CHAPTER

14

Gully-Erosion Monitoring

To the experienced geographer a map may illustrate perfectly the action of a stream working headward into higher land; but the student to whom the conception of headward erosion is new will certainly grasp the idea more readily from an aerial photograph. Willis T. Lee (1922)

14-1 INTRODUCTION

Gullies are permanent erosional forms that develop when water concentrates in narrow runoff paths and channels and cuts into the soil to depths that cannot be smoothed over by tillage any more. They are therefore the most severe form of soil erosion. Gullies occur all over the world mostly in semiarid and arid landscapes where high morphological activity and dynamics may be observed. Semiarid climate conditions and precipitation regimes encourage soil erosion processes through low vegetation cover and recurrent heavy rainfall events. Torrential rains with irregular spatiotemporal distribution result in high runoff rates, as the crusted and dry soil surface inhibits infiltration. In addition, widespread land-use changes of traditional agriculture toward both more extensive use, such as abandoned agricultural fields used for sheep pasture, and less-sustainable use, such as almond plantations, prepare the ground for soil crusting, reduced soil infiltration capacity, and increased runoff, which together aggravate the risk of linear erosion downslope and cause considerable off-site impairment such as reservoir siltation (Poesen et al. 2003).

In this context, gullies link hillslopes and channels, functioning as sediment sources, stores, and conveyors. The high variability of gully retreat rates and their important contribution to total sediment yield particularly in agricultural areas has been attested by many studies (Castillo and Gómez 2016; Vanmaercke et al. 2016). From a review of gully erosion studies in semiarid and arid regions, Poesen et al. (2002) concluded that gullies contribute an average of 50%–80% of overall sediment production in dryland environments.

Gullying involves a wide range of subprocesses related to water erosion and mass movements, such as headcut retreat, piping, fluting, tension-crack development, and mass wasting (Fig. 14-1), and it is the complex interaction of these subprocesses on different temporal and spatial scales that complicates reliable forecasting by gully erosion models (Poesen et al. 2003).

The evaluation of gully development rates under different climatic and land-use conditions provides important data for modeling gully erosion and predicting impacts of environmental change on a major soil

Fig. 14-1 Gully erosion in southeastern Spain. (A) Active headcut of small gully ~2.5 m wide and < 1 m deep. (B) Large gully with remains of piping hole and fluted walls typical for higher dispersible subhorizons. (C) Large gully filled with debris of collapsed sidewall.

https://doi.org/10.1016/B978-0-12-812942-5.00014-8

erosion process. Numerous authors have investigated (non-ephemeral) gully development in different environments (e.g. Burkard and Kostaschuk 1997; Oostwoud Wijdenes and Bryan 2001; Vandekerckhove et al. 2001; Gábris et al. 2003; Martínez-Casasnovas et al. 2004; Avni 2005; Wu et al. 2008; Frankl et al. 2012), but still both methodological problems and a lack of comparability across study areas exist.

Poesen et al. (2002, 2003) therefore stressed the need for more detailed and more precise monitoring and modeling of gullies. In addition, the importance of understanding the temporal variability of gully-erosion rates as well as the role of land use and other potential control factors in the catchment area is emphasized by Vanmaercke et al. (2016). Lane et al. (1998) pointed out that the monitoring of the changes in form may provide a more successful basis for understanding landform dynamics than monitoring the process driving those dynamics, as this morphological information may allow to estimate the spatial distribution of process rates. In this context, remote sensing is an obvious choice for monitoring gully erosion, as it allows the rapid and spatially continuous coverage of a site.

However, the measurement precision and repeat rate attainable with conventional remotely sensed images are not able to correspond with the process magnitudes and dynamics that are required for recording and investigating the short-term spatial and temporal variability of gully retreat (Ries and Marzolff 2003). Small-format aerial photography (SFAP), in contrast, has an excellent potential for gully-erosion research as it bridges the resolution gap between terrestrial and conventional aerial photography or very-high-resolution satellite imagery. However, when SFAP began to make a comeback in the late 20th century (Chap. 1-2), geomorphologists in general, and gully-erosion researchers in particular, were

Fig. 14-2 Selected gullies monitored by SFAP in Spain (A–F), Morocco (G–K), and Burkina Faso (L and M). Kite and hot-air blimp photographs by IM, JBR, and collaborators, taken between 1996 and 2014. (A) Barranco de las Lenas. (B) Barranco Rojo. (C) Salada 1. (D) Freila. (E) Casablanca. (F) Belerda 1. (G) Gchechda. (H) Hamar 1. (I) Hamar 3. (J) Lam 1. (K) Gorom-Gorom. (L) Oursi.

comparatively slow to adopt this niche remote-sensing technique. Images, after all, are two-dimensional representations, and gullies are three-dimensional, often highly complex landforms. This presents specific challenges with respect to analysis methods and digital data formats that were not easily dealt with 30 years ago.

Until the early 2000s, most gully-monitoring studies using remotely sensed imagery therefore resorted to standard large-format aerial photographs with medium to small image scales, looking at medium- to long-term intervals (e.g. Burkard and Kostaschuk 1997; Vandaele et al. 1997; Nachtergaele and Poesen 1999; Vandekerckhove et al. 2003). It is only in recent years that the rapid development of both UAS and photogrammetric techniques—in particular, Structure from Motion–Multi-View Stereo (SfM-MVS)—has made SFAP of interest for a wider gully-erosion research community (e.g. Stöcker et al. 2015; Wang et al. 2016; Koci et al. 2017; Wells et al. 2017; Bennett and Wells 2018; Feurer et al. 2018; Gudino-Elizondo et al. 2018).

For 25 years, SFAP has been a core method for gully-erosion research in numerous studies conducted by the authors (Marzolff 1999, 2014; Marzolff et al. 2003, 2011; Ries and Marzolff 2003, 2007; Marzolff and Ries 2007; Seeger et al. 2009; Ries et al. 2016). The following sections summarize some of the work done with hot-air blimps, kites, and fixed-wing and multirotor UAS across semiarid landscapes in southwestern Europe and North and West Africa, illustrating the benefits of SFAP not only for quantifying but also for understanding gully-erosion processes by selected examples.

14-2 STUDY SITES AND SURVEY

The study areas are situated in Spain, Morocco, and Burkina Faso along a transect running from semiarid to subhumid Mediterranean and subtropical desert climate to tropical wet-dry regions (Fig. 14-2; for additional study sites, see gully images in Chaps. 2, 4, 5, 10 and 11). Thus,

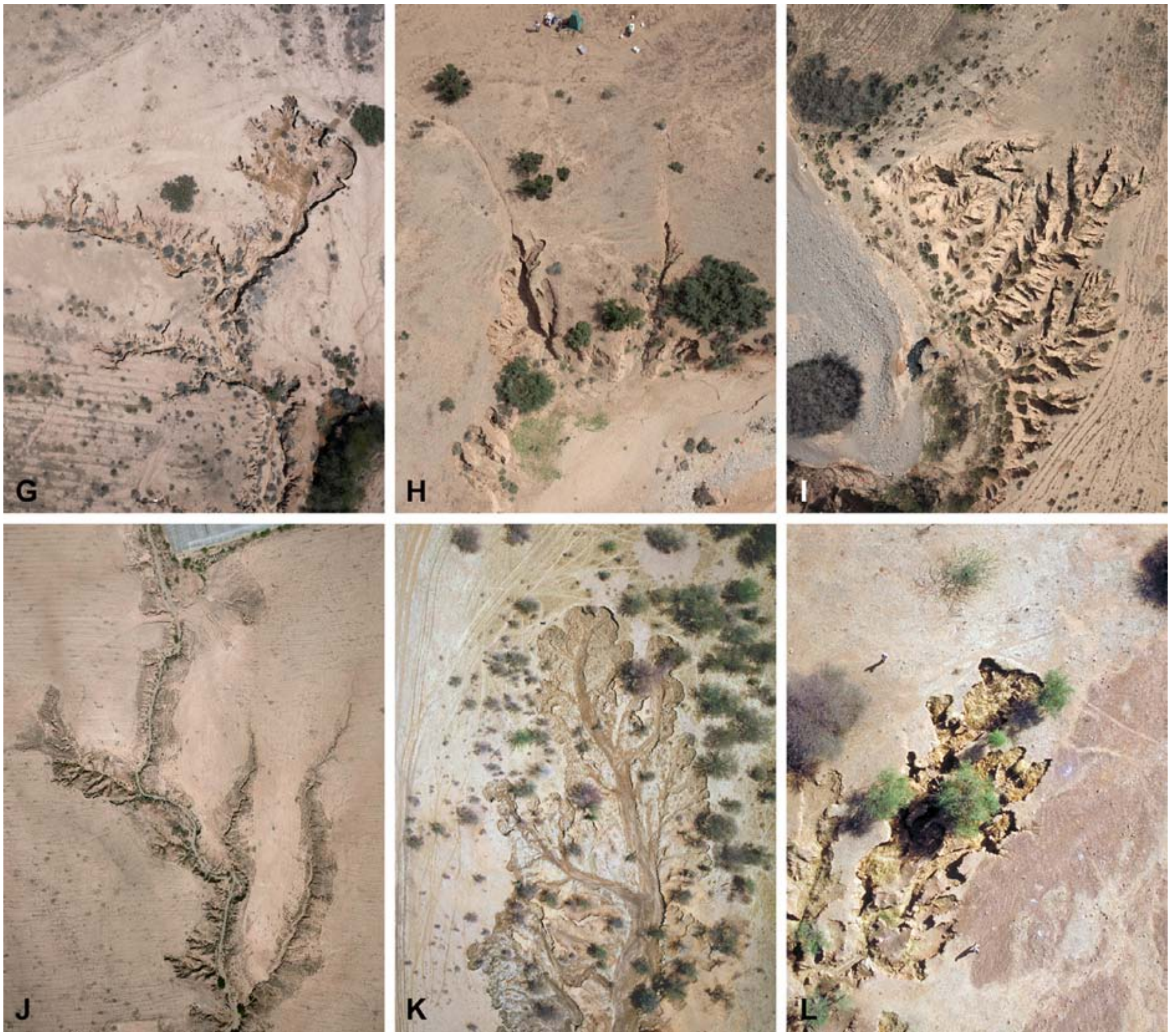

Fig. 14-2, Cont'd

they cover climatic regions where precipitation regimes are the most favorable for gully erosion. The gully environments range from agricultural areas and rangeland to deserts. Beginning between 1995 and 2010, >30 gullies of varying types, sizes, and ages have been monitored with stereoscopic SFAP in intervals of usually 1 or 2 years.

Both platforms and cameras have evolved over the years from more manually navigated and analog to autopiloted and digital. Depending on wind conditions and survey area size, a hot-air blimp (see Chap. 7-3.3) or a large rokkaku-type kite (see Chap. 7-4) was employed as a platform for analog (up to 2002) or digital single-lens reflex (DSLR) cameras. Since 2010, the platform used most is the *MAVinci Sirius* I (see Chap. 8-2), a fixed-wing UAV equipped with a digital mirrorless interchangeable-lens camera (MILC). Most recently, small quadcopter UAS (*DJI Phantom* 3/4) with integrated on-board cameras have joined the fleet.

The study sites that are monitored range from individual gullies to badland areas to whole gully catchments. The required image scales and resolutions vary depending on the processes observed and include detail photos as well as overview images. In order to take into account the different site extents and observation scales, the surveys are usually conducted at multiple flying heights. At all gully sites, ground control points (GCPs) measured with a total station or RTK-GPS in a local coordinate system are permanently or temporarily installed with steel pipes and marked with signals for the photographic survey (see Chap. 9-5). From the resulting stereoscopic images with extremely high ground resolutions of 0.5–10 cm, various techniques of analysis for measuring gully development and loss of soil material have been carried out with image-processing systems, geographic information systems (GIS), and digital photogrammetry.

14-3 GULLY MAPPING AND CHANGE ANALYSIS

During the early years of study, 2D measurements of headcut retreat and gully growth were accomplished by rectifying and—if required—mosaicking the photographs using GCPs installed in the surroundings of the gully. Thus, detailed mapping of the gully edges was possible despite the remaining relief displacement in the gully interior, which was not at the focus of the investigation and could not have been geocorrected accurately with polynomial rectification (see Chap. 11-2.2). In later project stages, 3D mapping in a stereoviewing environment and digital elevation model (DEM) extraction using digital photogrammetry software made it possible to map the complex gully forms even more precisely (see Fig. 11-20) and to create 2.5D or 3D models for measuring gully volume, analyzing hydrological flow, and delineating rill and gully catchments (Fig. 14-3; see also Figs. 11-22 to 11-24).

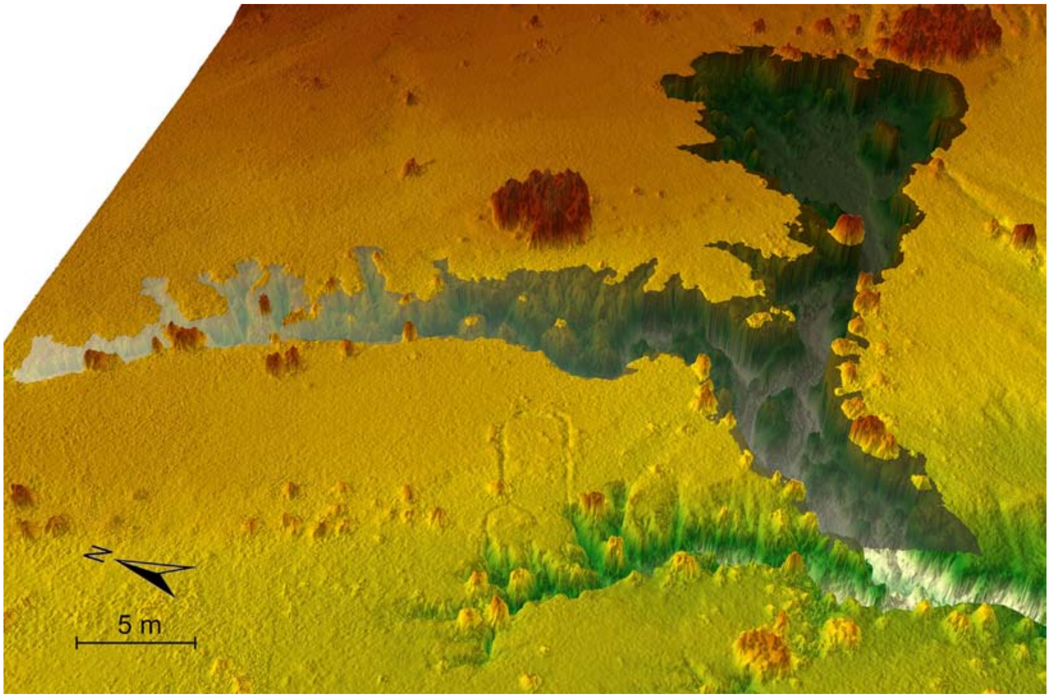

Fig. 14-3 Oblique 3D view of the digital elevation model of Gully Gchechda, near Taroudant, South Morocco, November 2011 (compare Fig. 14-2G). By constructing a "lid" for the gully (here seen in transparent gray) from the digitized gully edges, the gully volume below may be calculated. The covered part of the gully has a volume of 678 m^3; it has grown fast by 274 m^2 (343 m^3) since September 2009, with an annual maximum headcut retreat rate of 7.56 m. The headcuts of the eastern part continued to retreat by an average 1.1–1.2 m/a until March 2014, and slowed down to 0.15–0.25 m/a until October 2018 following changes in runoff conditions in the gully catchment.

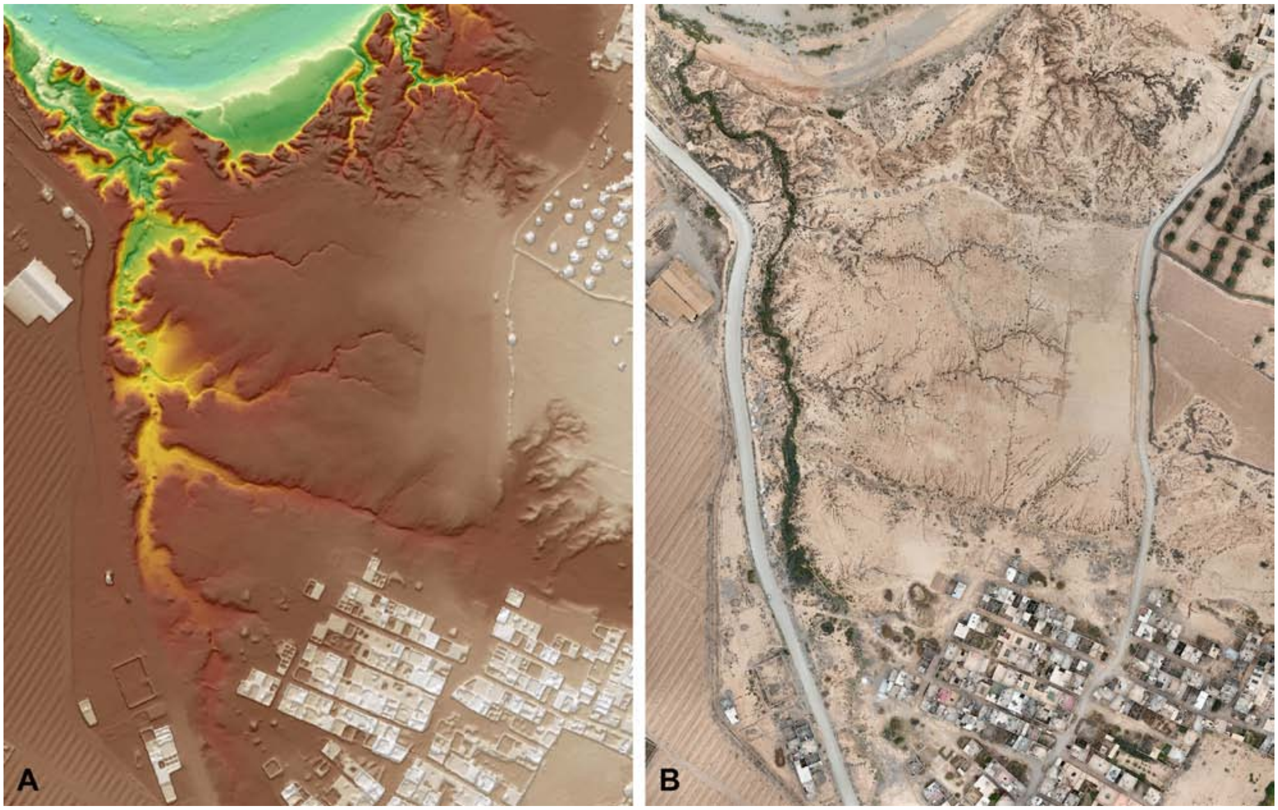

Fig. 14-4 Digital elevation model (A) and orthophoto mosaic (B) with 50 and 10 cm GSD of the 25-ha study area El Houmer, South Morocco (compare Fig. 3-13). For these datasets, 370 overlapping images were taken with an MILC on a fixed-wing UAV within 25 min flying time. Processing with SfM-MVS photogrammetry (as described in Chap. 3-3.5) was done without GCPs, using the images' exterior orientation from GPS/INS flightlog in a direct georeferencing approach. The positional accuracy is ~1.5 m, processing time was ~2 h. Image processing by IM.

Detailed change analysis from the multitemporal datasets for quantifying linear retreat and increase of gully area and volume at the site scale still requires precise ground control with GCP deployment and measurement as described in Chap. 9-5. At the study-area scale, lower resolution overview datasets may be processed with a direct georeferencing approach, using the GPS coordinates attributed to each UAS image during the flight (Fig. 14-4; see also d'Oleire-Oltmanns et al. 2012). Orthophotos and DEMs are used as a basis for maps of land use, relief, and hydro-geomorphological processes.

The following examples of gully development illuminate the variability in rates and control factors of gully evolution. Gully Gorom was monitored with SFAP over a period of three seasons in a project terminated in 2002; its change map is complemented with smaller scale satellite image data from 2007 (Fig. 14-5). Note the much coarser outlines of the last gully stage; high-resolution satellite data were a viable supplement in this case only because of the large size of the gully, the fast retreat rate, and the long final interval. The gully edges retreat along the full length of the gully, reshaping the gully form during each rainy season. The surrounding glacis area has little relief that might lead to preferential linear flow paths, apart from the shallow main drainage line and some off-road tracks left by occasional vehicles driving alongside the gully. It is in the direction of these tracks that one of the lateral headcuts swings during the last monitoring interval.

Along the gully edges, mass wasting is the main reason for gully growth, and large clods of soil come to rest beneath the gully rim before being washed away by further erosion. Piping (subsurface erosion), often promoted by desiccation cracks at the headcut vicinity, is also involved in the retreat process (compare Fig. 10-10). Despite the great width of the gully, incision is only shallow and the heights of the sidewalls are only between 40 and 100 cm. The maximum depth of the central drainage channel is ~1.2 m. Within the part of the mapped gully, areal growth is quite regularly around 800 m^2 per year, but maximum linear headcut retreat varies depending on the spatial development of the gully's shape. High-resolution satellite images on *Google Earth* allow roughly to follow the development for another 10 years: Guided by criss-crossing tracks, the gully had changed its course by 90° until January 2017, with an increased annual retreat rate of ~21.2 m, growing an average 1020 m^2 per year.

Our research at >30 gullies confirms that gully growth is strongly related to the characteristics of topography,

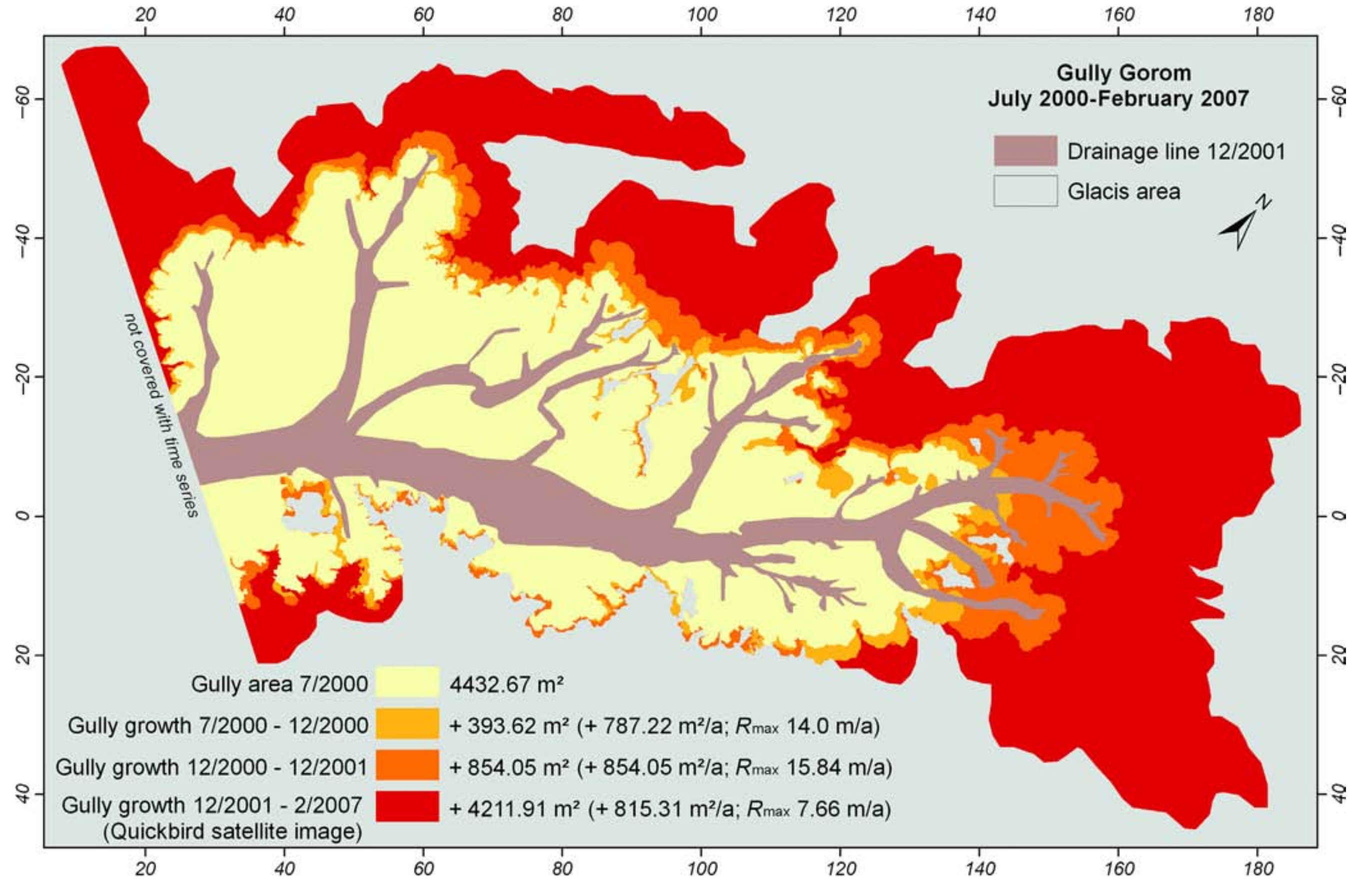

Fig. 14-5 Two-dimensional change analysis of Gully Gorom-Gorom, Province of Oudalan, Burkina Faso. Gully growth quantified between rainy seasons 2000 and 2001 (SFAP) and 2007 (*Quickbird*). Based on kite photography by IM, JBR, and K.-D. Albert; image processing and cartography by K.-D. Albert and IM.

substratum, runoff, and infiltration behavior as well as land use in the gully catchment. Many of these factors may be interpreted or analyzed and mapped with SFAP. A good example is Gully Salada 1, where human interaction plays an additional role (Fig. 14-6; see also Marzolff et al. 2011). Until 2004, this large gully cutting into the Quaternary deposits of the Guadalentín Basin in southeastern Spain was the fastest growing of the 14 Spanish gullies being monitored, with an average maximum headcut retreat of ~0.5 m (Marzolff and Ries 2007).

The immediately adjoining almond plantation, which was established only a few years before monitoring began, is kept weed-free by regular plowing. Soil crusting results in remarkably high runoff rates and in the formation of ephemeral gullies between the almond trees. To bar the gully from retreating farther into the plantation, the farmer had plowed up an earthen dam around the gully margin—a measure with limited success. Runoff from the plantation collected at the earthen dam subsequently resulted in subsurface erosion processes, creating a growing piping hole, which drained beneath a bridge remaining of the former dam (see also Vandekerckhove et al. 2003).

The piping hole increased rapidly in the following years, while the main gully was used as a rubbish dump, and building rubble was shoved repeatedly over its northern edge by tractors. In 2005, the upper part of the gully including the piping hole was completely filled with ~7000 m^3 rubble and soil material (as quantified from stereophoto analysis) up to the level of the former surface, sloping into the remaining gully beyond an earthen dam (Fig. 14-6A). This dam reestablished the former border of the field; the missing almond trees were replanted between 2006 and 2008. By 2006, the infilling already had begun to subside and show large settlement cracks, preparing the ground for resumed piping processes. In September 2009, heavy rainfall events resulted in terrace and dam breaches, intense sheet wash and ephemeral gully erosion in the upslope almond plantation (see also Fig. 10-40). In spite of the gully infilling and leveling, the shape and development of the former piping hole and gully still control the spatial pattern of overland flow concentration on the field (Fig. 14-6B).

This example illustrates two important aspects for gully-erosion research: Firstly, earthen dams or loose

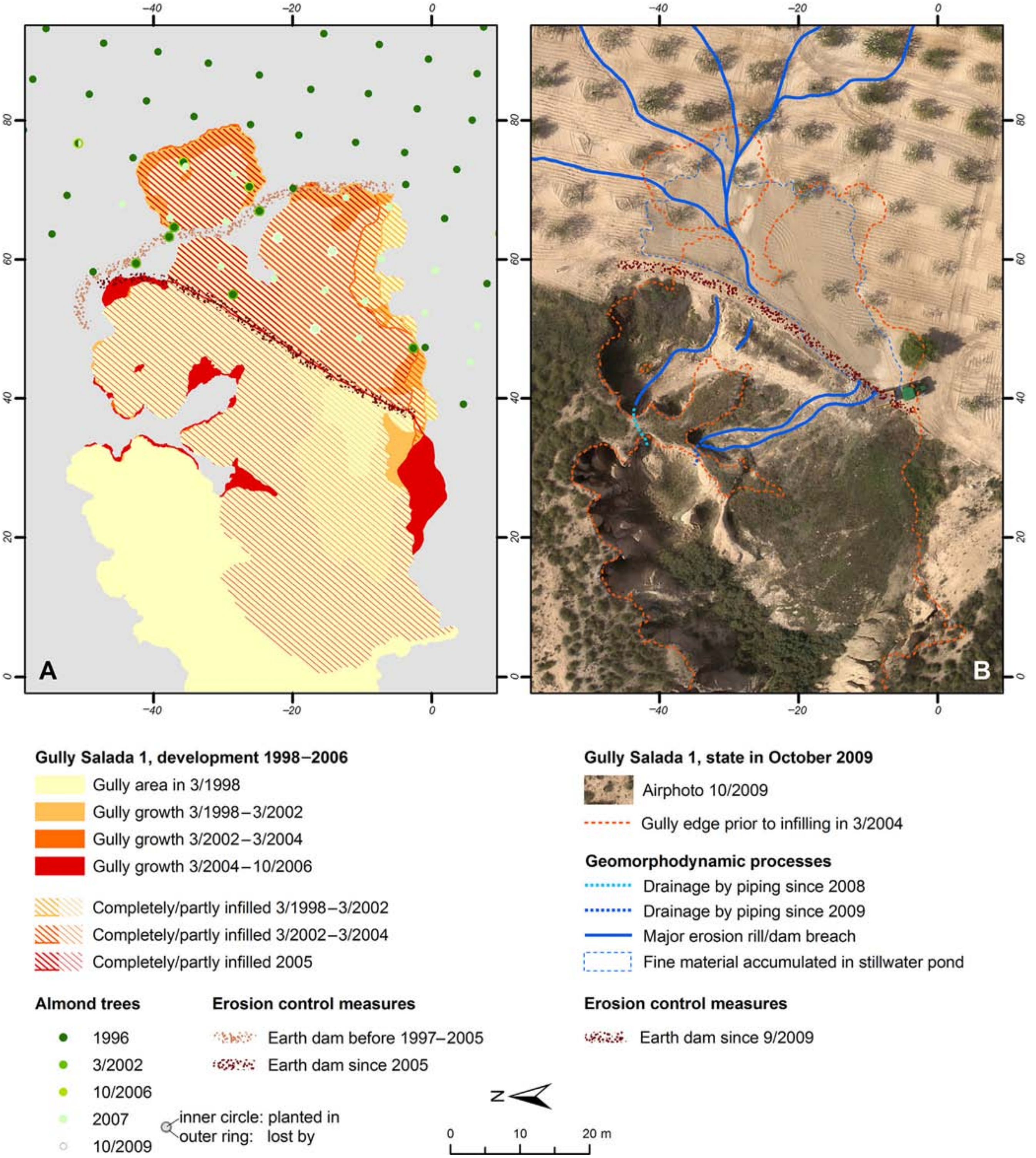

Fig. 14-6 Evolution of Gully Salada 1, Province of Murcia, Spain, 1996–2009, with indication of gully erosion, drilling and piping, erosion control measures, and almond tree plantings. Based on hot-air blimp and kite photographs by IM, JBR, and M. Seeger; image processing and cartography by IM. (A) Gully growth and infilling between 1996 and 2006. (B) Gully state and geomorphodynamic processes in October 2009. For a more detailed development history of this site, see Marzolff et al. (2011).

stone dams built up for erosion control are not able to withstand the high runoff volumes during extreme rainfall events. On the contrary, by retaining water in temporary ponds they may boost piping processes and headward erosion at the dam. Secondly, long-term monitoring with intervals of 15 to 30 years—typical for studies based on conventional large-format aerial photographs—is not able to reveal the influence of ad hoc erosion control measures by farmers. The average retreat rates measured in long-term monitoring should therefore be regarded as potentially too low.

Vandekerckhove et al. (2003, Table 2), for example, measured no retreat for Gully Salada 1 between 1957 and 1981 from conventional airphotos. In the same study, they also observed negative change at other gullies due to infilling by tilling. Possible alternation of infilling and renewed erosion during long-term monitoring, however, cannot be detected unless shorter observation intervals are used. Capturing spatially continuous, high-resolution 3D data using SFAP is of high value for avoiding such methodological errors in gully monitoring (Marzolff et al. 2011).

Beyond 2D mapping and quantification, 3D photogrammetric analysis of stereo imagery has numerous advantages for gully-erosion monitoring. Various methods and methodological issues of photogrammetric SFAP processing applicable to gully-erosion research have already been discussed in Chaps. 3-3, 10-4 and 11-6. For example, the identification and delineation of gully edges is greatly improved when mapping manually in a 3D stereoviewing environment. Furthermore, automatic terrain extraction allows creation of 2.5D or 3D elevation models that may then be analyzed by cut-and-fill operations in a GIS environment to enable determining the total soil loss at the gully site as well as volumetric changes between monitoring dates. Photogrammetric 3D modeling from SFAP is clearly superior here to traditional terrestrial measurement methods. Modeling the complete form rather than taking sample measurements of gully extent and depth allows for example the stratification of volumetric change in erosion and deposition aspects, yielding results for the gully's own sediment balance.

Fig. 14-7 shows results from an exemplary observation interval at Gully Salada 3—a typical bank gully of the simplest, single-headcut U-profile form (see Fig. 4-31)—that illustrates the complexity of the patterns often simplified as "headcut retreat." Between 1998 and 2002, ~4.4 m^2 area, corresponding to 13 m^3 soil material, was lost to backward erosion at the headcut (Marzolff and Poesen 2009). In the same period, the surface height within the gully increased when 45% of the material eroded at the headcut was deposited on the gully bottom. Most of this came to lie close to the headcut, but some was washed farther downslope at the gully bottom. Limited erosion only took place on the gully floor, and its longitudinal profile obviously experienced an increase of gradient not due to downslope erosion, but due to upslope deposition. This illustrates that not all material eroded at the headcut leaves the system directly and causes off-site damage (e.g. by reservoir siltation). This

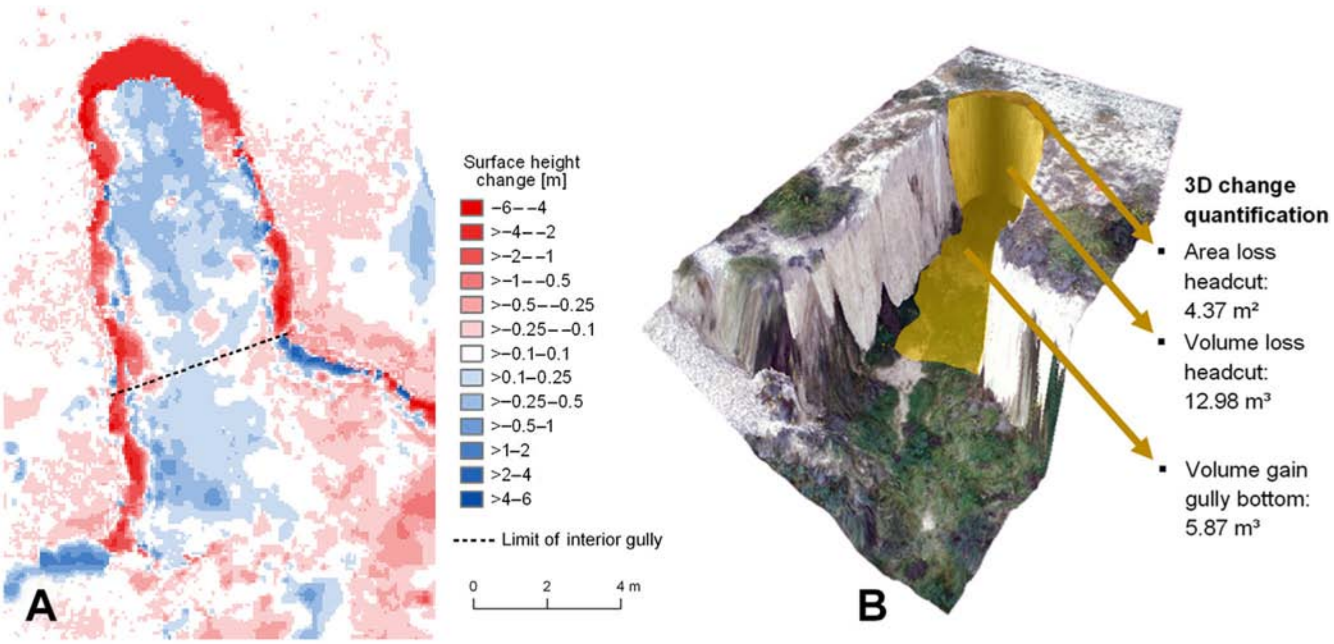

Fig. 14-7 3D change quantification of Gully Salada 3, Province of Murcia, Spain, between 1998 and 2002. Based on hot-air blimp photographs taken by IM, JBR, and M. Seeger; image processing and analysis by IM. (A) DEM of difference. (B) Orthophoto draped over 1998 DEM with summary of change measurements within the interior gully area.

function of a gully as a temporary sediment sink can only be detected with detailed 3D mapping from very high resolution imagery.

Fig. 14-7A also shows some of the difficulties associated with creating surface models for highly variable terrain (compare Fig. 3-15). Along the sidewalls, which contributed to the gully growth with another 0.7 m^2, the volume change visible in the change map must be considered somewhat inaccurate (note the improbable gain at the sidewall to the lower right of the calculation area limit). Here, the camera's perspective eye could not obtain an unobstructed view of the narrow and deep corridor carved by the gully, causing less inclined slopes in the 2002 model. With newer methods of SfM-MVS photogrammetry and 3D point cloud analysis, the combination of vertical and oblique imagery and true 3D data formats (rather than 2.5D) allow for considerable improvements in modeling and measuring such complex forms (see Fig. 11-22).

Gully-erosion studies usually report soil loss as linear, areal, and volumetric retreat rates, that is, positive gully development. However, in regions with high pressure on land as a resource, erosion-affected areas are increasingly being reclaimed as agricultural land, and negative development by infilling and leveling of ephemeral as well as permanent gullies and badlands may also be observed (Marzolff and Pani 2018). The example of Gully Salada 1 has already shown this for a region with moderately intensive rainfed agriculture in southern Spain. Although set in rural surroundings as well, the large sedimentary fans of the Souss Basin (South Morocco) in contrast are characterized by highly dynamic land-use changes with transformations from traditional agriculture to vast agro-industrial plantations. The area is heavily dissected by gully erosion that was triggered by deforestation and the decline of sugarcane cultivation at the end of the 17th century; the resulting badlands reach deep between the modern fruit tree plantations and greenhouses (Fig. 14-8; see also Fig. 10-19).

With the aim of restoring the original pre-erosion surface form and extent of existing agricultural land, gullies and badlands are leveled with bulldozers and filled up with topsoil material scraped from the non-eroded surroundings, as may be observed in Fig. 10-38. The success of the leveling measures strongly depends on subsequent land-use type and soil-erosion protection. Leveled sites in the Souss show a clear amplification of interrill and gully erosion processes compared to undisturbed sites (Peter et al. 2014). Fig. 14-9 illustrates the case of Gully Glalcha 1, an old dendritic gully system incising the bank of a small wadi that was infilled with soil material scraped from the surrounding hillslopes in 2009 in order to create space for a vegetable field. However, the original macro-relief with shallow depressions draining over the steep wadi bank remained.

Linear incision took place in the old thalwegs immediately during the next rainy period in 2010, reactivating the old gully system and eroding at least 720 m^3 of infilled soil. Of these, at least 693 m^3 (~1040 t) had previously been transferred by the leveling process from

Fig. 14-8 Badlands with deep gullies along a wadi cutting into the Pliocene-Quaternary deposits of the Oued Irguitène sedimentary fan in the Souss Basin, South Morocco (view toward South). Citrus plantations and plastic greenhouses, predominantly for banana cultivation, have largely replaced traditional small-scale agriculture and rainfed cereal cultivation during the last 50 years, pushing upslope from the Souss River toward the foothills of the High Atlas Mountains. Taken with on-board camera of quadcopter UAV.

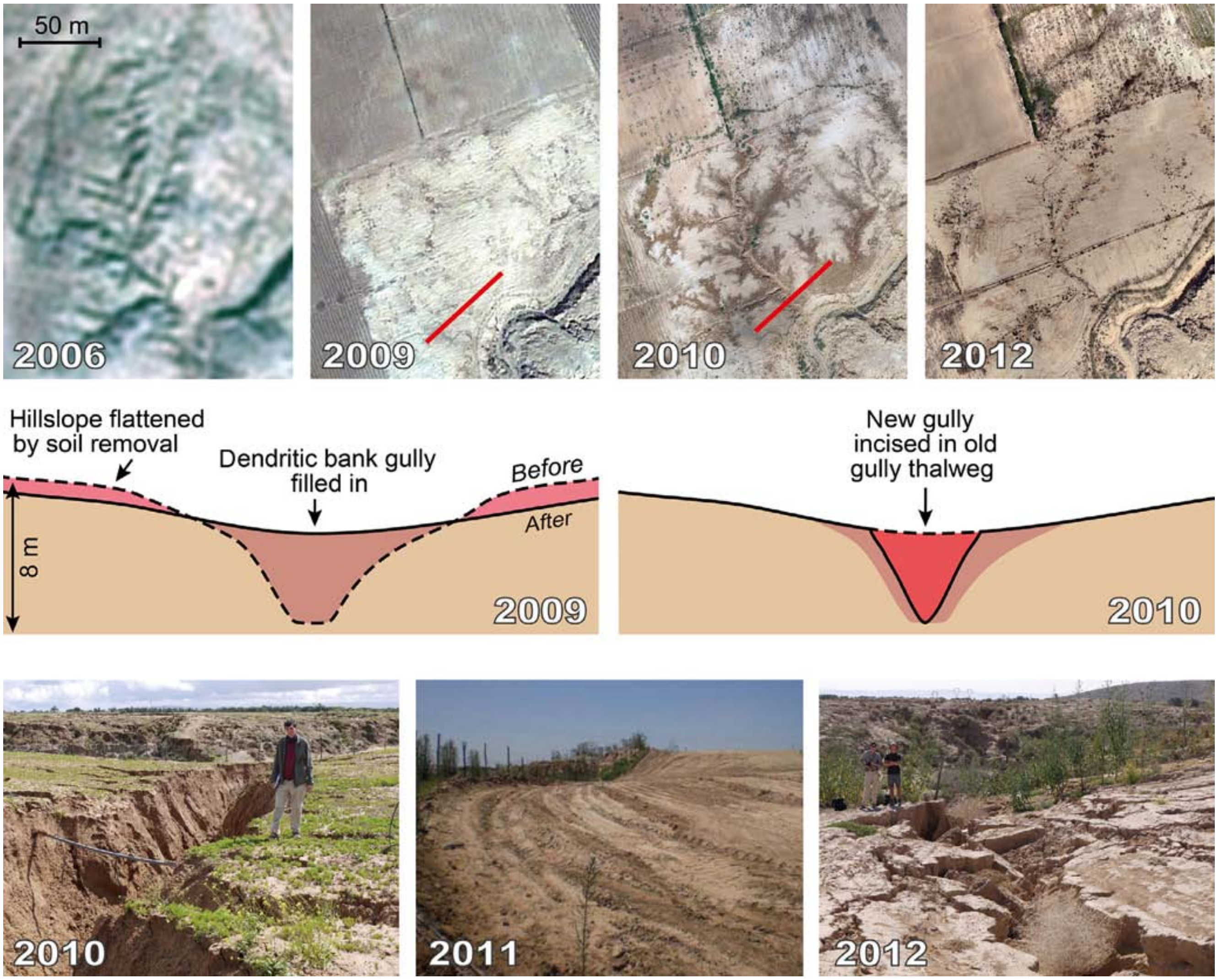

Fig. 14-9 Development of Gully Glalcha 1, near Taroudant, South Morocco. Top row: old gully system in 2006 (*Spot* satellite image), after leveling in 2009 (*Quickbird* satellite image), with renewed incision in 2010 and after second infilling in 2012 (SFAP taken with fixed-wing UAV). Central row: schematic diagram of gully evolution along the cross-profile shown as red line above. Bottom row: ground situation before and after second infilling.

the hillslopes into the gully channel and thus made available for linear erosion. When related to the gully catchment size (as derived by hydrological modeling from the regional-scale DEM; see Peter et al. 2014), the mean annual gully-erosion rate in 2009/2010 amounts to 204 m^3 per hectare (or 2 cm average terrain lowering). The mean soil depth removed by the remodeling of the terrain and gully infilling, in contrast, was even higher with 5.4 cm.

This volumetric quantification was computed by subtracting the gully DEM (Fig. 14-10) from a reconstructed pre-erosion DEM (d'Oleire-Oltmanns et al. 2012). The calculated soil loss must be considered a minimum value, as SFAP is not able to look beneath the surface for quantifying the subrosion processes that are taking place in the unconsolidated material of the infill. However, a closer look at the central part of the gully in Fig. 14-11 shows that SFAP is highly useful for qualitative assessments of the role of piping in gully erosion (see also Fig. 10-12 and Marzolff and Ries 2011). A second attempt of infilling at Gully Glalcha in 2011 was crippled again by subrosion and sacking processes. No additional attempts of gully-erosion control were made by the farmer, and recent SFAP from 2018 testifies to continued piping and side-rill incisions—a palimpsest of an old gully system that is still hidden beneath the surface.

As could be seen at Gully Glalcha 1, infilled bank gullies with unchecked connectivity to the local base level tend to be reactivated particularly fast. For preserving the newly reconstructed surface, protective measures at the outlet of the drainage area are imperative. Between Oued el Hamar and a small tributary wadi, a 13-ha interfluve area, which had occasionally been used for cereal dry-farming, was leveled in 2013 for a new citrus

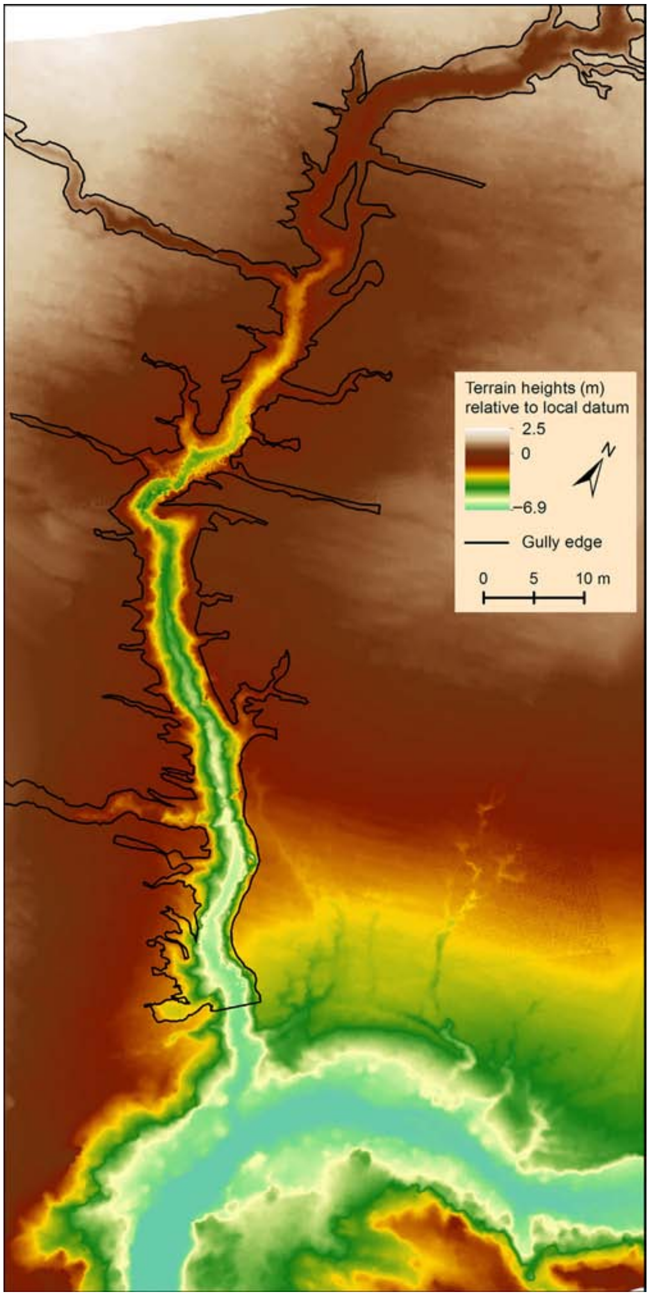

Fig. 14-10 Digital elevation model of Gully Glalcha 1 (subset) with 5 cm GSD, September 2010. Derived from vertical stereoscopic imagery taken with an MILC on a fixed-wing UAV by automatic DEM extraction; gully edge digitized manually in 3D view. Image acquisition, photogrammetric processing and cartography by S. d'Oleire-Oltmanns and IM.

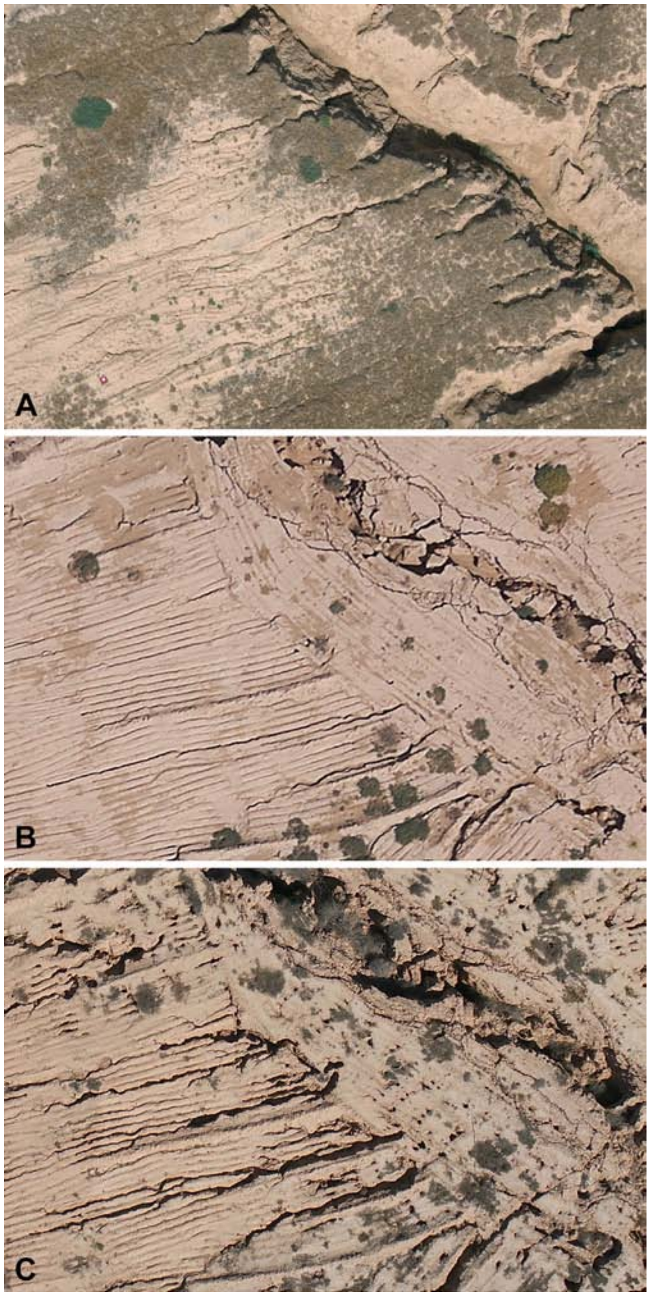

Fig. 14-11 Subsets of SFAP taken at Gully Glalcha 1 in 2010 (A), 2012 (B) and 2018 (C) continue to give evidence of an old gully system hidden beneath the repeated infillings of 2009 and 2011. Lateral rills draining into the gully follow the parallel leveling furrows. Strong signs of sacking may be observed along the main gully after the second infilling of 2011 (B and C). The cross-leveling by the bulldozer along the main drainage line of the gully creates a damming effect for the lateral rills. This triggers piping processes that allow the rills to drain beneath the infilling (see strings of piping holes in image C) and, in a feedback effect, intensifies deep headward erosion in the lateral rills.

plantation (Fig. 14-12). Numerous linear and dendritic bank-gully systems were infilled during leveling with soil material scraped off the flat ridge, and a low earth wall was formed at the edge of the field. 800 m of multistory gabions were built to protect the newly reconstructed wadi bank—resulting, however, in removal of point bars and narrowing of outside curves and the wadi bed. Some gabion foundations were already washed out by 2015, but the edges of the new plantation were still intact at the time of writing in 2018.

This short overview of gully-erosion research illustrates the great potential of SFAP interpretation and analysis for monitoring dynamic landforms. More details

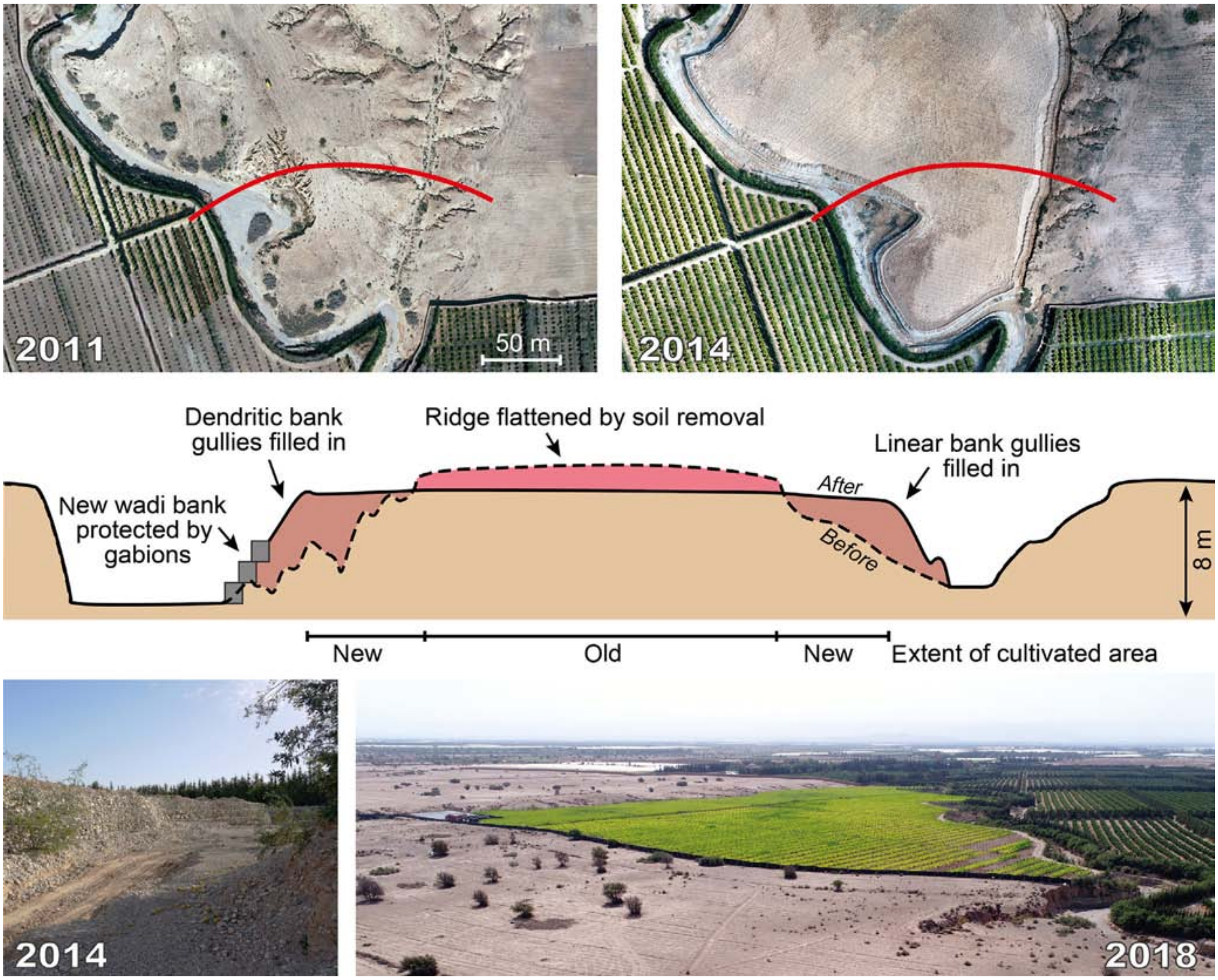

Fig. 14-12 Land-leveling of gullies at Hamar, north of Taroudant, South Morocco. Top row: southern end of the interfluve area between two wadis, dissected by bank gullies of various sizes and forms, seen before (2011) and after (2014) complete leveling and infilling with bulldozers. Orthophoto mosaics created from fixed-wing UAV imagery. Central row: schematic diagram of terrain remodeling along the cross-profile shown as red line above (the dendritic bank gully to the left may also be seen in Fig. 14-2 I). Bottom row: wadi after construction of gabion walls in 2014 (ground view looking south) and the complete 13-ha citrus plantation established on the leveled site in 2018 (oblique SFAP taken with quadcopter UAV, looking south).

about the gully development rates and their relation with local topography, substratum, and runoff and infiltration behavior in the gully headcut surroundings are given in the literature cited above. In summary, the development rates of the gullies vary strongly between individual study areas along the transect, and particularly the Spanish gullies retreat more slowly than expected. Improvements in 3D analysis methods during the last decade and thus increased possibilities of volumetric quantification have helped in revealing that the range of soil loss by gully erosion in different landscapes is even greater than the range of linear and areal retreat. In many cases, human activities aimed at soil-erosion mitigation have undesirable effects. In particular, land leveling is boosting rather than controlling gully erosion processes. Thus, gully erosion will continue to be a major topic for both land owners and researchers. In this context, SFAP may well be expected to transform natural resource management and soil-erosion models in future years (Bennett and Wells 2018).

14-4 SUMMARY

Gullies are permanent erosional forms that develop in many parts of the world, particularly in arid and semiarid environments. Gullies function as sediment sources, stores, and conveyors that link hillslopes to downstream channels. Human land use, and especially changes in land use and remodeling of terrain, may accelerate gully expansion by head cutting, sidewall collapse, piping, floor erosion, and other processes, which lead to widespread land degradation and potential damage to human structures and activities.

Beginning between 1995 and 2010, >30 gullies of varying types, sizes, and ages have been monitored by the authors using stereoscopic SFAP. The results prove the value of capturing spatially continuous, high-resolution 3D data for detailed gully monitoring and demonstrate the advantages of SFAP over field methods and conventional airphotos. 2D and 3D change quantification based on the detailed maps and DEMs provides additional information on the differences in headcut retreat behavior which cannot be described by simple linear measures. The spatially continuous 3D survey of the entire form offers the possibility of volume quantification and of distinguishing different zones and processes of activity both at the gully rim and within the gully interior. Multiscale SFAP surveys allow to capture the situation in the gullies' surroundings, providing orthophotos and DEMs for maps of land use, relief, and hydro-geomorphological processes.

Our research confirms that gully growth is strongly related to the characteristics of topography, substratum, runoff, and infiltration behavior as well as land use in the gully catchment. Human activities aimed at soil-erosion mitigation—such as leveling, infilling, or dam building around headcuts—often have undesirable effects, boosting rather than controlling gully erosion processes. The continuing role of gully erosion in land degradation together with recent improvements in modeling and measuring such complex forms with UAS and SfM-MVS photogrammetry is securing SFAP a key role in gully-erosion research in the future.