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Submission of revised manuscript on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" (hess-2016-239)

Dear Editor,
Dear Prof. Nunzio Romano

Herewith we would like to submit the revised version of our manuscript on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" by A. Hayas, T. Vanwalleghem, A. Laguna, A. Peña, and J. V. Giráldez (hess-2016-239) for publication in Hydrology and Earth System Sciences.

We have adapted all the final comments by the four Anonymous referees and would like to thank you deeply for the large amount of time the reviewers and yourself invested in the thorough review of our paper.
We have included the final version without and with track changes so that the reviewers can clearly identify the changes.
Please note that the point-to-point reply to the reviewers has been posted in the online discussion (AC 1 to 4).

Sincerely yours,

On behalf of the authors,
Antonio Hayas

Interactive comment on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" by Antonio Hayas *et al.*

Referee #1

This paper is a great topic and a novel approach to understanding dynamics through extrapolation and quantification of uncertainty through Monte Carlo. The detailed network mapping is impressive. However, the field sample sizes are fairly small, and a bit of a concern for understanding true field variability. More emphasis could be put on field interpretation of geomorphic processes and channel evolution, to match better with observations and extrapolation from air photo interpretation and generalized land use metrics.

Moderate revisions are recommended to correct some misunderstandings and also more importantly bring out the underlying geomorphic processes that could be operating in this catchment.

Moderate Comments There is nothing overly special about Mediterranean climates and gully erosion. Other areas of the globe with highly variable rainfall also have gullies. Perhaps downplay the Mediterranean climate emphasis or compare to other areas of the globe. Soils and geology and topography are also big factors with gully erosion.

We appreciate the encouraging comments of the Reviewer. We agree with the observation about the emphasis on the Mediterranean conditions. Therefore we have changed the text where such references were made:

-abstract, we deleted *especially*, leaving the sentence as *Gully erosion is an important erosive process in Mediterranean basins*
-The sentence of page 1 lines 1-3 has been rewritten as:

Understanding gully erosion dynamics under changing land use and climate conditions is essential for soil and water conservation

-Also on page 2 line 30-33 we have deleted the reference to Mediterranean climates:

Under different climates, especially where rainfall is less uniform and more concentrated in time

Page 2 Line 17 Focus more on field empirical data and methods of other authors, as models you review here do not really help estimate gully volumes at the catchment scale. Are there more references you can cite that use your methods of estimating gully volume from remote measurements of width and length, and field measurements of depth? And then the use of m Carlo simulation to extrapolate from small sample sizes of 35 and 27?

We have performed an additional literature search and have located several additional references on this topic, although most are on local and not regional scales. The study by Nachtergaele and Poesen (1999) uses a similar methodology, where gully cross sections are measured in the field, while gully length is extracted from aerial photos.

With respect to the use of Monte Carlo simulations in gully erosion research, this is relatively novel to our knowledge, so we found no references on this topic, irrespective of sample size. Further on, we have replied in more detail to the issue of sample. However, Istanbulluoglu *et al.* (2002) used a similar Monte Carlo approach to estimate channel incision locations in a catchment of about the same size as ours. For the different input parameters they have between 19-25 field measurements (see their Table 1), which they use to fit a theoretical probability distribution, similar to our method.

We have deleted:

More research will be needed in order to develop full three-dimensional models, capable of accurately predicting gully erosion volumes

We have included more references related to field empirical data in page 2, Line 20:

Different methodologies, apart from traditional field measurements with total station, laser profilemeters and poles (Castillo et al., 2012), have been proposed and successfully applied to estimate gully volumes. For instance, at the individual gully scale, 3D reconstruction from high resolution aerial photography and digital photogrammetry has been widely applied (e.g. Marzolff and Poesen, 2009). Recently, terrestrial imagery modelling and Structure from Motion-Multi View Stereo (SfM-MVS) procedures have also been used to determine *gully volumes (Gómez-Gutiérrez et al. 2014; Frankl et al., 2015 and Castillo et al., 2015). Terrestrial LiDAR has been applied to measure rills or gullies at both laboratory and plot scale (Vinci et al.,2016; Momm et al., 2011, 2012). Nevertheless, at the catchment scale, the number of studies is limited. At this scale, most studies focus on the areal extension of gully networks, using aerial photos or other remotely sensed imagery. Few studies report gully volumes, due to the inherent difficulties of determining depths for the whole gully network. Nachtergaele and Poesen (1999) determined gully length from aerial photos and by additional field measurements they established a mean cross section to calculate volumes of small ephemeral gullies in the Belgian loess belt. Martínez-Casasnovas (2000) mapped and quantified the erosion produced in a gully systems of big dimensions by processing multitemporal orthophotograms and DEMs in a GIS for a 25 km2 catchment located in NE Spain. Frankl et al. (2011) used sequential photographs to link long-term gully and river dynamics to environmental change in Northern Ethiopia. More recently, Peter et al. (2014) used UAVs and photogrammetric analysis to quantify gully erosion, albeit at local scale in the Souss Basin (Morocco).*

Page 2 Line 70 See recent paper by Shellberg *et al.* 2016 in Geomorphology as an example on the rates and dynamics of gully erosion pre- and post European settlement in Australia... and over long time periods. Many other examples around the world too.

We have modified Line 72 to include a new citation:

Also Shellberg et al. (2016) observed an increase in the gully erosion by the changes in the land use produced by post-European settlement in the Mitchell River fluvial megafan (Queensland, Australia). This relationship between pioneers and gully erosion was previously suggested by Leopold (1924) in the US.

Page 3 Line 48 What were the various scales that these air photos were originally collected at? Could differences in scales influence the accuracy of results between years, even with the working scale for measurement was set at 1:5000? Also, the data gas between 1956 and 1980 and 1984 and 1999 are large, compared to the other years. It would be good to highlight the dynamic uncertainty more for these years, as this data limit the ability for "high temporal resolution" analysis. Use the high resolution years for discussion if uncertainty in other years.

The scales of the air photos have been added to Table 1.

We believe scales do not influence the accuracy in our case. Our results on gully network evolution and drainage density for the years 1956 and 1980 (fig. 7) suggest that differences between scales (in this particular case) are not significant for our purpose. If scale differences were causing an impact on the accuracy of our results, a lower drainage density in 1956 than in 1980 could be expected, since the original scale of the air photos, *flight scales*, in 1956 and 1980 are, respectively, 1:33,000 and 1:18,000. The respective restitution scales vary between 1:10,000 and 1:5,000. However, our results show a different trend. This trend could be attributed to the frequent infilling operations favoured by the advent of the tractor in the middle of the decade of 1960-70. In addition, the large majority of the gully sections surpass widely the minimum raster resolution in the orthophotos (1 m), suggesting that the uncertainty is limited.

We agree that these 1956-1980 and 1984-1999 periods are longer and are aware of the limitations. We have noted this already in the Discussion section, on page 6 line 77-82:

However, given the length of this periods and since there are some particular years (i.e. 1961-1962) with extreme rainfalls it is likely that positive gully growth occurred during this period that was later masked by infilling.

We have added to this discussion:

This shows that longer periods, such as 1956-1980 and 1984-1999, are subject to a higher uncertainty with respect to the post-1999 period, when a higher temporal resolution is available.

Page 3 Line 74 Were these 35 stretches the same as the 27 sections visited below? If not, why were not the 35 stretches visited in the field to confirm measurements from air photos? There seems to be a mismatch here/

No, these 35 and 27 sections are not always the same. The sections used in the orthophoto interpretation (n=35) were established first. Afterwards, during the field truthing, some of the sections had to be moved due to practical limitations, but maintaining the essential morphological characteristics since the gully sections were

proximal. Practical limitations include accessibility, but mostly the alteration of gully sections due to farmer operations. Therefore, we always aimed to measure an undisturbed gully cross section.
To clarify this to the reader, we changed page 3, line 79:
Gully top width and depth were measured at 27 representative sections that were located as close as possible to the 35 sections used in the photointerpretation

Page 3 Line 74 Are there more references you can cite that use your methods of estimating gully volume from remote measurements of width and length, and field measurements of depth? And then the use of Carlo simulation to extrapolate from small sample sizes of 35 and 27? Will also need more convincing of the readers that 27 or 35 sample points are enough to extrapolate to a 20 km^2 catchment.

With regard to similar references, see our previous comment, we have added more references such as Frankl *et al.* (2011) which determined gully erosion from oblique photos and Nachtergaele and Poesen (1999) who used field measurements of gully sections in combination with gully length derived from aerial photos.

We added to the text page 3, line 85:

This methodology of combining photointerpretation with field measurements of gully morphology is similar to Nachtergaele and Poesen (1999).

With regard to the reduced number of sample points commented by the Reviewer, we are aware of this limitation. However, the objective of the Monte Carlo method is exactly to reduce the number of observations and avoid having to measure the cross section of each gully section. We do think that the gathered information is enough to develop a Monte Carlo method. Hammersley and Handscomb (1964, section 1.1) appositely explain that one of the reasons for adopting such a method is the inherent difficulty and high economic cost to get field information. In any case, the Monte Carlo simulates in the area occupied by gullies, not the entire catchment, which is less than a 5% of the total catchment area (20 km^2). As noted above, Istanbulluoglu *et al.* (2002) used a similar Monte Carlo approach to estimate channel incision locations in a catchment of about the same size as ours. For the different input parameters they have a similar amount of field measurements, between 19-25 (see their Table 1), which they use to fit a theoretical probability distribution, similar to our method. As long as the field measurements allow to characterize the probability distribution function (pdf) of the variable in question, we are confident that the Monte Carlo method gives a reliable estimate of the uncertainty. We believe that the results shown in Table 4, where we quote the fit between the observations and the theoretically fitted pdfs, with p-values of 0.64-0.98 demonstrate the good fit of these relations.

We have added to the discussion section some more explanation on this topic at page 7 line 39:

Although more field measurements of gully sections would be advantageous in order to reduce uncertainty, time and money spent on ground truthing will increase accordingly. However, the high p-values of 0.64-0.98 obtained here for the fit between the theoretical probability distribution function and the experimental data suggests satisfactory results can be obtained, even with a limited field sample. Moreover, also Istanbulluoglu et al. (2002) successfully used a Monte Carlo approach to estimate gully incision locations using a similar amount of field data.

Page 5 Line 1 Is this % of total catchment area? or % of all land uses? Or just % of occupied land by humans?

The comment is correct. In all cases we refer to total catchment area. Therefore to reduce the ambiguity of the terminology the sentences of lines 1 to 6 in page 5 have been modified as follows:

In the study period, olive orchards grew from 13% to 63% of the total catchment area. At the same time herbaceous crops decreased from 85% to 35% of the total catchment area. The main land use change occurred between 1984 and 1999, when the olive orchards passed from occupying 25% to 48% of the total catchment area.

Page 5 Line 64 Was there a correlation between farmer infilling and levelling activity during one period with an increase in erosion during the next period? That is, a lag effect of the influence of actual machine disturbance on gully erosion and perhaps water yield. Generally if you disturb a gully, it will erode faster for a while into the future until it settles back down.

We totally agree with this comment. This was also demonstrated by Gordon *et al.* (2008) who obtained much higher erosion rates for infilled gullies compared to gullies left alone. However, we cannot appreciate a clear correlation after a close inspection of our data, shown in the figures 6 and 13. Intense land use change between the photographs of 2005 and 2007 was followed by only a moderate gully erosion phase in the 2007-2009 period. Only in 2009-2011 gully erosion rate increased significantly, due to extreme rainfalls in this period. In other periods, as for instance 1984 - 1999 land use changes were more intense. However in the next period (1999-2001), erosion rates were negative.

We have included this now in the discussion, page 6 line 82:

It could also be expected that infilling phases were followed by phases of higher erosion rates. Gordon et al. (2008) obtained higher erosion rates from periodically infilled gullies compared to gullies that were left undisturbed. However, our results do not show such a trend. For example, land use change and infilling between 2005 and 2007 was followed by only a moderate gully erosion phase in the 2007-2009 period.

Page 5 Line 73 This is a key hypothesis, and needs to be brought out more here and in discussion, as you say that extreme rainfall is the dominant variable, but you do not have any other data on land use besides just % area covered, and thus do not have a metric that links runoff accelerated by land use to gully erosion.

It is true that more research on this issue is needed, we are currently investigating the effect of olive roots versus cereal roots on gully incision rates. At this point, the main conclusion that we draw from our data is the importance of rainfall. However, with the cited paragraph, we wanted to indicate that land use could play a secondary role to lower the resilience of the system. This is explained further in a following comment where we include the reviewers comments on thresholds.

We have added some more explanation on this in the Discussion section page 7 line 15:

Gioia et al. (2008) stressed the importance of different runoff thresholds to explain flood occurrence in the Mediterranean areas. Ordinary flows are produced when rainfall rate exceeds the infiltration rate of the soil in a small area, a typical case of Hortonian runoff generation, or Hortonian threshold, while what Gioia et al. (2008) denominated outlier events, occurred when the water of almost continuous rain spells surpassed the storage capacity of the soil in a large area of the catchments, extreme rainfalls for explaining the runoff behaviour of catchment, or Dunnean threshold. This behavior is similar to the complex response to the geomorphic thresholds discussed by Patton and Schumm (1975)

Our data seems to indicate that land use did not play a dominant role, although we cannot exclude that land use changes to olives and soil management have lowered the resilience towards gully incision.

Page 6 Line 27 Could this be partially due to the higher quality and resolution of air photo data late in the period? Mismatch of data sources here for these different periods.

We do not believe there is a quality or resolution effect at play here. The air photos of 2005, 2007 and 2009 present a similar quality and resolution. If this were a quality effect, we would expect a gully volume increase already in 2005. However, we do not observe such increase. Nonetheless if we look at the standardized annual rainfall (fig. 4) we see that rainfall in those periods have been below the average, which seems to corroborate our hypothesis that gully growth is conditioned by rainfall.

Page 6 Line 37 ha of total catchment area? Or ha of total gully area? ton or tonnes? which units? Metric or English? This is an issue through the paper.

We understand that the terminology used could be ambiguous. Units used through the paper are referred to the metric system. “ton” have been replaced by “t” all through the paper. We always refer to ha of total catchment area, never calculated with respect to gully area.

Line 36 in page 6 has been modified as follows:

Dynamics of gully erosion rate referred to the total catchment area are shown in Figure 13.

Page 6 Line 53 again, are these yields based on total catchment area or gully area? That is, are the gully rates averaged across the whole catchment area?

No, gully erosion rates cited here are reported with respect to the total catchment area.
Line 46 to 47 has been modified to clarify this point:

The average gully erosion rate of 39.7 t $ha^{-1} yr^{-1}$ *for the total catchment area obtained in this study, ...*

Correction in Line 54 to refer it to the total catchment area:

The highest gully erosion rate of 331 t ha-1 yr-1 referred to its catchment was found ...

Page 6 Line 84 Many of us in the world would consider Mediterranean Climate a type of Temperate Climate. Under the Koppen climate classification system, a Mediterranean climate is a type of the temperate climate group ("C" climates). Please expand more or change terms and classification. Maybe deemphasize the climate variable and talk more about soils and geology, and the build-up of colluvium/alluvial soils and then their release during major events and gully erosion.

The Reviewer is right, again. Both climates are temperate, what makes very unfortunate the sentence. Using the revised version of the Köppen-Geiger world climate types of Peel et al. 2007, we are rewritten the sentences in the text. We agree and have modified the original version, Line 83 now says:

Moreover, the data presented here clearly show than in Mediterranean-climate areas (Csa type in the Köppen classification) the gully growth dynamics are different than in Temperate Oceanic west-European areas (Cfb type) for instance.

And now Line 89 says:

Data for this study was from the Temperate Oceanic (Cfbn type) loess belt...

Page 6 Line 91 See recent paper by Shellberg et al. 2016 in Australia on continued near linear increases of gully erosion over time in highly erodible soils.

We appreciate the suggestion and consequently the reference has been included in the text:

This observation is not unique since in other environment Shellberg et al. (2016) have detected an almost continuous increasing trend in the gullies of the Mitchell River in Queensland.

Page 6 Line 103 Dams often decrease sediment yields and can create incision in main channels, and thus rejuvenate tributary systems. You cannot discount this without some references or data for overall channel stability in the catchment. Also over long time periods, most catchments are in a degradation state, and thus maybe you are in some part of a bigger cycle? No doubt human land use has also increased erosion. Plenty of references there. But is it from upstream or downstream impacts and controls, or both?

In a broader geomorphological context, the main Guadalquivir channel is in an incision stage. However, since the 1956 many new dams were constructed that control the stream dynamics. Although it is true that dams induce complex upstream and downstream impacts, in this particular case there are no dams upstream which could create incision in the main channels due to sediment deprivation. There is only a downstream base level control due to the dam, limiting any incision effect in the main channel network of our catchment.

We have added some more discussion on this on page 6 line 100:

progressive increase on the erosion rate. During the Quaternary, the main Guadalquivir River is in an incision stage due to base level fall. However, this incision has been slow, as demonstrated by Uribelarrea and Benito (2008), who found evidence of a 1.2 m incision over the last 500 years. In any case, since the 1950-60s, when many dams were constructed, the Guadalquivir is a highly regulated river. Such dams are known to have both a downstream incision effect due to removal of sediment load, and an upstream aggradation effect. With respect to our study area, there are no upstream but only downstream dams. Therefore, it is expected that the influence of the incision stage has been artificially limited in this catchment since the 1950s and that the observed changes in the gully network can be fully attributed to upstream changes in rainfall or land use regime.

Page 7 Line 37 How would this uncertainty be reduced if you had much more field data. 40 data points is a small sample size to be sure you have calculated uncertainty correctly.

See previous comments. This is difficult to know without measuring more profiles. We considered that in our study zone this data is enough since it comprises the whole range of widths present in the area and their frequency could be considered representative from that in the study zone. Although, we understand that more field data could be desirable, it is difficult to obtain more field data (due limit access to parcels, time and expenses limitations) which motivates the Monte Carlo simulation.

Page 7 Line 54 Please do not recommend more modelling. Field measurement is essential to understand gully dynamics. Or Repeat airborne LiDAR. or small scale terrestrial lidar.

We agree that field measurement is essential. We have modified the final version to not emphasise modelling in Line 54.
...further research of runoff, gully headcut retreat rates, and sidewall dynamics should be made at this last point

Page 7 Line 67. again, need field measurements not models to understand these dynamics.

As expressed above, we also acknowledge that field measurements are essential to improve our understanding on gully erosion, but this information needs to be inserted in a structure which help us to interpret how gullies start and evolve. Line 67 has been modified:

Further studies with more field data are needed to improve ...

Line 68 has been modified as well:

Implementation of physically-based models of gully retreat rates and sidewall collapse as well as more field measurements and interviews of local farmers on soil management practice could contribute to a better understanding...

Page 9 Figure 1 Figure 1 needs to be improved. The stream map shows not much. Perhaps this would be a great place to show the high resolution air photos so we can see what the landscape and land use looks like? Some field photos of gullies and land use would be really useful for the geomorphic reader. Page 10 Table 1 What about scale? 1:50000 etc...

Figure 1 has been reformed to inform better about the study site. The original scale of the aerial photos has been included in the new version of Table1.

Page 13 Figure 10 Were these from the field measurements at the 40 sites or from extrapolated estimates?

Figure 10 shows width dynamics obtained from the photointerpretation-measured widths. Caption has been modified to make it clear:

Gully top widths dynamics in the period 1956 - 2013 derived by measuring by photointerpretation.

Page 14 Figure 12 This is a major increase in gully volume. If real it shows a major permanent shift and increase in erosion.. Perhaps a threshold was reached due to intrinsic variables like sediment storage in valleys, or land use or rainfall, or combination. See threshold complex response by Schumm. Shellberg 2016 also has a decent literature review on the subject, as well as Tucker in USA.

This is an apposite observation. Certainly the threshold complex response is a common characteristic of natural phenomena. See the answer to the comments of Page 5 Line 73.

Page 15 Table 2 Should not crops just be used for crops, pasture for grazing, and dense scrub-land for not grazed or cropped areas? Are there only two simplified classes or 3?

This was an error carried on in the version of the manuscript used by the reviewer, not in the version appearing in the Journal web page (http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-239/hess-2016-239.pdf). The error was corrected in the final version. Pasture, dense scrubland, streams and natural watercourses and agricultural buildings and farms are grouped in a third class called “Other land use” since they comprise less than 5% of the total catchment area.

Minor Comments There are many grammatical English errors in the document, which is understandable for multiple-language speakers. There are too many errors to list here one-by-one, but a PDF of the original document is included/attached with "sticky-note" locations with grammar issues or suggestions.

We thanks the corrections of the Reviewer, completing a new grammatical revision of the manuscript.

Many paragraphs spaces are need to help flow of text.

We revised this point as well.

Interactive comment on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" by Antonio Hayas *et al.*

Referee #2

The manuscript describes work performed to quantitatively estimate gully geomorphologic dynamics under Mediterranean conditions. A series of historical aerial photographs were used to estimate gully channel length measurements throughout the catchment and gully channel width measurements at selected locations. Gully depths and widths were also measured during field surveys. Statistical procedures were developed to simulate volumes and erosion rates based on measured lengths, widths, and depths values. The measured and simulated gully network geomorphological dynamics were contrasted to rainfall patterns and land use/land cover temporal changes. This is an important topic that deservers attention from the scientific community. I am very appreciative to the authors? efforts to devote time and resources to study gully dynamics. The main contribution of this work is the development of a procedure to combine two-dimensional measurements from historical aerial photographs with three dimensional measurements from field surveys. This is especially important due to the expected increase in field surveys as result of recent technological advances in UAVs and photogrammetric software and hardware. The work also points to the relationship between irregular climate patterns and the respective channel network geomorphological response, an ever-growing concern given projected climatic changes.

Additionally, findings of this study shed light on the need for improved gully theoretical framework specifically developed to simulate gully formation, evolution, persistence, and, more importantly, contribution to soil degradation. This sought new theoretical framework should be able to capture local conditions represented by varying dominant energy regimes (incision, head-cut migration, and channel side-walls lateral expansion) at different environments.

I found that the manuscript reads well, the figures are adequate, and the use of the English language to be appropriate. I also found the topic to be relevant and inline with the scope of the Hydrology and Earth Systems Sciences journal.

My only suggestions are:

Figure 1. Add the locations of the cross-sections.

Maybe add an additional figure with photographs depicting selected locations. This would enhance the visualization from the reader of what Mediterranean conditions look like.

We appreciate the positive evaluation. We have incorporated two new figures, and have modified Fig. 1 to inclue cross-sections locations.

Interactive comment on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" by Antonio Hayas *et al.*

Referee #3

This is a valuable contribution, but one that could be improved by teasing out some of the realtionships as far as possible. There seem to be at least three development processes for the gullies: 1)Once started gullies tend to grow by positive feedback (as they gather collecting area)until they consume the source area. These gullies seem to be approaching this state in the south, but less so in the north. 2) Gullies grow in major events, and fill between them. Can the rainfall element be modelled, roughly, by summing a function of rainfall events for each interval [e.g. (rain-threshold) or a power of it)] to try and tease out the effect of the land use element. 3) Residual element may be due to land use (is it uniform over the area ?), which might change the threshold beyond which gullies expand. It is perhaps too much to hope that this can be rigorously carried through, but discussing the problem in these terms would greatly enhance the value and wider applicability of the research.

We appreciate the interest of the Reviewer for the manuscript. The observations are very attractive. We have tried to discuss the main traits of the gully network evolution in the comments to Fig. 9, in section 3.3. We have included the interesting observation about the difference between gully evolution in the south and north. Nevertheless we keep the idea to search for a more complete relation between gully evolution, rainfall, and land use by means of an explicit model for further research. For the time being we believe the idea too complex to include in this study and it would be better suited for a new, separate study.

We hace included a sentence in this section:

There seeems to be a greater increase in the south compared to the north, which suggests a more stable condition in the latter.

Also an additional discussion on land use and rainfall effects in section 4:

Gioia et al. (2008) stressed the importance of different runoff thresholds to explain flood occurrence in the Mediterranean areas. Ordinary flows are produced when rainfall rate exceeds the infiltration rate of the soil in a small area, a typical case of Hortonian runoff generation, or Hortonian threshold, while what Gioia et al. (2008) denominated outlier events, occurred when the water of almost continuous rain spells surpassed the storage capacity of the soil in a large area of the catchments, or Dunnean threshold. This behavior is similar to the complex response to the geomorphic thresholds discussed by Patton and Schumm (1975).

Interactive comment on "Reconstructing long-term gully dynamics in Mediterranean agricultural areas" by Antonio Hayas *et al.*

Referee #4

General comments

This paper is a very interesting study of gully erosion in a wide agricultural area, cultivated with important crops. Information from a wide time period is analyzed. The scientific questions addressed are within the scope of HESS. The complexity of gully erosion phenomenon in agricultural areas is highlighted and discussed in detail. The Monte Carlo-based approach proposed for reconstructing gully erosion rates from orthophotos is original and helps to get the most of the available information. The paper is well written and both methodology and analysis of the results are correct. Thus, the paper could be published after moderate revision.

We thank Referee #4 for his time in reviewing this manuscript and for his positive feedback.

Specific comments

Introduction is particularly good: concise but including all the key aspects, with well selected and suitable references. It would be desirable to explain in more detail the degree of representativeness of the selected study area.

We appreciate the positive evaluation of the introduction. In terms of representativeness, this area is typical for agricultural landscapes in Southern Spain, both in terms of topography, crops, as geology:

-The area is typical of the rolling landscapes of the Guadalquivir river valley (57 000 km^2), called "Campiña" (more explanation on this term and its extension can be found in Spanish- on https://es.wikipedia.org/wiki/Depresi%C3%B3n_del_Guadalquivir). The mean slope of our study area is 13%. The mean slope of all olive orchards in Southern Spain is between 8 and 16% according to official reports (Consejería de Agricultura y Pesca, 2002. El olivar andaluz).

- Main crops in our study area are herbaceous crops and olives. For Andalucía (S Spain), herbaceous crops and olives are respectively the 3rd and 1st most important crops, together covering almost 50% of the agricultural surface area. They are not just representative for Southern Spain, but also at the national level. According to a classification based on CORINE data, herbaceous crops and permanent crops (olives) are respectively the 1st and 4th most frequent crops (38.6% and 14.2% of the total agricultural area in Spain). Olives are probably one of the most typical crops of Mediterranean hilly areas in general.

-Geology and soil type are typical for the rolling landscapes of the Guadalquivir river valley, or Betic depression, where Vertisols are dominant. Vertisols occupy 9% of the total land surface of Southern Spain (Andalucía region) and possibly a much higher percentage of the agricultural soils (no estimate available).

Therefore, we expect that the observed gully dynamics are representative for other areas of the Guadalquivir or Betic depression.

We have added a more detailed explanation on the representativeness of our area to the manuscript, at the end of paragraph 2.1:

The study area can therefore be considered representative for agricultural landscapes in Southern Spain in terms of land use, topography and geology. Herbaceous crops and olives cover almost 50% of the total agricultural surface area of Southern Spain. Large parts of the Guadalquivir depression are characterized by rolling hills, geomorphologically similar to our study area, and similar soils dominated by clays and marls.

P5. "In order to measure gully width in a representative way, 35 stretches were selected: : :". "Gully top width and depth were measured at 27 representative sections: : :" It seems to me that the number of measurements of these key variables is too low. Please, justify.

This is an excellent question and was also raised by reviewer 1. However, we argue that the amount of measurements is not too low as it is specifically the objective of the Monte Carlo technique to diminish the number of observations in order to optimize sampling cost and time.

Really the central question is to what extent we can correctly characterize the probability distribution functions (pdf) of those key geomorphic parameters. Our own data and a similar study by Istanbulluoglu *et al.* (2002) indicate that the number of observations made should be enough to adequately represent the pdfs. We have added explanation in the text to clarify this issue (see also reply to Referee #1):

With regard to the reduced number of sample points commented by the Reviewer, we are aware of this limitation.

However, the objective of the Monte Carlo method is exactly to reduce the number of observations and avoid having to measure the cross section of each gully section. We do think that the gathered information is enough to develop a Monte Carlo method. Hammersley and Handscomb (1964, section 1.1) appositely explain that one of the reasons for adopting such a method is the inherent difficulty and high economic cost to get field information. In any case, the Monte Carlo simulates in the area occupied by gullies, not the entire catchment, which is less than a 5% of the total catchment area (20 km2). As noted above, Istanbulluoglu et al. (2002) used a similar Monte Carlo approach to estimate channel incision locations in a catchment of about the same size as ours. For the different input parameters they have a similar amount of field measurements, between 19-25 (see their Table 1), which they use to fit a theoretical probability distribution, similar to our method. As long as the field measurements allow to characterize the probability distribution function (pdf) of the variable in question, we are confident that the Monte Carlo method gives a reliable estimate of the uncertainty. We believe that the results shown in Table 4, where we quote the fit between the observations and the theoretically fitted pdfs, with p-values of 0.64-0.98 demonstrate the good fit of these relations.

We have added to the discussion section some more explanation on this topic at page 7 line 39:

Although more field measurements of gully sections would be advantageous in order to reduce uncertainty, time and money spent on ground truthing will increase accordingly. However, the high p-values of 0.64-0.98 obtained here for the fit between the theoretical probability distribution function and the experimental data suggests satisfactory results can be obtained, even with a limited field sample. Moreover, also Istanbulluoglu et al. (2002) successfully used a Monte Carlo approach to estimate gully incision locations using a similar amount of field data.

The Monte- Carlo approach selected is very interesting. However, the authors should explain why they dont consider other methods (such as photogrammetry from stereoscopic pairs, etc.) to estimate gully depths.

This is a good point. The motivation is twofold. Firstly, this study is part of a larger project, whose objective it is to calculate gully volumes over large areas. In order to use photogrammetry for that, we would need to measure all gullies, which would imply a lot of processing time. Monte Carlo allows to obtain a gully erosion rate estimate from a limited sample and obtain a measure of uncertainty. Secondly, we wished to establish a methodology to estimate gully volume using publicly available data that are available under the form of orthophotos. Eventually, our future goal is to extract gully networks automatically from these photos (or use existing algorithms for that), so our MC method would then allow for gully volumes to be rapidly calculated for larger regions without the need of a technician to process stereopairs.

Although this explanation exceeds the objectives of the manuscript, we have added more explanation to the text to clarify the usefulness of MC to the reader:

The advantage of this new Monte Carlo method over traditional photogrammetry is twofold. Firstly, a measure of volume can be obtained from a limited number of measurements whereas traditional methods required the entire area to be processed. Secondly, this allows us to use freely available orthophotos and opens new possibilities towards automatic gully volume determination, as extraction of two-dimensional gully networks using image classification techniques has already been implemented successfully in a variety of environments (e.g. Shruthi et al., 2014).

Shruthi, R.B.V., Kerle, N., Jetten, V., Stein, A., 2014. Object-based gully system prediction from medium resolution imagery using Random Forests. Geomorphology 216, 283-294.

P6. Field observations suggested that a triangular section is a reasonable approximation of most gully sections, so a shape factor k=0.5 was adopted in order to compute the simulated sections". It is not enough just to say that "field observations suggest". The shape factor k is very important for the results obtained and the considered value of 0.5 has to be justified.

We have based this statement on: i) field observations during the measurement of the sections; ii) field measurements made with terrestrial LiDAR (results not shown here) and iii) from other studies in similar environments. From the field mapping, all 27 measured sections were classified as triangular. From the LiDAR data, the same conclusion was drawn (see for example figure 1).

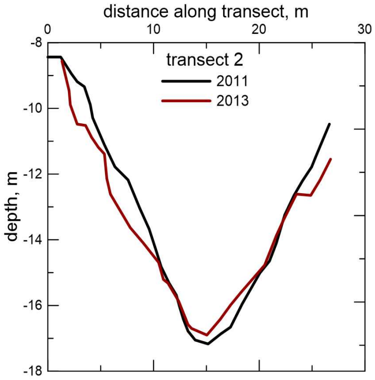

Fig. 1. Cross-section of a representative gully in the study area based on terrestrial LiDAR data in 2011 and 2013.

We however agree that the explanation was not clear on this, and have now explained this better in the text, under section 2.5: "...Field observations suggested that a triangular section is a reasonable approximation of most gully sections, so a shape factor k = 0:5 was adopted in" was replaced by:

During the field mapping, all 27 measured cross sections were classified as triangular, so a shape factor k=0.5 was adopted"

P7L9. I wonder if "extreme annual" makes sense:

The comment is correct. The text has been changed to:

"a big number of high annual rainfalls"

P7. I think that the meaning of the expression "anomalous" used in this paper deserves deeper explanations.

In order to avoid imprecision we have made the following changes:

In section 3.1, at the end of the first paragraph:

can thus be taken as a severe rainy period.

And in section 3.3, in the middle of the first paragraph:

and to severe rainy periods in 2009-2011.

P8. "From 1984 to 1999 and 2009 to 2011 there was an increment of 14.6 $m\,ha^{-1}$ and 23.6 $m\,ha^{-1}$ respectively, which account for 84% of the total drainage density growth". The duration of the two periods is very different, what has to be considered in the discussion.

This is a very good point and was also raised by referee #1. With respect of the different duration of the periods between photos, we have considerably extended the discussion. As commented also by referee #1, at the beginning of the time series the temporal resolution is lower than during the last years, which has an impact on uncertainty.

We agree that these 1956-1980 and 1984-1999 periods are longer and are aware of the limitations. We have noted this already in the Discussion section, on page 6 line 77-82:

However, given the length of this periods and since there are some particular years (i.e. 1961-1962) with extreme rainfalls it is likely that positive gully growth occurred during this period that was later masked by infilling.

We have added to this discussion:

This shows that longer periods, such as 1956-1980 and 1984-1999, are subject to a higher uncertainty with respect to the post-1999 period, when a higher temporal resolution is available.

P10, paragraph 3.7. When calculating the erosion rates in ton ha^{-1} yr^{-1}, is the considered surface area constant or varies from year to year? Please explain.

Again, this is a very good point and was also raised by referee #1. We always calculate erosion rates with respect to the total area of the study area (the motivation being that we are characterizing gully erosion rates in this area; if there would be only one gully in the entire area, calculation with respect to the gullys catchment area would overestimate gully erosion rates in the study area that in this hypothetical case would be largely ungullied).

We have now clearly indicated this throughout the text.

Line 46 to 47 has been modified to clarify this point:

The average gully erosion rate of 39.7 $t\,ha^{-1}yr^{-1}$ *for the total catchment area obtained in this study,...*

Correction in Line 54 to refer it to the total catchment area:

The highest gully erosion rate of 331 $t\,ha^{-1}yr^{-1}$ *referred to its catchment was found...*

P10, L27. Is not the Mediterranean climate temperate?

Again, this is correct. See also reply to referee #1

Both climates are temperate, what makes the sentence very unfortunate. Using the revised version of the Kppen-Geiger world climate types of Peel *et al. 2007*, we are rewritten the sentences in the text. We agree and have modified the original version, Line 83 now says:

Moreover, the data presented here clearly show than in Mediterranean-climate areas (Csa type in the Köppen classification) the gully growth dynamics are different than in Temperate Oceanic west-European areas (Cfb type) for instance.

And now Line 89 states:

Data for this study was from the Temperate Oceanic (Cfbn type) loess belt...

Technical corrections

P2L16: "New"

P3L11: remove comma

P7L1: "difference"

P8. "In most of the analyzed period variations on drainage density occurs are small. However, there are two significant periods where the increase". Please rewrite.

All technical corrections were adapted following the indications of referee #1

Reconstructing long-term gully dynamics in Mediterranean agricultural areas

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Abstract. Gully erosion is an important erosive process ~~, especially~~ in Mediterranean basins. However, the long-term dynamics of gully networks and the ~~variation of~~ variations in sediment production in gullies ~~is~~ are not well known. Available studies are often ~~done~~ conducted only over a few years~~only~~, while many gully networks form, grow, and change in response to environmental and land use or management changes over a long period. In order to clarify the effect of these changes, it is important to analyze the evolution of the gully network with a high temporal resolution. This study aims at analyzing gully morphodynamics over a long time scale (1956-2013) in a large Mediterranean area in order to quantify gully erosion processes and ~~its~~ their contribution to overall sediment dynamics.

A gully network of 20 km^2 located in SW Spain, has been analyzed using a sequence of 10 aerial photographs in the period 1956-2013. The extension of the gully network both increased and decreased in the study period. Gully drainage density varied between 1.93 km km^{-2} in 1956, ~~with~~ a minimum of 1.37 km km^{-2} in 1980, and a maximum of 5.40 km km^{-2} in 2013. The main controlling factor of gully activity appeared to be rainfall, while land use changes were found to have only an indirect effect. A new Monte Carlo-based approach was proposed to reconstruct gully erosion rates from orthophotos. Gully erosion rates were found to be relatively stable between ~~1956-2009~~1956 and 2009, with a mean value of 11.2 ~~ton~~ t ha^{-1}yr^{-1}, while in the period 2009-2011, characterized by ~~extreme~~ severe winter rainfalls, this value increased significantly ~~,~~ to 591 ~~ton~~ t ha^{-1}yr^{-1}. These results show that gully erosion rates are highly variable and that a simple interpolation between the ~~start and end date would highly~~ starting and ending date greatly underestimate gully contribution during certain years, such as~~for example between 2009-2011.~~, for example, between 2009 and 2011. This illustrates the importance of the ~~applied methodology~~ methodology applied using a high temporal resolution of orthophotos.

1 Introduction

Understanding gully erosion dynamics under changing land use and climate conditions is essential for soil and water conservation~~especially in Mediterranean areas~~. Erosion is one of the most significant threats to soils and sustainable agriculture worldwide (Amundson *et al.*, 2015). To satisfy long-term food production and food ~~security~~safety, soil erosion rates ~~must~~ should be drastically reduced to the level of soil formation rates. Additionally~~the~~ , sediment dispersion induces environmental pollution, with severe downstream problems ~~to~~ for infrastructure. Soil erosion is a major factor in the anthropogenic perturbation of the global carbon cycle (Regnier *et al.*, 2013)~~. Given the importanceof soil erosion~~, and, given its importance, much research effort has gone into characterizing and modelling erosion rates in order to identify key problem areas and propose management solutions. Recently, a European-wide effort was ~~done~~ conducted to improve the quantification of water erosion either with RUSLE (Panagos *et al.*, 2015), or with similar models (Quinton *et al.*, 2010; Van Oost *et al.*, 2007). Nevertheless, such models represent a minor part of the water erosion processes ~~,~~ by not considering the contribution of gullies. Poesen *et al.* (2002), concluded that gully erosion could be the source of up to 83% of sediment yield ~~of~~ in Mediterranean areas. Recent efforts to measure gullies in detail confirm these numbers. For instance Castillo (2012) estimated the range of gully erosion ~~rate~~ rates in a set of cultivated catchments in Cordoba ~~in~~ as being 37 to 250 ~~ton~~ t ha^{-1}yr^{-1}.

Most erosion models for gully erosion focus on modelling headcut growth. Examples are REGEM ~~,~~ and its adaptation TIEGEM, both used in the model Annualized AGricultural Non-Point Source (AnnAGNPS; Gordon *et al.*, 2007; Taguas *et al.*, 2012), CHILD (Flores-Cervantes *et al.*, 2006; Campo-Bescós *et al.*, 2013) or the headcut growth model by Rengers and Tucker (2014). Kirkby and Bracken (2009) presented an areal gully growth model that showed how the ratio of channel versus sidewall processes is a key determinant in its evolution. In contrast, Dabney *et al.* (2015) ~~model~~ modeled gully erosion rates by shear stress by inserting a ~~nee~~ new Ephemeral Gully Erosion Estimator, (EphGEE), included in a new version of RUSLE2, in a small agricultural watershed in Iowa. More mathematically based models ~~look for~~ seek general laws controlling areal gully growth and ramification (*e.g.* Devauchelle *et al.* 2012). ~~More research will be needed in order to develop full three-dimensional models, capable of accurately predicting gully erosion volumes.~~ In general however, there is an important lack in suitable field data for understanding and modelling long-term gully evolution.

Different methodologies, apart from traditional field measurements with total station, laser profilemeters and poles (Castillo *et al.*, 2012), have been proposed and successfully applied to estimate gully volumes. For instance, at the individual gully scale, 3D reconstruction from high resolution aerial photography and digital photogrammetry has been widely applied (e.g. Marzolff and Poesen, 2009). Recently, terrestrial imagery modelling and Structure from Motion - Multi View Stereo (SfM - MVS) procedures have been used to determine gully volumes (Gómez-Gutiérrez *et al.* 2014; Frankl *et al.*, 2015 and Castillo *et al.*, 2015). Terrestrial LiDAR has been applied to measure rills or gullies at both laboratory and plot scale (Vinci *et al.*,2016; Momm *et al.*, 2011, 2012). Nevertheless, at the catchment scale, the number of studies is limited. At this scale, most studies focus on the areal extension of gully networks, using aerial photos or other remotely sensed imagery. Few studies report gully volumes, due to the inherent difficulties of determining depths for the whole gully network. Nachtergaele and Poesen (1999) determined gully length from aerial photos and, by using additional field measurements, they established a mean cross section to calculate volumes of small ephemeral gullies in the Belgian loess belt. Martínez-Casasnovas (2000) mapped and quantified the erosion produced in a gully systems of big dimensions by processing multitemporal orthophotograms and DEMs in a GIS for a 25 km^2 catchment located in NE Spain. Frankl *et al.* (2011) used sequential photographs to link long-term gully and river dynamics to environmental change in Northern Ethiopia. More recently, Peter *et al.* (2014) used UAVs and photogrammetric analysis to quantify gully erosion, albeit at a local scale in the Souss Basin (Morocco).

Due to the recent nature of most of these field studies on gully erosion, their temporal coverage is limited to a few years at best. More recent studies usually focus on one specific moment in time, where the gully system is visited and measured once or during a couple of years. This implies that ~~any~~ no dynamic behaviour of the gully system ~~cannot~~ can be described adequately and that it is difficult to single out the controlling processes. Growth of gully systems in the Belgian loess belt was shown by Vanwalleghem *et al.* (2005) to be a highly non-linear process, with a rapid initial growth followed by a stabilization phase. Under different climates, ~~especially under a Mediterranean climate,~~ where rainfall is less uniform and much more concentrated, such non-linear gully dynamics can be expected to be accentuated. It ~~may therefore turn out~~ could therefore happen that a single measurement of a gully volume that has been growing for several decades, ~~will~~ does not offer a good estimate of yearly growth rates. Gully growth can be expected to be much ~~higher~~ greater during specific years compared to the long-term mean. Any model efforts will therefore need experimental data collected with a high temporal resolution.

Over such longer time scales, exceeding several decades, ~~little experimental data is~~ few experimental data are available. Over ~~the very long~~ one time scale of up to several centuries, different studies indicate that gully erosion is not a new process. In Northern and Central Europe, gullies have been dated between Early Bronze Age and Late Medieval times (Vanwalleghem *et al.*, 2006). In the Western Mediterranean, with a long history of land use, such historical studies are rare however (Dotterweich, 2013). Over the medium term, of several decades, available studies ~~also~~ point to an important dynamic of ephemeral gullies, with erosion phases and ~~phases of infilling~~ infilling ones. These can be due to normal tillage operations for small, ephemeral gullies; deliberately done by farmers in case of larger gullies; or during ~~phases of~~ land use change ~~where~~ phases, in which farmers erase such topographic features by tillage, as has been supported by field evidence. Gordon *et al.* (2008) showed by simulations using the REGEM model that ~~such cycles of~~ those erosion and infilling cycles could produce up to double the amount of sediment as when gullies were left to erode naturally. Each infilling phase prepares sediment for the next important storm event. Field data for this time scale are rare and generally ~~comes~~ come from the analysis of historical ~~air~~ aerial photos. Frankl *et al.* (2013) quantified the evolution of a permanent gully network in Ethiopia using long-term historical ~~air~~ aerial photos over the period 1963-2010 for an area of 123 km^2. After an initial stability phase, they identified a peak erosion period in 1994, after which the system stabilized again. These results stress the importance of ~~intensive~~ frequent temporal observations. Saxton *et al.* (2012) ~~analysed~~ analyzed multitemporal aerial photographs between 1951 and 2006 to ~~derived~~ derive historical gully erosion rates in terms of ~~superficial~~ surface growth per year in three catchments in south-east Queensland in Australia and ~~,~~ associated the gully initiation to post-European settlement land use practice and above average rainfall and runoff. Also, Shellberg *et al.* (2016) observed an increase in the gully erosion by the changes in the land use produced by post-European settlement in the Mitchell River fluvial megafan (Queensland, Australia). This relationship between pioneers and gully erosion was previously suggested by Leopold (1924) in the US. Other methods have been tested, such as using local farmer knowledge on gully morphology (Nyssen *et al.*, 2006; Tebebu *et al.*, 2010) or ~~using~~ multi-temporal oblique photography of gully cross sections (Frankl *et al.*, 2011), but the uncertainty ~~on~~ in the results is generally too ~~high~~ great to allow a quantitative analysis of controlling climate or land use factors.

The objective of this study ~~is then~~wass, then, to quantify the erosion and infilling dynamics of a gully network in a typical agricultural area of SW Spain, from historical air photos between 1956 and 2013. A new method is presented that not only allows one to determine the evolution of gully length, but also, by using Monte Carlo analysis to generate gully width and depth, to calculate the volume of gully erosion and infilling and to constrain ~~the~~ uncertainty. Moreover, the controls in terms of land use and rainfall variability are ~~analysed~~ analyzed and the importance of these results for the regional sediment budget ~~is~~ assessed.

2 Materials and methods

2.1 Study site

The study area is located between 37.74 and 37.81° N, 4.36 and 4.43° W, in the West Campiña of the Guadalquivir basin in the SW Spain (Fig. 1) and comprises an area of 20.6 km^2. The studied gully network drains towards a series of small ephemeral rivers (Arroyo de Garuñana, Arroyo del Cuadrado, Arroyo del Pozo Muerto, Arroyo de las Monjas, and Arroyo del Barranco), which all drain to the Guadajoz, a tributary of the Guadalquivir river. Although the limits between rills, gullies and larger ephemeral river channels are subject to discussion in the scientific community, this ephemeral river network was not included in the analysis, as it is indicated on the topographical maps and assumed to be stable. The observed gullies can be considered ~~mostly permanent~~to be mostly permanent (Fig. 2), although some ephemeral ones are ~~also~~ included as long as they have a width equal to or higher than the resolution of the orthophotos that were used, ranging between 0.5 and 1.0 m (Table 1).

Gentle hills prevail in the study area except ~~from~~ for the south and the ~~centre~~ center east where steeper ones exist (up to 32%). Altitudes range from 233 to 558 m high and mean slopes are 13%. The soils in the area are dominated by Vertisols, formed mainly in marls and calcareous sandstones deposited during the Miopliocene.

Currently the dominating land uses are olive orchards and herbaceous crops covering almost the whole area, except some 5% of the surface area occupied by grassland. Mean annual precipitation varies between 500 and 600 mm (Córdoba Airport station and Baena RIA station). The distribution of the precipitation shows a marked dry season between June and September, while the main wet period occurs from October to May.

2.2 Rainfall characterization

Characterization of the rainfall regime was performed from daily rainfall collected in the ~~period~~ periods 1956-2013 at Castro del Río ~~meteorological~~ weather station (37.69° N, 4.47° W), belonging to the Spanish National Meteorological Agency

(AEMET). Isolated data gaps of between 1970 and 1971 were ~~completed~~ filled from the data recorded at Cañete de las Torres ~~meteorological~~ weather station (37.83° N, 4.36° W, Phytosanitary Warnings Network of Andalusia, RAIF) and Córdoba Airport ~~meteorological~~ weather station (37.84° N 4.84° W, AEMET). Anomalies in annual rainfall were evaluated by means of normalization, through average and standard deviation of annual rainfall for a 57 years period (1956-2013), following Martínez-Casasnovas *et al.* (2003). Values falling outside the interval R_{mean} (average rainfall) $\pm$ sd (standard deviation), which correspond to the normalized values >1 and <-1, were considered as anomalies.

The frequency distribution of daily rainfall above a threshold value of 13 mm was analysed, considering this as the minimum rainfall that produces erosive effects as proposed by Wischmeier and Smith (1978) and Renard *et al.* (1997). In addition, the frequency distribution of records above the average daily rainfall event plus the standard deviation were ~~also analysed~~analyzed as well, assuming that these events represent the extreme rainfall events within the study period.

2.3 Photointerpretation process

Analysis of gully evolution and land use change was conducted by photointerpretation based on a dataset of aerial orthophotos of different years from 1956 to 2013. Performance characteristics of the orthophotos dataset are summarized in Table 1. The working scale in the photointerpretation processes was established ~~to~~ at 1:5000 for the whole dataset.

2.3.1 Land use

Land use in the study area for 2001, 2005, 2009, 2011, and 2013 was derived from the respective orthophotos while for the rest of the years (1956, 1980, 1984, 1999, 2003, and 2007) existing Maps of the Land Use and Vegetation Cover of Andalusia (Red de Información Ambiental de Andalucía, REDIAM) were ~~used~~employed. Different land uses present in the area were simplified to three classes as shown in Table 2.

2.3.2 Gully network length

Gully length was obtained by digitizing the extension of the ~~gully~~ network for each available year (Fig. 3), distinguishing between newly incised and infilling stretches. Gully network was decomposed in m_y segments, where subscript y indicates the year. Each segment comprises the length between consecutive junctions (Fig. ~~2~~4). Due to changes in the drainage network during the study period, the number of segments ranged between 108 in 1980 and 940 in 2013. The total length of the drainage network for a given year, L_y, was calculated as the sum of the lengths of individual segments, $l_{y,i}$

$$L_y = \sum_{i=1}^{m_y} l_{y,i} \tag{1}$$

with m_y equal to the total number of individual segments of the gully network for each digitalized year.

2.3.3 Gully network width

In order to measure gully width ~~in a representative way,~~ representatively 35 stretches were selected from the earliest digitalized gully network of 1956 (Fig. 1), covering a wide range of widths. Gully width was measured at the same locations on later orthophotos, allowing the evaluation of the widening process during the complete study period.

2.4 Field campaign

During 2013 and 2014, several field campaigns were conducted to ~~measured~~ measure current gully widths and depths with measuring tape and a clinometer (Suunto PM-5/360 PC). Gully top width and depth were measured at 27 representative sections ~~distributed randomly over the gullies catchments~~that were located as close as possible to the 35 sections used in the photointerpretation. These representative sections covered the entire range of width and depth variability, including different landscape positions, from upstream close to the divide to the junction with the stream network, and both in gullies on herbaceous crops and under olive ~~orchards gullies.~~ trees. This method of combining photointerpretation with field measurements of gully morphology is similar to Nachtergaele and Poesen (1999).

2.5 Monte Carlo-based simulations

Although gully length for the different years between 1956 and 2013 could be determined directly from observations using the available air photographs, determination of the gully volume was not so straightforward. As we used freely available orthophotos, it was only possible to measure the size of the gullies in two dimensions and no measure of depth was readily available. Also observations of gully width for each year were limited to the representative sections measured on the orthophotos of that particular year, and therefore included a term of uncertainty as the real population mean remained unknown.

Estimation of overall gully network volume for each year, $\bar{V}_y$, was therefore tackled by conducting a Monte Carlo simulation in which a volume and an associated uncertainty were calculated for every single gully segment, $l_{y,i}$, described in paragraph 2.3.2 (Fig. ~~2~~4).

For each year, y, a set of $n = 1000$ estimated cross area sections, $S_{y,i} = \{s_{y,i,j}, j = 1, ..., n\}$ for every single segment, $l_{y,i}$, were generated as ~~show in Figure 3~~shown in Figure 5, which required the generation of sets of width and depth values for each year. Each generated section is calculated as

$$s_{y,i,j} = k w_{y,i,j} d_{y,i,j} \tag{2}$$

where k is a shape factor, and $w_{y,i,j}$, and $d_{y,i,j}$, the simulated gully width and depth respectively. Field observations suggested that a triangular section is a reasonable approximation of most gully sections, so a shape factor $k = 0.5$ was adopted in order to compute the simulated sections.

To generate a representative measure of gully width, first of all, the gully width distribution measured for each year by photointerpretation at the representative sections was fitted to different probability distribution functions (normal or Gaussian, gamma, lognormal, exponential and Weibull) using the maximum likelihood method. Next, goodness of fit was evaluated for these different distributions by means of the Kolmogorov-Smirnov statistics. Finally, the best overall fitting theoretical probability distribution was selected to obtain the necessary parameters (μ_y, σ_y) to generate n random simulations of representative gully widths for any particular year.

The estimation of gully depth for each year was based on the field data gathered in 2013-14. In order to estimate depth for previous years, firstly a width-depth relationship was estimated by linear regression analysis from the collected field data. Such a relationship could only be established for the present-day situation. Uncertainty on this linear width-depth relation was then taken into account by computing the estimated intercept, slope and their respective standard deviations (a, b, s_a, s_b). Assuming a normal distribution, a set of one thousand slope and intercept pairs were simulated. Depths for unique segments $(D_{y,i})$ were then ~~derivate~~ derived from simulated widths and slope-intercept pairs.

Finally, a set of n simulated volumes $V_{y,i} = \{v_{y,i,j}, j = 1, ..., n\}$ was calculated for each year and segment multiplying individual measured lengths by the simulated sections (Fig. ~~3~~5)

$$v_{y,i,j} = s_{y,i,j} l_{y,i} \tag{3}$$

A set of n different simulated volumes of the complete gully network for a particular year V_y was eventually calculated as the sum of volumes of single segments $v_{y,i,j}$

$$V_y = \{v_{y,i,j}, j = 1, ..., n\} \tag{4}$$

and

$$v_{y,j} = \sum_{i=1}^{m_y} v_{y,i,j} \tag{5}$$

Finally average volume of the total gully network for a given year, $\bar{V}_y$, was computed as

$$\bar{V}_y = \frac{1}{n} \sum_{j=1}^{n} v_{y,j} \tag{6}$$

Erosion rates were then obtained from the ~~different~~ difference between pairs of simulated volumes ~~in~~ on consecutive dates divided by the duration of the period.

3 Results

3.1 Rainfall characteristics during the study period

The annual rainfall depths in the analysed period ranged between 180 mm in the hydrological years 2004/2005 and 973 mm in 2009/2010, with an average value of 546 mm (Table 3). Figure ~~4~~ 6 shows standardized annual rainfall between 1956 and 2013 and the anomalies of annual rainfall. Annual rainfalls ~~greater than~~ over the 0.75 percentile (656 mm) were ~~registered in~~ recorded on 15 occasions of which 10 surpassed the average annual rainfall plus the standard deviation (748 mm). Among the lapses between aerial orthophotos dataset, the period 1984-1999 and 2009-2011 concentrated the ~~major~~ highest number of positive extreme annual ~~rainfalls~~rainfall events. In 1984-1999 eight out of fifteen records were ~~greater than~~ over the 0.75 percentile, and 6 of them were considered to be anomalies since they were ~~greater~~ higher than the average annual rainfall plus the standard deviation. In the period 2009-2011, ~~both years recorded annual rainfall amounts higher~~ in both years, larger amounts of annual rainfall than the standard deviation were recorded and can thus be considered ~~an anomalous extreme~~ anomalous severe rainy period.

Figure ~~5~~ 7 shows the distribution of the 3698 daily rainfall events recorded during the study period. Daily rainfall events (R_{24}) higher than 13 mm accounted for 21.7% of the total ~~registered~~recorded. Among the different periods the highest proportion of R_{24} >13 mm ~~were~~ was recorded in 2009-2011 (27.5 events per year, Table 3) whereas the average proportion was 13.9 R_{24} events>13 mm per year. Rain depths higher than the average value (8.4 mm) plus the standard deviation (10.8 mm) were considered extraordinary events, which were concentrated in ~~major~~ a higher proportion in the periods 1984-1999 (10.5 records per year) and 2009-2011 (13 records per year) (Table 3). Maximum daily rainfalls were ~~registered~~ recorded in the hydrological years 1997/1998 (140 mm) and 2007/2008 (126 mm), with an average value of 48.68 mm for the entire period.

3.2 Land use change

Land use experienced a progressive conversion from herbaceous crops to olive orchards as shown in Figure ~~6.~~ 8. In the study period, olive orchards grew from 13% to 63% of ~~occupation of the land use in the study area . At the same~~ the total catchment area at the same as time herbaceous crops decreased from 85% to 35% of the ~~occupied land~~total catchment area. The main land use change occurred between 1984 and 1999, when the olive orchards ~~passed~~ went from occupying 25% to 48% of the total catchment area. The highest rates of change however were observed in the period 2005-2007 with a more than 4% rate of annual land use change from herbaceous crop to olive orchards.

3.3 Gully network length dynamics

Figure ~~7~~ 9 shows the evolution of the gully network derived by photo-interpretation between 1956 and ~~2013. Drainage density is includedthere~~2013, with drainage density included. From 1956 to 2013 the gully network increased not only in length but in number of branches as well. Further analysis on the length and area ratio showed that the drainage density ~~has~~ had grown from 17.2 m ha^{-1} to 53.3 m ha^{-1}. There seeems to be a greater increase in the south compared to the north, which suggests a more stable condition in the latter. In most of the analyzed period~~variations on drainage density occurs are~~ , the variations in drainage density were small. However, there ~~are~~ were two significant periods ~~where the increase is~~ when the increase was very high and that account for the main increases in the overall value. From 1984 to 1999 and 2009 to 2011 there was an increment of 14.6

m ha^{-1} and 23.6 m ha^{-1}, respectively, which ~~account~~ accounted for 84% of the total drainage density growth. When comparing these gully length dynamics to controlling factors of land use and rainfall, it can be seen in ~~table~~ Table 3 that ~~these~~ this rapid growth could be related to extreme rainfall events that occurred in 1997 and anomalous rainy periods in 2009-2011. In contrast, in some periods, such as for instance in 1956-1980, 1999-2001, 2001-2005 and 2007-2009 the gully network ~~experimented~~ underwent several decreases in the drainage density, although in no case ~~this decrease was~~ was this decrease more than 4 m ha^{-1}, and can therefore be considered modest. These decreases ~~can~~ may be directly related to farming operations~~where~~, in which farmers fill in the upstream gully stretches that are limited in depth and can be considered to be ephemeral gullies.

Figure ~~8~~ 10 shows the frequency distribution of headcut growth and infilling of individual gullies for the different periods between 1956-2013. Some of the observation periods ~~show~~ exhibit a balance between infilling and growing reaches, which leads to a very minor overall change of the total gully network length. During a few distinct intervals however, 1984-1999 and 2009-2011, this balance shifts drastically and results in a fast increase of the gully network's total length, as can be seen in Figure ~~9. This can be in part explained because~~ 11. This can partly be explained by the fact that, in these two periods infillings are almost negligible (Fig. ~~8~~ 10 and Fig. ~~9~~11). However, in Figure ~~9~~ 11, the growth of the gully at the end of those periods (1999 and 2011) is much ~~higher~~ greater (31 km and 49 km) than those from the other end periods (13 km as the highest value), which clearly shows that gully growth ~~is~~ was the dominant process controlling gully dynamics in those periods.

Figure ~~9~~ 11 shows how the total length of the gully network tripled from 35.4 km in 1956 to 109.8 km in 2013 (Fig ~~9~~11). Main ~~enlargements~~ enlargement periods were registered in 1980-1984 (10.6 km), 1984-1999 (29.9 km) and 2009-2011 (48.8 km). In contrast, during some other periods, ~~as for instance~~like, for instance, in 1956-1980, 1999-2001, 2001-2005 and 2007-2009, the balance between infilling and growing stretches resulted in a net reduction of the total gully network length. Infilling gully stretches identified during photointerpretation, ~~may be classified in~~ could be classified into two different types: those made ~~while~~ during regular tilling operations at the end of the summer, usually in the order of several tens of meters and those resulting from land levelling during ~~phases of~~ land use change phases, which may reach some hundreds of meters.

Extraordinary annual rainfalls as well as individual extreme precipitation events seem to be the main factors that can be linked to gully retreat (Table 3). Land use does not seem to control these observed peaks in gully length increase~~directly~~. However, we cannot exclude that land use change could have contributed to the rainfall extremes inducing high peak discharges, because, since 1956, a shift from cereal crops to olive orchards occurred in half of the study area, and ~~which~~ was especially intensive from 1984 ~~forward~~onward. Young olive trees with limited root systems and small canopies leave an important ~~bare soil surface and~~ soil surface bare and give little protection to overland flow or gully headcut advance. However, further analysis should be ~~done~~ made in order to confirm this hypothesis.

3.4 Gully network width dynamics

Top width at the representative cross sections, as derived from the orthophotos dataset, experienced ~~a continued~~ continuous widening over time (Fig. ~~10~~12). While at the beginning of the study period (1956), the maximum top width was close to 12.0

m, this value progressively increased over subsequent years, until reaching a maximum value of 59.0 m in 2013. ~~Average~~ The average value increased smoothly from 4.5 m wide in 1956 to 8.0 m in 2005, whereas the rate of increase for the period ~~2005–2013~~ 2005-2013 clearly got steeper, resulting in final average width of 13.1 m in 2013. Although widening could be expected at every time step, average widths derived from the cross sections in 2007 (7.7 m) actually experienced a narrowing with respect to those measured in 2005 (8.0 m). Since this period (2005-2007) ~~experimented~~ underwent the highest rate of land use change in the series, this reduction in cross section could be explained ~~to~~ by the reopening of gullies that had previously been removed by land ~~levelling~~ leveling during a land use shift to olive orchards.

Table 4 ~~summarize~~ summarizes p-values obtained by means of the Kolmogorov-Smirnov statistic, which was used to evaluate the suitability of different theoretical probability distributions for fitting the observed top widths. The lognormal distribution showed itself to be the most suitable for almost all the years, with the highest p-value of 0.98, in 1980 and 1999 and lowest p-value of 0.64 for 2011, although it was still the best fit ~~from all tested distributions~~ for all the distributions tested. These fitted probability distributions were then used to simulate 1000 random widths for each year and single segment composing the gully network.

3.5 Width and Depth relationship

In order to compute the volume of the gully network, depths at the different stretches were derived from the Monte Carlo simulated widths using a width-depth relation ~~derived~~ resulting from field work, shown in Figure ~~11.~~ 13. A coefficient of determination $R^2 = 0.83$ was obtained from a logarithm-based fitting, with slope, intercept and their standard deviation~~respectively~~ , respectively, 1.73 ± 0.16 and 0.55 ± 0.32. Normal deviates based on those coefficients were used to generate 1000 width and depth pairs.

3.6 Gully volume dynamics

Figure ~~12~~ 14 presents the final volume evolution, as calculated by means of the Monte Carlo simulation. Gully stretches with a ~~unique~~single, observed length were multiplied by the generated width and depth pairs, resulting in 1000 simulated gully network volumes for each stretch and for each period. Average volume in addition to minimum and maximum ~~volume were then derived~~ volumes were then obtained from the set of simulations, showing the growth of the gully in terms of mean eroded volume, as well as a measure of uncertainty, by means of the 5-95% confidence interval of these inferences, shown in grey. Gully network volume ~~grows~~ grew from 0.18 hm^3 in 1956 to 3.24 hm^3 in 2013. These results show how the original value of the total gully volume has increased ~~by~~ 17 times~~its original value~~. Main periods of rapid volume growth occurred at the end of the study period, between 2009 and 2013, when the gully volume increased from 0.82 hm^3 until its final value of 3.24 hm^3. Moreover, the period 2009-2011 alone accounts for nearly 52% of the observed growth. Infilling phases were also reflected in the volume evolution curve shown in Figure ~~12,~~ 14, such as for instance at the end of the period 1956-1980~~when~~ , when the gully volume decreased until it reached its minimum value (0.15 hm^3), and in 2007 which shows a 0.015 hm^3 decrease from the average volume in 2005 (0.81 hm^3).

3.7 Gully erosion rate dynamics

Dynamics of gully erosion rate are shown in Figure ~~13.~~ 15. Maximum erosion rate was reached in the period 2009-2011 when 591 ~~ton~~ t ha^{-1}yr^{-1} were lost according to the ~~simulation process~~Monte Carlo results. Minimum erosion rate (-5.21 ~~ton~~ t ha^{-1}yr^{-1}) was ~~registered~~ recorded in the period 2005-2007. Negative values here reflect the decrease of the gully network volume, and ~~therefore should not be considered an erosion rate but an infilling rate~~it should therefore be considered as an infilling not an erosion rate. Average erosion rate for the whole study period was 39.7 ~~ton~~ t ha^{-1}yr^{-1}.

4 Discussion

The average gully erosion rate of 39.7 ~~ton~~ t ha^{-1}yr^{-1} for the total catchment area obtained in this study, by means of photo-interpretation techniques combined with stochastic methods, ~~are~~ is of the same order of magnitude ~~with~~ as those found in the literature in Mediterranean basins. Oostwoud Wijdenes *et al.* (2000) reported erosion rates of 1.2 ~~ton~~ t ha^{-1}yr^{-1} in bank gullies ~~developed~~ developing into highly erodible sedimentary deposits in the southeast of Spain, derived by aerial photo analysis over a 38 year period. The highest gully erosion rate of ~~1,322 ton~~ 331 t ha^{-1}yr^{-1} referring to its catchment was found by Martínez-Casasnovas *et al.* (2003) in large gullies in the NE Spain, from high resolution DEMs and GIS analysis in a 36 year period. Compared ~~with~~ to other erosion processes, the gully erosion rates measured here almost double the average erosion rates for sheet and rill erosion reported for olive orchards in the Mediterranean (23.2 ~~ton~~ t ha^{-1}yr^{-1}) by Gómez et al. (2008). Olive orchards are one of the most important crops in the Mediterranean and are generally considered to be highly affected by sheet and rill erosion. This clearly stresses the importance of adequately considering gully erosion processes when modelling soil losses from water erosion.

Most importantly, the results show a wide variability in gully erosion rates, ranging between -5.21 and 591 ~~ton~~ t ha^{-1}yr^{-1}. This includes periods dominated by infilling and rapid growth, underlining the importance of measuring erosion rates at the finest temporal resolution possible in order to ~~overcome~~ prevent under- and/or overestimations in sediment production. Such variability is in part explained by the inherent irregularity of the local rainfall regime, which appears to be the main controlling factor for gully erosion at this site. However, land use change has played an important role, intensifying in some cases and masking in other cases ~~the rates of gully erosion~~ gully erosion rates. For instance, in the initial period between 1956 and 1980, ~~erosion rate shows~~ the erosion rate gave a negative value. However, given the length of this period and since there ~~are~~ were some particular years (*i.e.* 1961-1962) with extreme ~~rainfalls~~ rainfall, it is likely that positive gully growth occurred during this period, that was later masked by infilling. This shows that longer periods, such as 1956-1980 and 1984-1999, were subject to a greater uncertainty with respect to the post-1999 period, when a higher temporal resolution was available. Infilling phases could be expected to be followed by those with higher erosion rates. Gordon *et al.* (2008) obtained the latter from periodically infilled gullies compared to gullies left undisturbed. However, our results do not show that trend. For example, land use change and infilling between 2005 and 2007 was followed by only a moderate gully erosion phase in the 2007-2009 period.

Moreover, the data presented here clearly show that, in Mediterranean areas (Köppen climate type Csa), the gully growth dynamics are different~~than in temperate areas~~ , for instance, to those in Temperate Oceanic west-European areas (Köppen type Cfb). A review of different studies on gully growth over time by Poesen *et al.* (2006) indicated a rapid initial growth, followed by a stable phase with slow growth for “mature” gullies. Data for this study was from the ~~temperate loess~~ Temperate Oceanic (Cfb) Loess belt or from lab experiments under constant discharge conditions. In our case, with a high variability in natural rainfall, even after several decades, intense growth phases were observed. This observation is not unique since, in another environment Shellberg *et al.* (2016) have detected an almost continuous increasing trend in the gullies of the Mitchell River in Queensland. As stated before, these could mainly be attributed to an increase of the gully’s cross sections, and less to a gully headcut retreat. Therefore, models such as CHILD or REGEM, which have been applied with success to gully modelling, but focus mainly on headcut activities, would probably not yield good results in this case.

From a wider geomorphological perspective, other phenomena such as lowering of the base level and incision of the river bed could be suggested as being a cause of the progressive increase ~~on~~ in the erosion rate. ~~Nevertheless, there was no field evidence of this. In addition, the Guadalquivir river basin is~~ During the Quaternary, the main Guadalquivir River was at an incision stage due to its base level fall. However, this incision has been slow, as demonstrated by Uribelarrea and Benito (2008), who found evidence of only a 1.2 m incision over the last 500 years. In any case, since the 1950-60s, when many dams were constructed, the Guadalquivir has been a highly regulated river~~, with many dams, which could be expected to limit any such effects~~. Such dams are known to have a downstream incision effect due to removal of sediment load and an upstream aggradation effect. With respect to our study area, there are no upstream but only downstream dams. Therefore, it is surmised that the influence of the incision stage has been artificially limited in this catchment since the 1950s and that the observed changes in the gully network can be fully attributed to upstream changes in the rainfall or land use regimes.

Gully erosion rates computed between the start and the end of the study period would incur in gross underestimation. Erosion rates between 1956 and 2009 ~~are~~ were under the average (39.7 ~~ton~~ t $\text{ha}^{-1}\,\text{yr}^{-1}$), while the last period (2009-2013) accounted for around 52% of the gully volume growth, reaching a peak value of ~~590 ton~~ 591 t $\text{ha}^{-1}\,\text{yr}^{-1}$ in the period 2009/2011. Nevertheless, these observations are in accordance with other studies in the Mediterranean. Gully erosion rates after some extreme rainfall events in the Mediterranean ~~Basin~~ basin has been reported to ~~reach occasionally~~ occasionally reach 207 ~~ton~~ t ha^{-1} (Martínez-Casasnovas *et al.*, 2002). In a review of the western Mediterranean basin, González-Hidalgo *et al.* (2007) found that~~on average~~ , on average, the three largest daily events per year accounted for more than 50% of the total sediment exported from the basin. Gioia *et al.* (2008) stressed the importance of different runoff thresholds to explain flood occurrence in the Mediterranean areas. Ordinary flows are produced when rainfall rate exceeds the infiltration rate of the soil in a small area, a typical case of Hortonian runoff generation, or Hortonian threshold, while what Gioia *et al.* (2008) denominated outlier events, occurred when the water of almost continuous rain spells surpassed the storage capacity of the soil in a large area of the catchments, or Dunnean threshold. This behavior is similar to the complex response to the geomorphic thresholds discussed by Patton and Schumm (1975). The so-called time compression of Mediterranean climate with respect to soil erosion is therefore very high, as is demonstrated by the data from this study. Our data seem to indicate that land use did not play a dominant role, although we cannot exclude that land use changes to olives and soil management have lowered the land's resilience towards gully incision.

The Monte Carlo stochastic modelling performed ~~also allow to identify~~ allows one to verify that while gully length dynamics (Fig. ~~9~~11) could explain some of the rapid increases in the volume and erosion rate computed, widening processes (Fig. ~~10~~12) determine the shape of volume curve (Fig. ~~12) pointing out~~ 14) pointing to the importance of that parameter in the computed volume as ~~opposite~~opposed, in this particular case, ~~as~~ to that suggested by other authors~~who found~~, who, for other areas and climates that the leading controlling parameter is gully length (Nachtergaele and Poesen, 1999). This observation will lead to future field work and modelling efforts, which should not only consider gully headcut advance, but also ~~on~~ the mechanisms of gully sidewall collapse and erosion. Possibly a very important factor here, ~~also~~ in order to control ~~the~~ gully growth, is the ~~effect that roots may have~~ possible effect of roots on stabilizing the gully walls (De Baets *et al.*, 2008).

The main advantage of the new method described here, is that by means of Monte Carlo simulation, an estimation of the uncertainty ~~associate along with the measure~~ associated with the measurement of gully erosion volume is generated. This is especially relevant when suitable knowledge of erosion dynamics is required, and management systems need to be evaluated or compared. Although more field measurements of gully sections would be advantageous in order to reduce uncertainty, time and money spent on ground truthing would increase accordingly. However, the high p-values of 0.64-0.98 obtained here for the fit between the theoretical probability distribution function and the experimental data suggests satisfactory results can be obtained, even with a limited field sample. Moreover, also Istanbulluoglu *et al.* (2002) successfully used a Monte Carlo approach to estimate gully incision locations using a similar amount of field data.

5 Conclusions

A new method was presented to evaluate gully growth over decadal time scales, combining airphotos interpretation with a stochastic approach through Monte Carlo ~~modelling~~ modeling for the channel section parameters. This ~~resulted to be~~ method constitutes a reliable procedure to determine gully network dynamics over time. Uncertainty ranges obtained in the simulation provide an unprecedented view on the gully network dynamics useful from a management perspective. ~~Whereas~~ While highly variable, the observed erosion rates were in accordance with previous studies in Mediterranean basins. The fluctuations in erosion rates were mainly attributed to the variability in rainfall regime variations, likely to have been exacerbated by land use changes, although further research ~~using physical modelling~~ of runoff, gully headcut retreat rates and sidewall ~~dynamics~~ dynamics should be made at this last point.

Simple interpolation between the start and end date would highly underestimate gully contribution during certain years, as it could be verified when comparing the average erosion rate (39.7 ~~ton~~ t ha^{-1}yr^{-1}) with ~~punctual~~ sporadic erosion rates at the end of the study period at to a maximum of 591 t ha^{-1}yr^{-1}. Gully erosion is confirmed to be an important ~~process of sediment generation~~ sediment generation process in Mediterranean basins. Average erosion rates from gullies in the study period almost double their values for similar locations and conditions obtained for rill and sheet erosion.

Further studies with more field data are needed to improve the estimations of the contribution of the different land uses to gully growth. Implementation of physically-based models of gully retreat rates and sidewall collapse as well as more field measurements and interviews with local farmers on soil management practice could contribute to a better understanding of the ~~processes of elongation~~ of the elongation processes, and predict gully erosion under different scenarios, including the effect of added root cohesion to sidewall stability or gully headcut protection.

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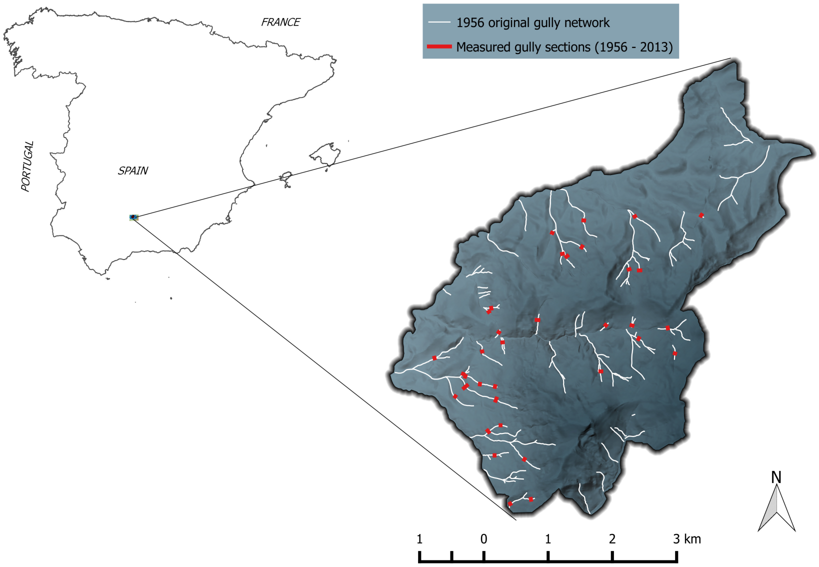

Figure 1. Site location with details of the original gully network and measured gully sections.

Table 1. Orthophoto dataset properties.

capture year	1956	1980	1984	1999	2001	2005	2007	2009	2011	2013
resolution, m	1.0	0.5	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5
color	b/w	b/w	b/w	b/w	b/w	col.	col.	col.	col.	col.

b/w: black and white; col.: color

all restitution scales are 1:10,000 except 1980 with scale 1:5,000

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Figure 2. Typical gullies in olive orchards (left) and in herbaceous crops (right) in the study zone.

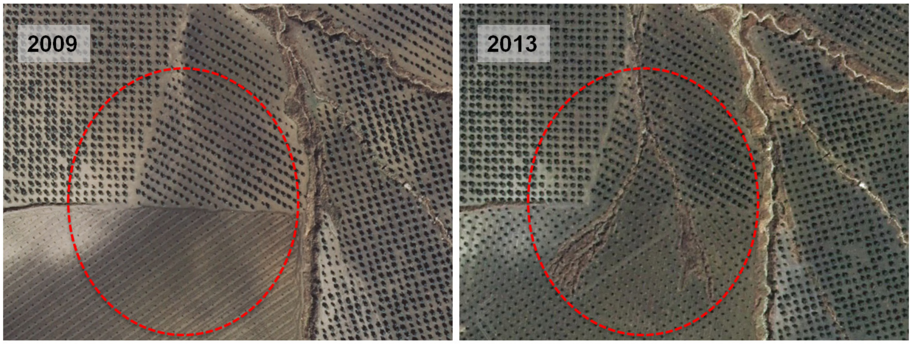


Figure 3. Example of orthophotos showing gully incision between 2009 and 2013 from and old (top) into a new plantation (bottom).

Table 2. Correspondences of the simplified land use classes adopted in this study with the Map of the Land Use and Vegetation Cover of Andalusia (MUCVA, REDIAM).

MUCVA classes	Simplified classes
Herbaceous crops with scattered trees	Herbaceous crops
Non-irrigated herbaceous crops	
Irrigated herbaceous crops	
Non-irrigated tree crops: olive orchards	Olive orchards
Pasture	Other land use
Dense scrubland	
Streams and natural watercourses	
Agricultural buildings and farms	

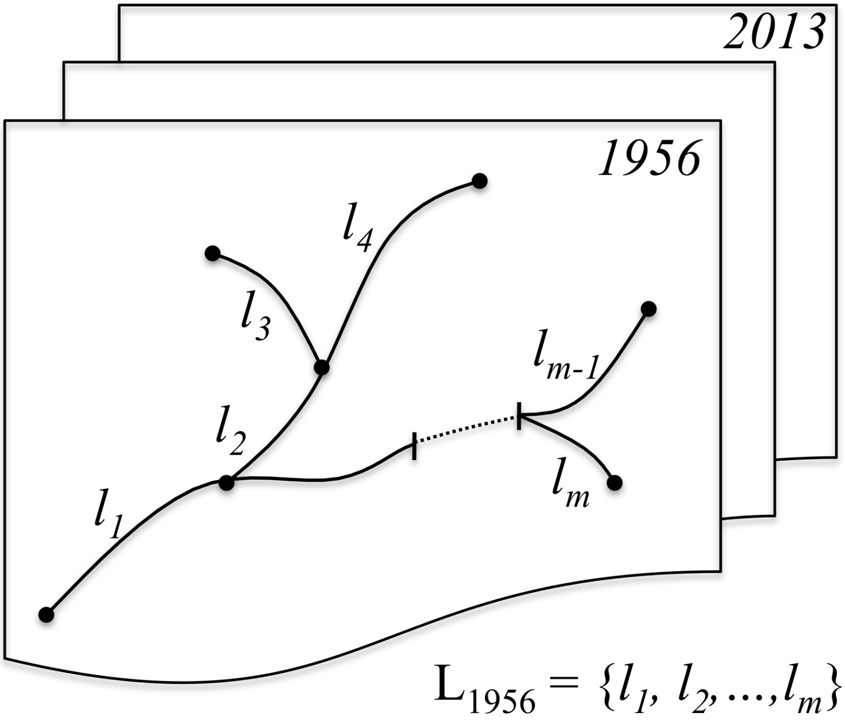


Figure 4. Illustration of the decomposition of the gully network into individual segments for the Monte Carlo-based simulation process.

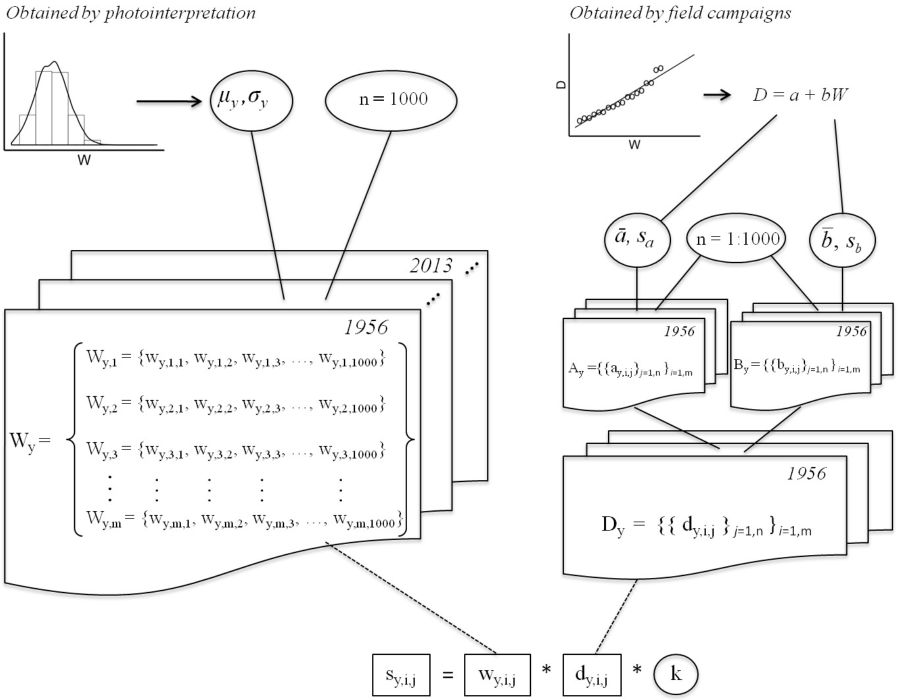


Figure 5. Conceptual scheme of the Monte Carlo simulation processes conducted to generate gully widths ($w_{y,i,j}$: single simulated width for a given segment and year, $W_{y,i}$: set of 1000 simulated widths for a given segment and year) and depths ($d_{y,i,j}$: single simulated depth for a given segment and year, $D_{y,i}$: set of 1000 simulated depths for a given segment and year) and calculate the cross section ($S_{y,i}$) for each gully segment and year. k is a shape factor for the gully cross section, m is the number of gully segment, n is the number of simulations, and a and b are fitted linear regression coefficients of the depth-width relation, with respective means ($\bar{a}$, $\bar{b}$) and standard deviations (s_a, s_b).

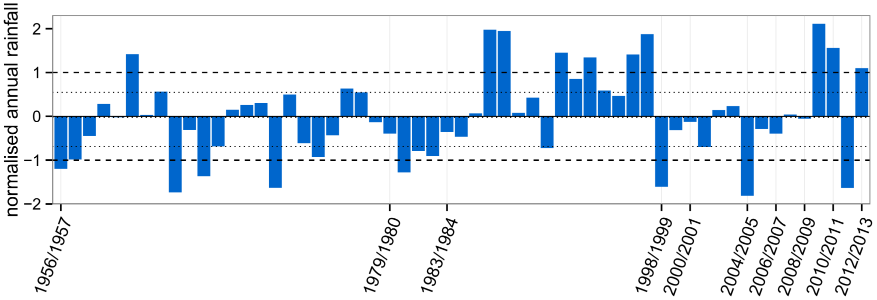


Figure 6. Standardized annual rainfall in the period 1956-2013.

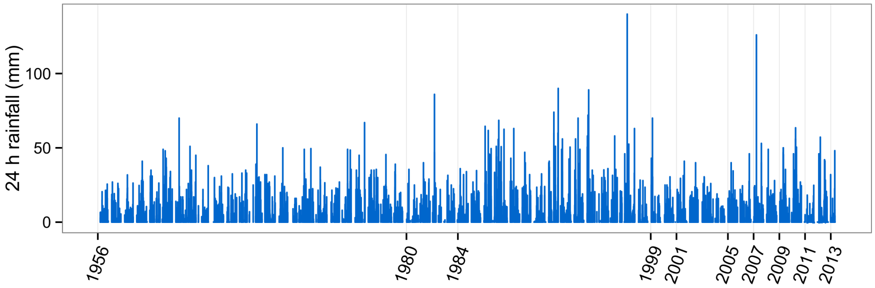


Figure 7. Daily rainfall recorded in the period 1956-2013.

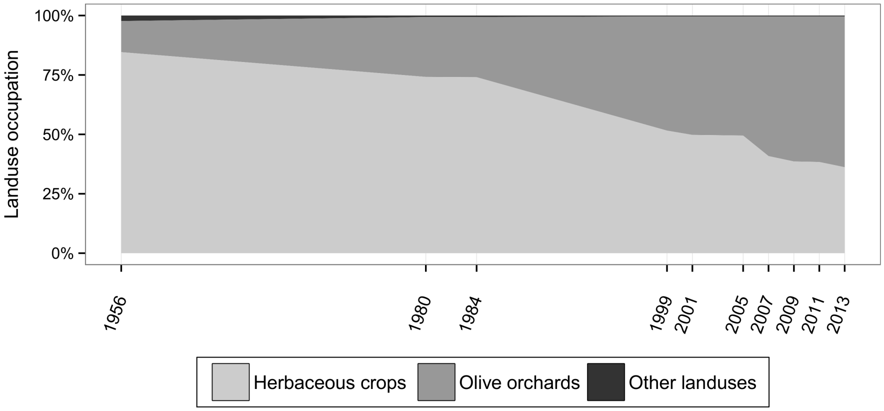
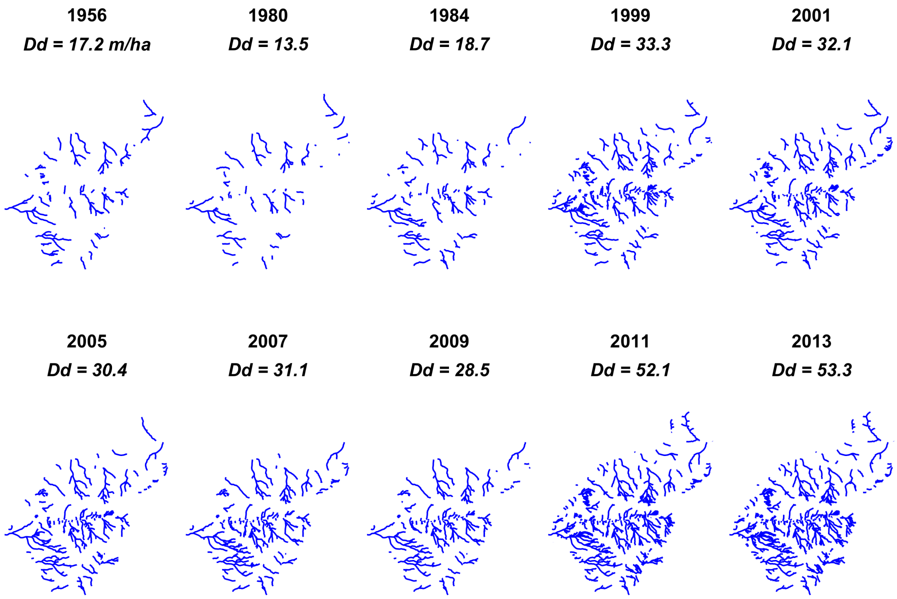


Figure 8. Land use changes in the period 1956-2013.



1956 *Dd = 17.2 m/ha*

1980 *Dd = 13.5*

1984 *Dd = 18.7*

1999 *Dd = 33.3*

2001 *Dd = 32.1*

2005 *Dd = 30.4*

2007 *Dd = 31.1*

2009 *Dd = 28.5*

2011 *Dd = 52.1*

2013 *Dd = 53.3*

Figure 9. Gully network evolution and drainage density (D_d), in m ha^{-1}, at each period.

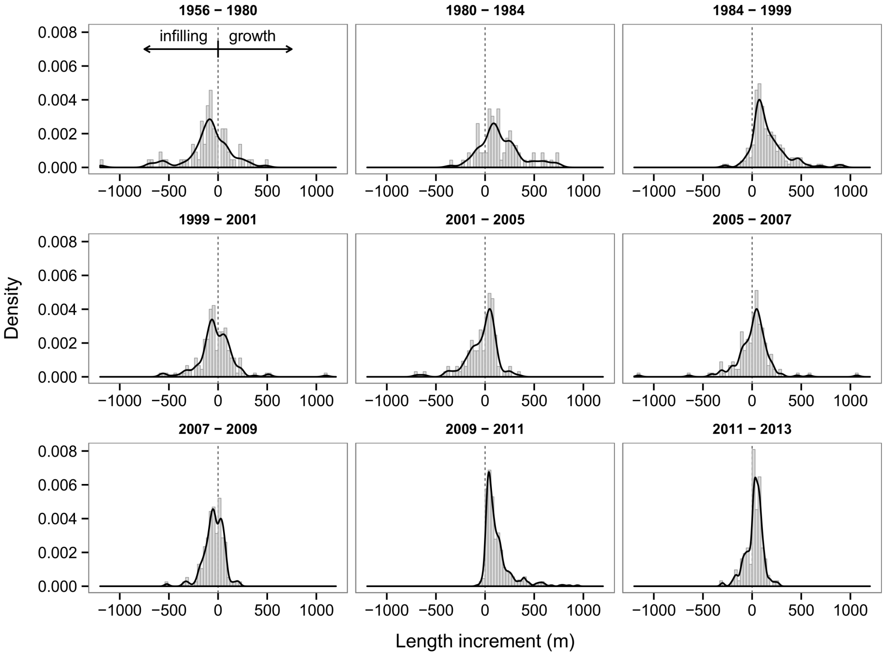


Figure 10. Gully headcut growth or decrease in the different periods between 1956 and 2013.

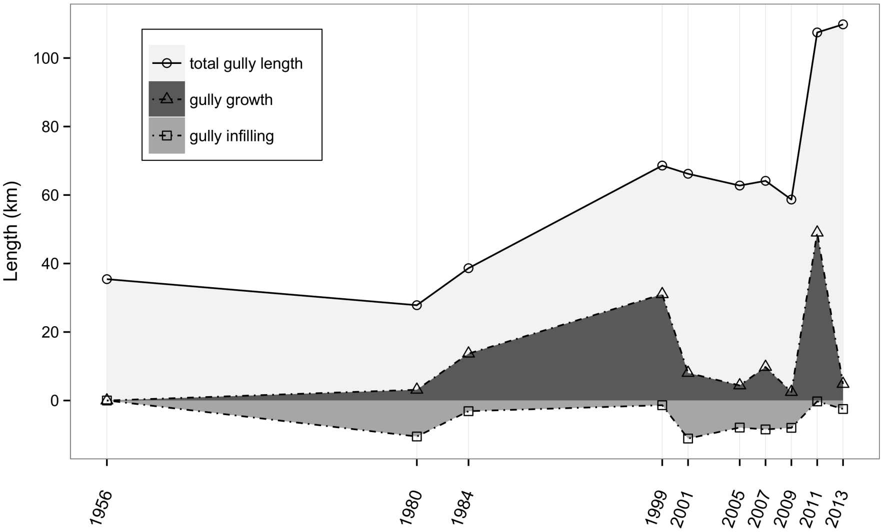


Figure 11. Gully length dynamics in the period 1956-2013.

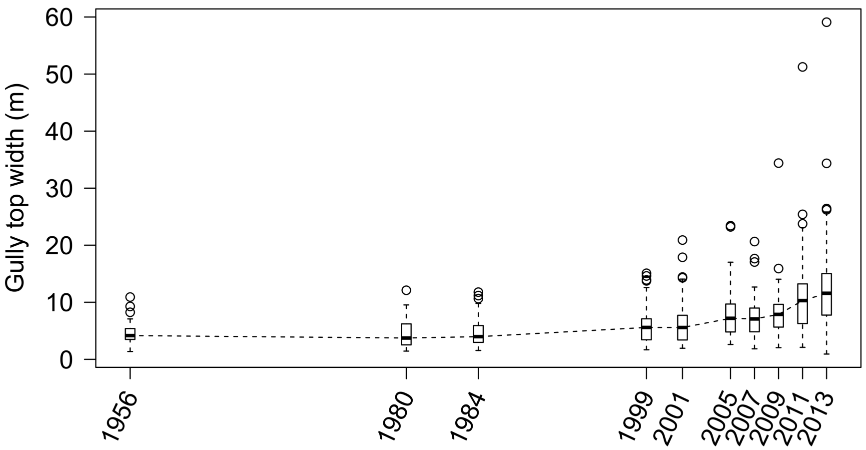


Figure 12. Gully top widths dynamics in the period 1956-2013 derived by measuring by photointerpretation. The dashed line indicates the mean, box and whiskers indicate the 25-50% and 5-95% quantile ranges, respectively.

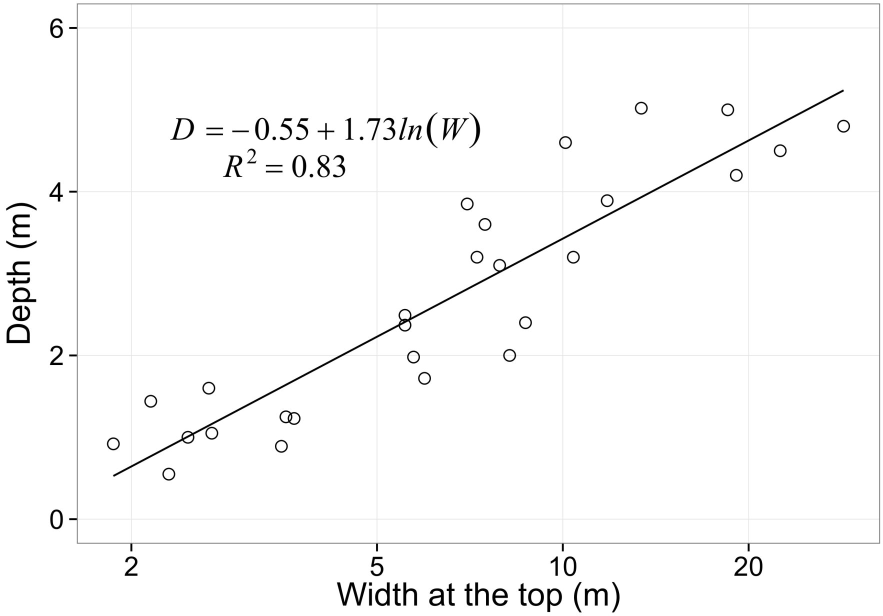
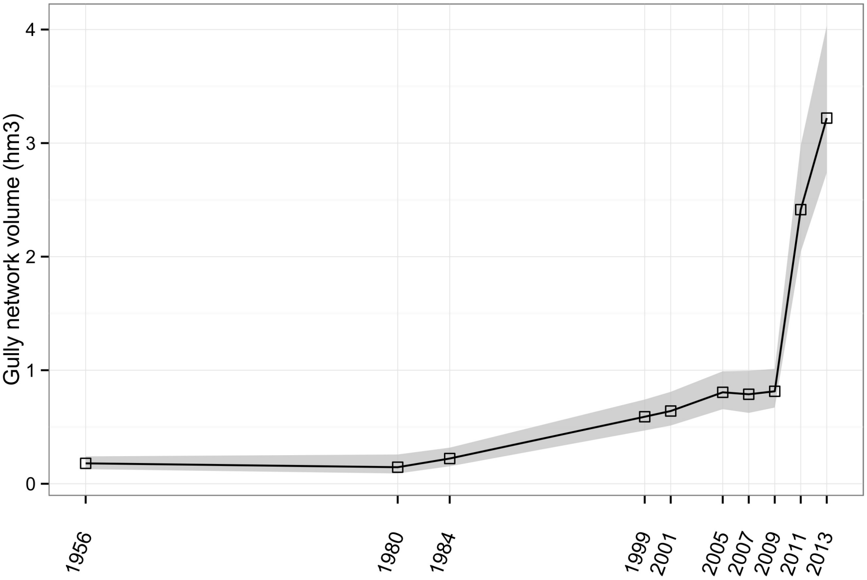


Figure 13. Width-depth relationship derived from field measurements.

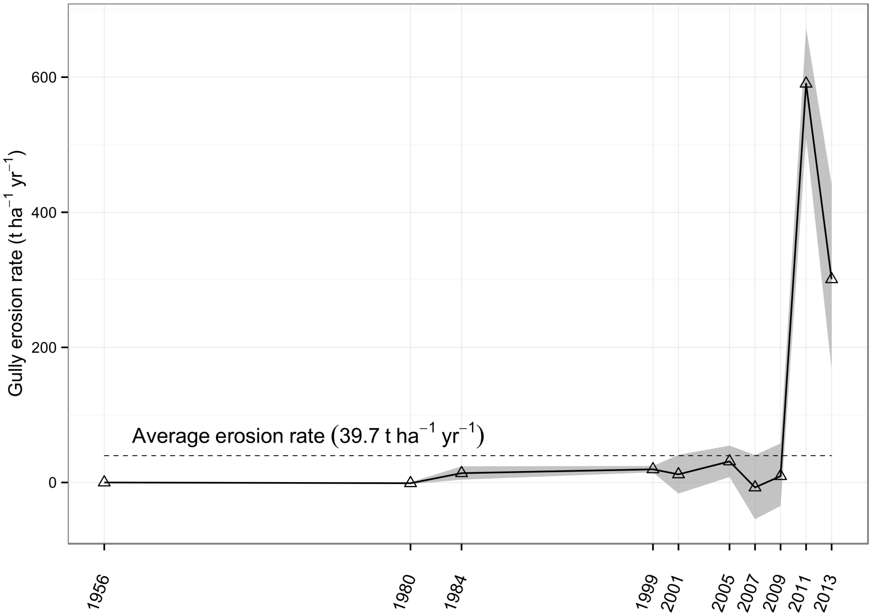
~~Gully network volume dynamics in the period 1956-2013 and uncertainty interval~~



~~(grey).~~

Figure 14. Gully network volume dynamics in the period 1956-2013 and uncertainty interval (grey).

~~Gully erosion rate in ton ha^{-1} yr^{-1} calculated by Monte Carlo simulation method, and average erosion rate in the period 1956-2013.The grey~~



~~area represents the 90% uncertainty level~~

Figure 15. Gully erosion rate in t ha^{-1} yr^{-1} calculated by Monte Carlo simulation method, and average erosion rate in the period 1956-2013.The grey area represents the 90% uncertainty level

Table 3. Land use, rainfall indicators and gully growth. f_h and f_o: fractions of surface dedicated to herbaceous and olive crops, in the first year of each period. nle: number of 24 hours rainfall events per year higher than 13 mm, $nleo$: number of 24 hours rainfall events per year over the average 24 hours rainfall plus the standard deviation, R_{max}: highest daily rain depth registered within the period, MAR: Mean annual rainfall in the period. ΔL: total, and $\Delta L/\Delta t$, partial increase in gully length, and GH: gully headcut growth, averaged over the area.

		land use		rainfall				gully growth		
period	Δt	f_h	f_o	nle	$nleo$	R_{max}	MAR	ΔL	$\Delta L/\Delta t$	GH
	yr					mm		km	$km\,yr^{-1}$	$m\,ha^{-1}yr^{-1}$
1956		.85	.13							
1956-1980	24	.74	.25	12.9	6.8	70.0	494	-7.37	-0.31	-0.15
1980-1984	4	.74	.25	9.5	5.0	86.0	377	10.58	2.65	1.25
1984-1999	15	.52	.48	17.1	10.5	140.0	677	29.67	1.98	0.94
1999-2001	2	.50	.50	11.0	5.0	70.0	501	-3.06	-1.53	-0.72
2001-2005	4	.49	.50	11.8	4.5	41.0	438	-3.49	-0.87	-0.41
2005-2007	2	.41	.59	13.0	5.5	46.0	477	1.36	0.68	0.32
2007-2009	2	.39	.61	11.5	5.5	126.0	545	-5.48	-2.74	-1.30
2009-2011	2	.38	.61	27.5	13.0	68.5	917	48.77	24.39	11.54
2011-2013	2	.36	.63	12.5	6.0	57.2	492	2.36	1.18	0.56

Table 4. Kolmogorov-Smirnov tests (p-values) obtained by fitting observed gully widths during different years.

pdf	1956	1980	1984	1999	2001	2005	2007	2009	2011	2013
normal	0.18	0.24	0.25	0.19	0.21	0.33	0.21	0.12	0.03	0.07
gamma	0.66	0.77	0.55	0.81	0.74	0.96	0.77	0.67	0.43	0.71
lognormal	0.71	0.98	0.69	0.98	0.97	0.94	0.90	0.92	0.64	0.76
weibull	0.36	0.60	0.60	0.48	0.66	0.65	0.42	0.47	0.21	0.48

pdf: Probability distribution function