slope is one of the most important factors contributing to pipe collapse, with steep and uncultivated slopes being the most susceptible to piping erosion since they result in a higher topographic gradient. Wilson et al. (2008) underlined the need for sufficient slope gradient that may produce critical hydraulic gradient, so the preferential flow may start. It seems that the hydraulic gradient, needed to cause preferential flow, may be caused by high slope gradients or by earth banks, such as agricultural terraces, lynchets and sunken lane banks (e.g., Poesen et al., 1996; Romero-Díaz et al., 2007). Climate also plays a significant role in pipe collapse and gully erosion; for instance, higher intensity and volume of rainfall increase the occurrence of these events (e.g., Liu et al., 2021). In this study, Fig. 7 illustrates the correlations between morphometric characteristics and field abandonment. Thus, the highest and steepest fields were the first to be abandoned. Similarly, areas with a larger piping extension and with a higher structural hydrological connectivity were also the first abandoned. Pipe collapse fragment the landscape into smaller segments due to water infiltration through pipe holes, thereby reducing the slope length factor for sheet and rill erosion, which, in turn, affects hydrological connectivity within the catchment (Fig. 7).

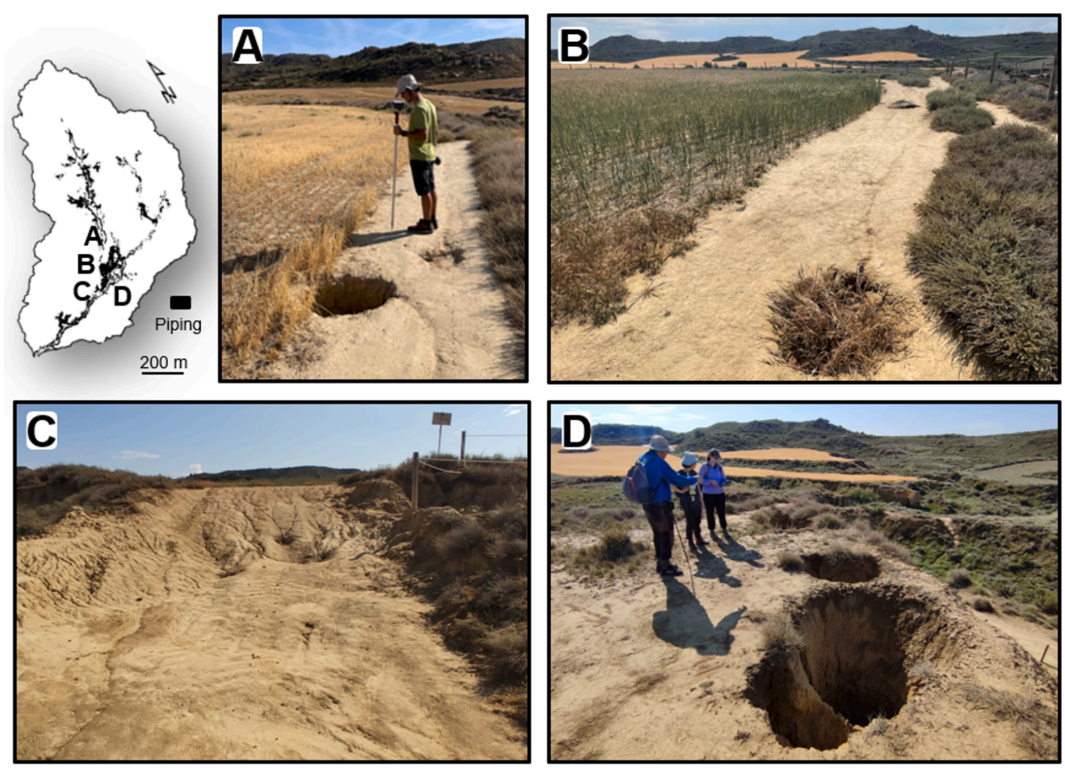

Fig. 9. Field work photos of different phases of pipe collapse affecting agricultural fields within the study area. A-B. Pipe collapse directly affecting field crops. Note that the collapse showed in A occurred after cereal sowing. C. Incipient pipe collapse affecting access to a crop field. Note that this road was repaired several times after previous collapses (Photos: E. Nadal-Romero). D. Two piping collapses within an old field crop that was abandoned between the 1957 and 1977 study years (Photo: M. Llena).

Looking at the impact of pipe collapse on croplands over the study period (Fig. 8), it can be observed that pipe collapse and subsequent gully erosion affect up to 80 % of the fields, while these erosive processes are directly responsible (direct degradation) for up to 15 % of the total abandoned area. This percentage can increase considerably and indirectly, for example, due to the pipe collapse on the access to fields located in more remote areas, whether by other croplands or specific roads (Fig. 9C). This highlights that, although pipe collapse and gully erosion cannot explain the entirety of the abandonment, they exert greater control and have a more direct effect on agricultural abandonment than changes in land management in the study area, such as abandonment of fields that are at higher elevations, on steeper slopes and more difficult to access. Abandonment caused by soil erosion processes occurs in areas of higher agricultural value because they are located in valley bottoms, which are flatter and more productive lands.

5.2. Impact of piping erosion on agriculture and society

Piping erosion processes pose threats to land productivity and food security by converting productive land into unproductive land. They also jeopardize agricultural sustainability, soil nutrient loads, and can destabilize socio-economic conditions, particularly in agricultural lands. Verachtert et al. (2011) provided a review of soil loss in piping-affected environments. In temperate regions (primarily loess-derived soils), piping erosion yields higher values than those observed due to surface erosion. This study has discovered that the average annual soil loss ranges from 2.3 to 4.6 Mg ha^{-1} yr^{-1}, which is an order of magnitude greater than the soil loss resulting from surface water erosion under the same land use conditions (Verachtert et al., 2011). Bernatek-Jakiel et al. (2017) reported soil loss due to piping up to three orders of magnitude higher than loss due to sheet and rill erosion in grasslands with temperate climate. Piping erosion and soil loss are more intense in semiarid and arid environments. Lesschen et al. (2008) estimated soil loss from bench terraces in SE Spain with mean erosion rates of ~ 87 Mg/ha yr^{-1}. Higher values were recorded in piping-prone areas: Romero-Díaz et al. (2009) obtained around 287 Mg/ha yr^{-1}, while in the present study, erosion rates vary between 203.2 Mg/ha yr^{-1} and 120 Mg/ha yr^{-1} for the periods 1977–2009 and 2009–2021 respectively.

Soil erosion caused by water on cultivated land results in a range of on-site, as well as off-site, damage and problems, and is regarded as the most serious threat to food production. On-site costs, predominantly borne by farmers, include declines in productivity and loss of farming areas. However, it has been noted that assessing the economic consequences of these on-site effects is challenging (García-Ruiz et al., 2017). At European level, Panagos et al. (2018) estimated economic losses of around 1.25 billion € due to the decline in land productivity. In Valpalmas, the largest abandoned surface area was recorded during the initial study period (1957–1977), with approximately 20 % of the cultivated land being abandoned over the entire period. Considering that the price of rain-fed cultivated area is estimated, by the Ministry of Finance for the Spanish Government (2023,) to be around 2,500€ ha^{-1}, and accounting for the loss of 7 ha during the total period, the economic loss due to land abandonment is around 17,400€ in the catchment of 124 ha. In addition, based on production estimates for rain-fed lands and current prices of barley and wheat (typical crops in the study area), it has been estimated that the loss is around 5,000 € yr^{-1}, representing approximately 25 % of the total present gross income.

Extrapolating soil piping impacts to other aspects of the environment and society, Bernatek-Jakiel and Nadal-Romero (2022) identified possible new areas in the research of soil piping in relation to: (i) natural hazards, (ii) carbon cycle, (iii) biodiversity and (iv) geodiversity heritage. In relation to this last point, soil piping is recognized as a significant geomorphic process contributing to global geodiversity. Geotourism serves as an excellent platform for educating people on geomorphology, including surface and subsurface soil erosion processes, with geosites or geomorphosites as a basis of such tourism activities (Reynard et al., 2011; Coratza and De Waele, 2012, Zgłobicki et al., 2019). Despite the socio-economic and land degradation problems, it is important to note that within the Valpalmas catchment, the Aguarales Badlands area was classified as a Site of Geological Interest by the Aragón Government in 2015. These badlands have high geotourism potential and constitute a significant element of the tourism development strategy. Despite the loss of agricultural land and soil erosion, the badlands, located in the lower part of the catchment, serve a protective, scientific, educational and tourist function. Hypothetically, the benefit provided by the Aguarales at local level outweighs the costs associated with soil degradation processes, especially in low-productive rain-fed areas like the study area. An economic study on these variables would be necessary to quantitatively corroborate this hypothesis.

To date, it is the first time that archive-SfM techniques have been applied to quantify soil loss due to subsurface erosion. Despite its limitations in terms of spatial resolution and precision (Llena and Vericat, 2023), this method allows for the reconstruction of historical topography from which it was possible to infer geomorphic changes and soil degradation processes. In contrast, spatial datasets obtained from airborne LiDAR surveys have better resolution and precision, allowing for a more reliable representation of the topographic surface. However, as some authors have already demonstrated (e.g., Bernatek-Jakiel and Jakiel, 2021), this method still has limitations when it comes to representing the internal part of collapses, pipes, tunnels, or even very vertical walls. Further studies will focus on the development of methodological tools to understand geomorphological processes and quantify soil losses in Los Aguarales badlands, characterized by ruiniform and chaotic badlands landscape that merits further exploration and understanding (see Ferrer et al., 2017; Llena et al., 2023).

6. Conclusions

This study has shown the effects of pipe collapse and gully erosion on agricultural land abandonment in a semiarid Mediterranean area in a context of LULC changes. The abandonment trajectory of agricultural lands in the Barreiro catchment (Ebro Basin) was reconstructed from archival SfM and LiDAR datasets. The study site offers the opportunity to analyse and disentangle the impact of both pipe collapse and gully erosion together with LULC changes on land degradation and agricultural abandonment throughout the prolonged study period (1957–2020). Methodologically, archival aerial imagery has allowed us to analyse the planform dynamics of agricultural fields, while historical-SfM and LiDAR datasets permit us to study pipe collapse and gullying areas and degradation reconstruction right through the different phases of the study period. Such datasets available for long study periods (since 1950) have a unique value when surmising long-term changes of land use affected by soil erosion processes.

Within the study basin, an area of agricultural lands goes through a clear reduction throughout the study period (i.e., 21 %). Abandonment is correlated with morphometric variables; such as altitude, slope and connectivity (IC), which may respond to a driving force of LULC change, as in the rest of the Mediterranean region. Abandonment is also significantly correlated with the extent of areas affected by pipe collapses and gully erosion, which are responsible for soil degradation of up to 165.1 Mg/ha yr^{-1}, affecting up to 80 % of the agricultural fields. Despite pipe collapse and gully erosion directly affecting 15 % of the total abandoned area, its impact on access routes is indirectly responsible for the abandonment of other fields. In the same way, due to its characteristics, pipe collapse erosion took place adjacent to the lower and flatter areas of the catchment, affecting directly the more productive lands. Thus, this study confirms that agricultural abandonment in the chosen area is mainly conditioned by land degradation that occurred due to pipe collapse processes and gully development.

Despite the economic losses associated with land abandonment conditioned by pipe collapses and gully erosion (total loss of land counted as 17,400€, loss of income from cereal sale is around 5,000 €

yr^{-1}), the study site has reinvented itself as a geomorphosite now under institutional protection. This ruinform landscape has been transformed into a local attraction (*Los Aguarales de Valpalmas*) that allows for diversifying and expanding economic activity within the municipality. Pending further tourism and economic studies, the adaptation followed in the present case study could be extrapolated to other areas of the world experiencing similar magnitudes of piping and gully erosion or areas of degradation with geomorphological interest.

CRediT authorship contribution statement

M. Llena: Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **S. Carreras:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **A. Bernatek-Jakiel:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **A. Ollero:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **E. Nadal-Romero:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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