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Geomorphological changes in fire affected landscapes: field and laboratory techniques for soil erosion analysis.

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Chapter 4. Soil erosion assessment approaches: overview and specificities under post-fire conditions

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Introduction

Soil erosion by water addresses natural phenomena integrating in a complex way several physical processes, involving energy and mass transfer from the atmosphere to the soil surface along actual topographical gradients. This complexity generates complexity in both selection of assessment methods and interpretation of assessment results. It is therefore important to clearly identify the object under assessment in order to reduce such fundamental constraints, which is not always a simple matter.

Time and spatial scales very much affect erosional processes occurrence and rates. In fact, erosion is a spatially distributed phenomenon, involving sediment transfer along hill-slopes and from slope plans to the linear structures of the natural drainage network. As well, erosion is a time discontinuous, episodic, phenomenon, following the lack in time continuity of the erosive agent, the rainfall. Moreover, erosion phenomena combine continuous and threshold type of mechanisms, meaning that erosional responses may vary from nil to very high magnitude. This range is determined by changes in erosion processes contribution to total loss, from splash everywhere in a field or catchment in virtually all rainfalls (negligible to low loss), to interrill erosion in some events with Hortonian overland flow generation (low to severe loss), to gully incision in very few heavy and prolonged rainfall episodes, with topographically concentrated overland flow running over saturated soil (severe to very severe loss).

Assessing runoff erosion encompasses these wide ranges of processes time and space occurrence and continuity. Therefore, no such thing as a normalized erosion measurement methodology exists, and a wide set of methods historically developed, according to research needs and progresses in specific technology and instrumentation. The principles to be followed when assessing erosion are:

- to set the basic time and space measurement unit according to information requirements and practical feasibility;

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- to accept the black box approach for those units and ensure that it is experimentally respected (known inputs and outputs through system boundaries);
- to withdraw any wish to extrapolate measurement results to other time spans and spatial scales.

The present text aims at providing an overview on methods for measuring water erosion. In this sense, modelling, mapping and estimation techniques are not explicitly mentioned in this overview. The structure of the text is based in a general classification scheme of methods to assess water erosion, basically reflecting the commonly accepted categories of erosion research approaches. The fundamentals of each category of methods is presented in each section, together with the methods scope, description, discussion, including application conditions. Furthermore, the specificities inherent to the context of post-fire erosion measurement is also addressed when applicable.

1. Field surveys

Field surveys are currently performed to obtain a direct insight on actual erosion processes occurring and their spatial distribution within the survey area, to derive estimates of past or actual rates and trends of soil loss, to assess and eventually classify land degradation status (Hudson, 1981; Morgan, 2005). Field surveys may be also performed under specific conditions, as those following an extreme and evidently damaging rainfall erosive event, providing therefore a timed picture (Vandekerckhove *et al*., 1998; Figueiredo, 2009). Furthermore, they may be performed in sample areas as part of a cartographic approach to wide regions where erosion or land degradation has to be assessed, this way, contributing to draw the regional picture of the problem or status (LADA, 2009).

Field surveys are basically an organized way to collect the necessary information for the survey purpose, which, normally, may not be obtained with similar detail and quality by other means, as existing map or remote sensing techniques. As so, it is important to clearly define the specific objectives of the survey for the area selected for observations, which may be more geomorphic process-oriented or degradation assessment-oriented. Also, as costly, time and labour consuming operation, surveys should be carefully prepared, assembling prior to field work, all information needed to draw an anticipated picture of the area and limit the information that might be redundantly collected there. Scheduling of the survey is a matter of operation management.

A field survey comprises visual observation of erosion features and signs in the field as, for instance, runoff flow paths, crusts, surface rock fragments, rills and gullies. Observations are appropriately recorded together with notes on impressions or perceptions built on-site, that may provide interpretations helpful to data treatment. Some involve extensive data collection, others are much simpler; some add field measurements of soil properties or erosion features, others simple record their occurrence. Data collection has to be geo-referenced either locating sites in a sufficiently detailed map or by means of a GPS device; forms might be prepared in hardcopies or in a portable electronic device as a PDA, tablet or laptop (Eicher, 2005; Fleskens and Strosnijder, 2007; LADA, 2009; Zanden, 2011). Examples of recording sheets are found, for instance in Zanden (2011), and in LADA (2009). Hurni (1988) published a form specifically focused on agricultural land. Other less oriented forms are provided in Goudie *et al*.cols. (1990).

Results obtained with this approach are limited in quantitative terms, although in cases information collected might provide the basis for quantifications on soil loss rates or amounts. On the contrary, these methods are very valuable to identify active processes and their spatial distribution, as well as damage determined by those processes during erosive events, on-site or off-site. They are also helpful for locally calibrating models or indirect quantitative assessments via soil properties and ground features.

2. Field measurements

Research methods to quantify erosion rates in the field, under actual conditions, evolved through time towards a short number of types, specific to processes measured, which may be setup with more or less instrumental sophistication. Besides, according to measured object, they can be grouped as: (i) methods materially measuring soil export from a known area by runoff erosion (splash collectors, sediment traps, runoff plots); (ii) methods measuring topographic changes associated to runoff erosion (erosion pins, benchmark-based micro-relief surveys, and rill and gully volumes). These methods are described in the following sub-sections.

2.1. Splash measuring devices

Splash is measured with cups or boards (Figure 1). Splash cups may be of two types: source-cups (soil containers) and sink-cups (splash collectors) (Morgan, 2005). In the first case, a container (metal, PVC or glass cylinder), filled with the testing soil, is exposed to rains and the mass loss due to splash removal of soil particles is measured after each rainfall or a period of precipitation. Early studies of the erosive characteristics of rainfalls, by Ellison cited by Hudson (1981), applied this method with sand as test material.

The second type is more commonly used and consists of a PVC cylinder, inserted into the soil with its top rim at a similar slope gradient as that of the surrounding ground, that should outcrop a few millimeters to avoid incoming runoff washed particles (Poesen, 1986,; Morgan, 2005; Fonseca, 2005) (Figure 1). Inside the cup, a filter paper traps incoming particles splashed from the surrounding area. Drainage of precipitation water has to be ensured, and can be obtained with a hole deeper than the cup itself.

After each rainfall or group of rainfalls, the filter paper cone is replaced by a clean one and the mass of trapped particles is measured in lab.

Figure 1. Splash cup, 5.5 cm diameter installed in a field experiment (Fonseca, 2005; Figueiredo *et al*., 2012) (left), splash boards installed in outdoor micro-plot experiment with simulated rock fragments (Figueiredo and Posen, 1998) (centre), and board capturing splashed particles during a rainfall simulation micro-plot experiment using burnt soil samples (Alves, 2018 and Royer, 2019) (right).

Splash boards, are rectangular plates (metal, plastic), placed vertically besides the area under assessment, that receives particles splashed and collects them in a container at its foot (Morgan, 2005) (Figure 1). Mass of these particles is measured in lab. Splash boards have problems in windy areas and their height cannot be shortened because trapping efficiency declines (Figueiredo and Poesen, 1998).

The mass loss from soil containers or the mass of particles trapped in cups or by board requires corrections before being taken as splash loss. Correction procedures to account for the size of cups are provided by Poesen and Torri (1988). As well, Figueiredo *et al*. (2004) adds correction procedures to account for the presence of rock fragments in soil surface. Furthermore, splash measurements are sometimes taken as a surrogate of soil detachability. However, in sloping areas, there is an actual net splash transport downhill which can be assessed with a model developed by Poesen (1986).

2.2. Sediment traps

Sediment traps collect soil particles washed by runoff along hill-slopes (Dunne, 1977). A common model is named Gerlach trough and consists on a buried metallic box with a gutter upslope, to drive in washed material, and an exit pipe to drain the box of excess runoff water (Morgan, 2005). Gerlach trough is covered to avoid collecting precipitation and normally has an internal grid to separate large (organic) washed material from sediment (Coelho *et al*., 1990). This is deposited in the box bed, or in a removable container, which is pull-out ad cleaned in every sediment collection, therefore facilitating this operation. Sediment trapped is oven-dried and weighted and referred to runoff contributing area to express results in soil loss mass per unit area.

The system is commonly installed down-slope unbounded areas, where the contributing drainage area is fairly defined by natural ground topography (Coelho *et al.*, 1990). However, it can be applied for bounded areas, therefore becoming a special case of erosion plots. Nevertheless, they are designed to collect runoff but simply washed soil particles, unless additional or alternative design elements allow runoff storage or sampling, as it is the case of bottles to where runoff water and suspended sediment are conveyed through a pipe, after reaching a certain level inside the box.

A series of stakes inserted into soil normal to surface, along contour lines, holding a plastic sheet adequately fixed into soil, can trap washed particles by upstream runoff (Dunne, 1977). These devices are currently named silt fences or erosion fences (Figure 2), they are also used to measure post-fire erosion rates (Prats *et al.*, 2012) and Robichaud and Brown (2002) provide details on installation and operation of these devices. As water is diverted laterally or surpasses the trap, sediment accumulates upslope and. Erosion rate estimates may be based on measurement of the deposited oven-dry mass removed in each collection operation, or on deposition volume changes, assessed via changes in relative height of deposition surface during the observation period.

Figure 2. A silt fence (unbounded drainage area) installed in forest land, NW Portugal.

2.3. Runoff plots

Runoff or erosion plots are the most commonly applied method to measure runoff and soil loss from areas affected by interril and, eventually, also rill erosion (Hudson, 1993; Roose, 1994; Lal; 1994; Morgan, 2005). They are bounded areas with size, shape and boundaries adequate to purpose and means available to perform measurements, which correspond to runoff water and washed soil collected in devices installed down-slope, normally preceded by a gutter on their front edge. Such devices vary in instrumental or structural sophistication depending also on means and purpose of measurements, and have to account on plot size and characteristics, that determine potential runoff and sediment yields (Figure 3 to Figure 6).

Plot boundaries may be earth ridges, wood or metal plates inserted in soil (both repaired every time leaks are detected), or concrete walls, in the case of well-designed and funded long term monitoring programmes (Fleskens and Stroosnider, 2007; Fonseca, 2005, Figueiredo *et al*., 2012; Figueiredo and Ferreira, 1993, Tomás, 1997, respectively) (Figure 3 to Figure 6). Plots may vary in shape but are normally rectangular, although microplots installed in semi-arid matorral by Bochet *et al*. (1998) had a shape fitting shrub plant canopy ground projection. Plot size varies sharply, indicative surface area and slope length being: (i) micro-plots, smaller than 5m2 (less than 4-5m long); (ii) meso-plots, from 10 to 500m2 (5 to 50m long); (iii) macro-plots, larger than 500m2 (longer than 30m). Plot size has to be adjusted according to the local land use and management practices being monitored for assessing their erosional response. For example, micro-plots can be installed in a heterogeneous land cover area, if they are intended to assess the independent erosional response of land cover patches. However, large plots have to be installed in the same area if the assessment is focused on the global response that results from the connectivity of such patches.

Figure 3. Erosion micro-plot (1 m wide, 4 m long) installed in a burnt area at Aveleda, NE Portugal (left), with collection of washed soil particles and ashes (top right), and runoff water and suspended sediment (bottom right) (study area described in Fonseca et al, 2017).

Measured soil loss in each case should be the outcome of actually active erosion processes occurring in the plot area, even though, in some cases this is not a simple design problem, because of temporal changes in vegetation cover and ground condition, and because of the episodic pattern of precipitation and the threshold pattern of runoff and erosion processes. In very large plots, most of the recorded soil loss events do not outcome from the entire plot area, whereas small plots cannot represent the most significant erosion events, issued from a runoff concentration virtually impossible to occur in such small size. Runoff and sediment collection devices can be as simple as tanks connected to the upstream gutter, installed at plot front edge, by means of a conveyor, in which total washed material (soil and water) yielded in an erosive event is stored. Gutter may be concrete, PVC or metal half-pipe or a metal plate onto the ground. Conveyors may be part of the gutters (concrete) or independently installed (half-pipe, rigid or flexible pipe). Both elements are selected according to purposes and conditions of the monitoring system installed, but, in any case, they have to ensure fast conveyance and no loss of material from plot to tank (Figures 4 and Figure 5).

Figure 4. Erosion meso-scale plots (7.5 m wide, 15 m long) in an olive grove, with earthen boundaries and open runoff and sediment collecting pond, NE Portugal (study site described in Fleskens and Stroosnijder, 2007).

The system may apply from small plastic tanks or bottles (5 or 10l, for example), to large plastic or metal tanks (50, 100 or 200l, for example), or even trenches open in the soil at plot front edge, covered with a plastic sheet, that also collect rainfall (Figure 4 and Figure 5). The collection procedure normally comprises: (i) water volume measurement (or estimate from a calibration height-volume curve for each container); (ii) suspended sediment sampling, e.g. with a beaker, after thorough stirring of tank contents, and sample oven-dry mass determination; (iii) if present, removal of bed load after draining most runoff water, oven-dry mass determination of total bed load or, when too large, wet-weighing of total bed load and sampling it for water content. Total soil loss in each event is the sum of suspended sediment oven-dry mass (the product of runoff volume by sediment concentration) with bed load oven-dry mass (if present), referred to plot area. It should be noted that, sediment resting on gutter, actually exported from plot but not able to reach the container, is accounted for as bed load. Runoff may be also converted to equivalent height (volume collected divided by plot area, expressed in mm).

In large plots, where large runoff volumes can be expected, the problem of storage volume of tanks is overcome by setting small tanks in series (not more than 3 in total), connected with pipes and runoff divisors. In this case, the first tank collects water and the soil washed from plots, but the remainders receive only a part (e.g. 1/11) of the incoming clear runoff water, the rest being spilled out (Tomás, 1997; Figueiredo, 2001) (Figure 4).

Figure 5. Erosion meso-plots (5.2 m wide, 32.1 m long) in a vineyard of the Dourio region (study site described in Figueiredo et al, 2021, and Figueiredo, 2001; photo by Jean Poesen).

Recording systems allow a detailed insight on runoff water and soil loss evolution during an erosive event and this is especially useful when studying erosion processes or modelling. Recording devices for measuring runoff are connected to a data-logger, from which the data can be directly or remotely retrieved or accessed. They may be: (i)inspired in limnigraphs (river stage recorders), in which a sensor (e.g. a pressure transducer) measures runoff water level conveyed through a stable section in the flow circuit (channel segment or a spillway, metal, plastic or concrete); (ii) inspired in rain gauges, in which a runoff convey pipe drips on a tipping-bucket device, or a multiple bucket tilted metal wheel, that rotates when a bucket is filling in with runoff (Morgan, 2005) (Figure 6).

Figure 6. Runoff tipping-bucket recorder (Haute Normandie, France).

Runoff recorders may be coupled with mentioned above systems, so as tanks collect total sediment exported during the erosive event, while runoff evolution is is recorded in detail. However, sediment concentration evolution may also be monitored installing sampling bottles filled in during the erosive event water diversion scheme, collected afterwards and oven-dried for sediment mass determination. More sophisticated systems use turbidity sensors to record sediment concentration evolution during runoff event. Both allow coupled analysis of sedigrphs and hydrographs for each event recorded.

2.4. Ground level monitoring

Measuring height differences relative to reference surfaces or points, and repeat them through time, provides estimates of soil loss amounts and rates, associated with erosion processes taking place in a given observation area. Methods for measuring runoff erosion considered under this heading include erosion pins, benchmarks for micro-relief surveys and root exposure surveys (Dunne, 1977).

An erosion pin comprises a metal rings resting over the soil surface, fixed there by a nail. Distance from nail top to ring is repeatedly measured through time. Pedestals may form as the ring protects the soil underneath from raindrop impact, and they have to be removed prior to measurement. Nails are taken as local benchmarks and changes in ring position are attributed to soil loss due to runoff erosion. A large number of pins is required for a fair representation of surface evolution, because wash and deposition occur in the same area of observation as sediment is transferred along the hill-slope, and because preferable flow paths and ridges have clearly different pattern of surface evolution.

Benchmarks of any kind, installed, as concrete pillars, or naturally set in place, as embedded rocks, serve as references for micro-elevation surveys at neighbouring areas affected by runoff erosion. Repeated surveys help assessing wash rates from eroded volumes estimate. Tree root exposure is an indicator of land degradation by severe runoff erosion (e. g., Rubio-Delgado *et al*., 2018). Assessment of eroded volumes requires micro-elevation surveys as in the above indicated cases, however with increased practical difficulties. A particular case of benchmark based measurements is the erosion bridge developed by Shakesby *et al*. (2002). The device is perforated metal bridges kept leveled during measurements, as its 2 supporting fixed length legs step over 2 benchmarks. The surface soil profile between the 2 legs (or rods) is obtained measuring vertical distances to ground surface taken from bridge with c. 50 metal sticks sliding through the bridge holes down to the soil surface. Time changes in average elevation are estimates of erosion rates of soil between benchmarks.

Removal of soil particles by runoff erosion in interrill areas also lowers ground surface, actually corresponding to the geomorphological concept of denudation rate (Ahnert, 1998). Due to ground surface roughness it is hardly possible to describe it as sheet removal, but such approach has been adopted for long. It is a useful approach to assess local erosion rates, provided extrapolations are performed very carefully. In fact, the heterogeneity of surface ground features makes them simply point assessments that may not represent larger land tracts. If land lowering rates are converted in equivalent soil loss rates (mass per unit area and time), then a critical conversion factor has to be estimated – soil bulk density – that is normally taken as equal to the actual one, locally measured, assessed or assumed. Bulk density changes during erosive rainfall events (van Wesemael *et al*., 1995), introducing an additional conversion constraint.

Surface micro-topography is generally required for improving accuracy in ground level assessments and monitoring. Developments in micro-topographical surveys, however, were driven far more on account of surface roughness assessment than on account of erosion rates assessment, despite their common basic data requirements. In fact, results from such surveys may serve either the computation of roughness indexes or of mean or local ground level changes following rainfall events, which may aloe the quantification of net erosion rates or those of gross erosion and deposition, and their spatial distribution. This justifies a specific subsection on dedicated to surface roughness in the context of ground level monitoring approaches to measure soil erosion rates.

Methods for measuring surface roughness aim at providing a description of soil surface micro-topography, from which parameters or indexes may be extracted and used for runoff erosion interpretations or as input in erosion models. As detail in description of micro-topography increases, so increases sophistication of methods and equipment, and so increases complexity in data treatment and outcoming results. Full descriptions are 3D, while the simpler approaches provide a 2D description of soil micro-topography, meaning that a direction must be selected for the measurements performed along a straight line.

The simplest method is the chain method, consisting in a chain with a certain length that is placed along a line onto the soil surface, after adequate selection of measurement direction (Morgan *et al*., 1998). This is generally taken that of actual or expected overland flow paths. Once placed onto the ground, the straight line distance between the two edges of the chain is shorter the higher is surface roughness. An index is derived from the two lengths: that of the chain (normally between 50cm to 1m) and that of the straight line distance between chain edges when resting over ground, named roughness index.

The profilemeter method provides a longitudinal profile of miro-relief, as a result of measurement of vertical distances from a reference level to ground surface, taken at regular horizontal distances. In the 3D approach the reference level is a plan and measurements are taken in two orthogonal directions in the plan. Reference plan or line are not necessarily leveled if their slopes are precisely known. The number of measurements taken depends on the required detail of assessment and it is limited by practical feasibility combined with instrumental capabilities.

In a needle profilemeter, a set of sticks, pins or needles, supported by a frame at regular short distances from each other (e. g. 5cm), are slide down to the ground and the heights to the reference frame measured or represented in a chart draw on the opposite edge of the sticks, pins or needles, to be later measured indoor. A very simple and straight forward variation of the method consists in a ruler along which, at regular intervals, the distanced to the soil surface is measured with a tape (Fonseca, 2005). Either frame or ruler are fixed by two legs and leveled with a bubble level (Figure 7).

Figure 7. Assessing surface micro-relief with: home-made device on a micro-plot in NE Portugal (description in Fonseca, 2005) (left); laser profilemeter (centre) and camera capturing images for surface photogrammetric reconstruction (right) on soil samples in NW Spain (centre and right photos by Douglas Bandeira, description in Bandeira, 2019).

Data treatment consists in determining total length of ground surface and use it, together with ruler length, to compute the index above. Alternatively, random roughness, a second index is derived from data, which corresponds to the de-trended standard deviation of surface heights, meaning that a trend of data is obtained by regression, measured data subtracted from the trend line, and the standard deviation of the residuals around the trend line computed (van Wesemael *et al*., 1996).

The procedures and instruments described above do not allow a very much detailed representation of soil micro-topography, as shortening distance between point measurements rises the number of measurements so as they become practically unfeasible. Besides, shortening distances is limited by instrumental capabilities. Laser profilemeters overcome these limitations and provide non-contact measurements (van Wesemael *et al*., 1994; van Wesemael *et al*., 1996). They are sophisticated equipment, commonly placed in lab to work on simulated surfaces, but models exist to work in the field. Also models exist that allow working to output 3D results. The equipment consists in a frame supporting a laser source running over it at constant velocity by means of a motorized system. The laser beam is oriented to the soil surface and according to programmed operation, yet limited by equipment capabilities, measurements can be taken at very short distances along a line (0.1mm). Data is stored during runs and later transferred to perform data treatment and from which indexes may be derived. Due to the highly detailed data provided, complex approaches to deriving indexes are possible, as it is the case of using fractal analysis (van Wesemael *et al*., 1996).

In the case of 3D ground micro-relief surveys, more complexity of data treatment requires spatial analysis and GIS based methodologies. They can be applied with data sets issued form laser profilemeter measurements. However, approaches to this topic include also taking paired ortho-photos of surface ground, later treated with methods typical of aerial photo based surveys (Merel and Farres, 1998). More recently, the increase in performance of image treatment tools allows obtaining very detailed photogrammetric reconstruction of surface micro-topography with non-orthogonal photos and with no height reference requirement (Bandeira, 2019). Also, unmanned aerial vehicles (drones), equipped with cameras capturing high resolution images provide data to obtain a very detailed representation of the surface ground (Barroso, *et al*., 2021). In both cases, robust approaches to data treatment are required and, again, fractal analysis is applied to comprehensively represent the complexity of micro-relief and its changes due to soil erosion processes.

2.5. Gully erosion assessment

Linear erosion features primarily result from the incision of ground surface, and further scouring of the soil profile, by concentrated overland flow, to which might be added effects of other processes as splash, sheet flow and mass movements at micro to meso-scale (Govers and Poesen, 1988). They are normally classified according to size and stability, rills referring to short-living structures lower than 900 cm^2 crosssection area (1 ft^2) (Morgan, 2005). Large stable incisions are called gullies, in spite that these are labeled ephemeral when they meet size requirements but are fresh incisions that may be erased by regular tillage operations as it is the case of rills.

The basic principle in gully erosion assessment is to estimate gully volume and refer it the estimated catchment area draining to the gully system (Vandekerckhove *et al*., 1998; Vandekerckhove *et al*., 2000). This is based on the assumptions that actual gully volume is simply due to linear erosion) meaning that sedimentation and other processes occurring in gully walls are not considered), and that topographically defined catchment area contributed with erosive overland flow to gully incision and development. For most cases, these assumptions are practically acceptable, taking into account either the constraints associated with assessing the contribution of process other than concentrated overland flow to gully actual configuration, and with actual runoff contributing area determination, or the accuracy of estimation procedures applied to outcome gully volume.

Approaches to estimate gully volume may be based in: (i) direct measurements (ruler based or geodetical); (ii) remote sensing techniques (low and high altitude aerial photos) (Vandekerckhove *et al*., 1998, Figueiredo, 2009; Dunne, 1977; Vandaele *et al*., 1997, respectively). In the first case, at selected points along the gully measures are taken to estimate the respective cross-section area, which are integrated over the length of the gully segment they represent to output gully segment volume, the sum being total gully volume. Number of sample sections, measurements performed to estimate crosssection area and integration procedures, depend on gully size on one hand, and required accuracy of estimates on the other hand. In fact, very large gullies (several meters deep and several hundreds of meters long) require geodetically performed measurements. Smaller gullies may be approached with direct measurements with a ruler for gully cross-sections and and a tape for gully segment length (Figure 8). Area of complex cross-sections may be accurately assessed with a needle profilemeter but it is a rather time consuming technique. A much simpler approach consists in assuming a certain regular cross-section shape (triangular, rectangular, trapezoidal, and parabolic) and performing the measurements required determining its area (normally top width and average depth). For a more accurate integration, sections should be selected so as to define gully segments with regularly changing crosssection area, therefore avoiding abrupt changes in size and shape within the segment length.

Remote sensing techniques for gully erosion assessment are applied when the scale of assessment, the extent of the area under assessment, and the expected or required detail of assessment results. Accordingly, the range in resolution of the aerial photos used in this approach is quite large, depending on purposes and practical conditions to perform the assessment. These include available time, consistency and quality of the available information (photos), quality of ground references for photo-interpretation. Ries & Marzoff (2003) used photos taken from a blimp to study gullies in Spain, whereas Vandaele *et al*. (1997) made use of aerial photos in Alentejo, Portugal.

Gully erosion rates can be calculated if a temporal reference exists. Normally this means repeated observations through time, in a monitoring scheme. However, in fully installed permanent structures as large gullies dating techniques may be used to obtain a temporal reference for calculating rates. This is the case of dendro-chronology of plant roots exposed in gully walls. It should be noted that rates calculated are averages that do not, and could never be, representing the actual changes in process rates over time, as erosion sensu lato is an episodical phenomenon.

An extensive recent review on gully erosion assessment methodologies can be found on Vanmaercke *et al.* (2021), covering a wide set of contexts, including burnt areas.

Figure 8. Gully formed following heavy rainfalls over a recently burnt scrubland and measuring a rill in a forest road in NE Portugal (top left) (study area described in Figueiredo *et al*., 2012).

3. Experimental simulations

3.1. About simulations

Due to the very high time and space variability of erosion factors, experimental simulation is quite often the approach adopted to study and assess erosion (Hudson, 1091; Morgan, 2005). This approach by-passes some of the difficulties associated with installing and monitoring field experiments and with performing field surveys. Simulations allow triggering rainfall erosion events and controlling their precipitation characteristics and ground or soil conditions, according to convenience. These advantages shorten time required for obtaining research results.

However, the main advantage of simulations is the possibility they provide to control factors and processes, bounding systems to be studied with control of their boundaries. Such conditions are not possible to obtain in the field, considering the large set of interactions between factors and the chaining of processes that are commonly found outdoors, which are the main constraint to scientifically grounded interpretation of assessment results.

Simulations face the problem of reliability in representing the real world, even though it is a fragmented real world. This is a key issue when comparing simulation with field results in erosion experiments. In fact, natural rainfall is hardly replicated by simulators, due to technical limitations, and soil samples used in simulations hardly replicate natural soils, due to disturbance or scale. Scale is often a limitation in simulation experiments, as size of the experimental setup is upper limited by actual instrumental conditions, meaning that those experiments are normally small scale.

All advantages and constraints considered, experimental simulations were and are, undoubtly, a very valuable approach for the advancement of knowledge of runoff erosion processes.

3.2. Rainfall simulators: general

Addressing simulation in erosion experimental research commonly means focusing in rainfall simulation and simulators. As the agent, without which no process occurs, emulating a rain shower has been since long a core research concern. Steps towards this goal were grounded in the deep insight on natural rainfall characteristics that are required to set a reference to be replicated. Drawing the full picture of precipitation characteristics and of how they relate either to easy measurable rainfall parameters, or to synoptic conditions or climatic features is still a hard task. However, since Ellison and with later definite contributions by Laws & Parsons, Ghadiri & Payne, Sfalanga & Torri (cited by Hudson, 1981), natural rainfalls were experimental studied and described with the existing technologies and results obtained are the basis for actual rainfall erosivity estimates. An important advancement was provided by disdrometers, an equipment used for the refined measurement of rainfall characteristics (Tomás, 1997; António, 2010).

To summarize, it is possible to set a reference for natural precipitation characteristics, namely rain drop size distribution and its variation with rainfall intensity, for certain geographical regions, normally accepted as reliable even for other regions. The relationship between rainfall kinetic energy per unit rainfall height and rainfall intensity expresses that variation in useful form, since kinetic energy of raindrops provides the work necessary to breakdown exposed soil aggregates and start erosion processes. On the other hand, such relationship changes geographically, the data sets for deriving it being compiled in the USA, South Central Africa and with a much shorter record length in Italy (Wischmeier and Smith, 1978; Hudson, 1981; Raglione *et al*., 1980).

The simulated rainfall should match natural rainfalls with certain frequency and duration, or, inversely, selected for the specific experiment. This means that a frequency analysis of rainfalls for the area to be emulated in experiments should exist. The most practical result of the mentioned analysis is the Intensity-Duration-Frequency (IDF) curves for the selected weather station. IDF curves provide a tool for setting or knowing the frequency (expressed in terms of return period) of the precipitation being simulated with a certain duration and intensity. Although a relevant approach, this should be complemented with natural rainfall kinetic energy frequency analysis, which is a much more difficult task because it requires performing the frequency analysis itself with basic rainfall data records whilst IDF curves may be published or available and can be used without a prior analysis (Tomás, 1997; Figueiredo, 2001).

Rainfall simulation characteristics are duration, intensity (normally kept constant during the experiment), and kinetic energy of the dropping water at ground or other reference level (e. g., canopy) and spatial uniformity within the target area. Additionally, if technical constraints do not ensure a steady water flow in the simulator, temporal changes should be known as well. As duration is arbitrarily selected (preferably with a sound justification given the natural and experimental conditions), all other characteristics need to be measured, assumed or neglected, according to accuracy required for the experiment. Full calibrating runs with the simulator should include sampling the shower with cups placed in the target area at the required level (normally ground level). Cups may be of various materials (plastic, metal, glass), sizes (accommodating target area size, number of cups and sampling intensity accepted), and shapes (simple cups or funneltopped where funnels are the actual interception device). The longer the run the large the amount of water intercepted by cups, the smaller the relative experimental error. Volume or mass of water captured in the cups averaged and adequately converted to mm h-1 allows assessment of simulated rainfall intensity. Uniformity of water distribution in the target area is assessed via statistical dispersion of water amounts collected in cups (Tomás, 1997; Bompastor *et al*., 2009).

Assessment of simulated rainfall kinetic energy requires additional measurements, namely fall height, initial drop velocity and water drop size distribution. The latter is assumed zero for drippers but has to be assed in the case of sprinklers, the two simulator types described later. To do so, discharge from the simulator nozzles is measured conveying sprinkled water to a bucket and measuring time to fill it or to reach a defined volume. The nozzle diameter is normally given by the commercial provider, otherwise it is measured. Velocity is computed with discharge and crosssectional area of flow in the nozzles (Bompastor *et al*., 2009). If the simulator is multi-nozzle, uniformity should be assessed too, with data dispersion analysis. Height is measured from dripper or nozzle to ground surface or other upper reference level and it is normally fixed according to experimental convenience. Water drop size distribution can be assessed in several ways according to instrumentation available. The most reliable device is the disdrometer, which has a sensor plate hit by falling water drops and the detected signal is converted in drop size distribution, allowing the computations of kinetic enegy and intensity (Tomás, 1997). Acoustic sensors, stroboscopic photos, high time resolution image capture are other means of reaching the same goal, with or without measurement of the falling velocity (Tomás, 1997; Morgan, 2005). The most traditional and low-technology input methods is the flour pellet method, that consists in exposing a pan filled with a thick uniform layer of flour to the water shower at the required level, for a short time span so as to allow pellet formation and limit flour soaking. Pellets formed represent drop hitting flour but a calibration procedure is required to adequately assess water drop size from pellet size (Hudson, 1981). A set of sieves screens pellets by size and a drop size distribution curve can be drawn from the mass pellets trapped in each sieve and the size limits defined by each pair of sieves (Bompastor *et al*., 2009) (Figure 9). The larger the set of sieve the more accurate is the curve. The curve allows derivation of D50 of the simulated rain shower, meaning the median diameter of water drops that halves the total precipitation (the mass of water drops) (Hudson, 1981). Kinetic energy can be computed with this data. If the height of simulation is to be change, the measurements have to be repeated for several heights (Bompastor *et al*., 2009). Operational parameters of the simulator that affect or better control simulated rainfall conditions, should be tested during calibration procedures, and be the actual simulation parameters during experimental runs. They include for instance water pressure at outlet in the case of sprinklers (Figure 9). Simulations should only start when steady state at the defined simulation conditions is reached, normally a short time after starting operating the simulator. To limit water loss, a closed circuit water flow should be possible. Water saving is a crucial issue for simulations, especially under outdoor conditions in remote areas, where water availability is seriously limited.

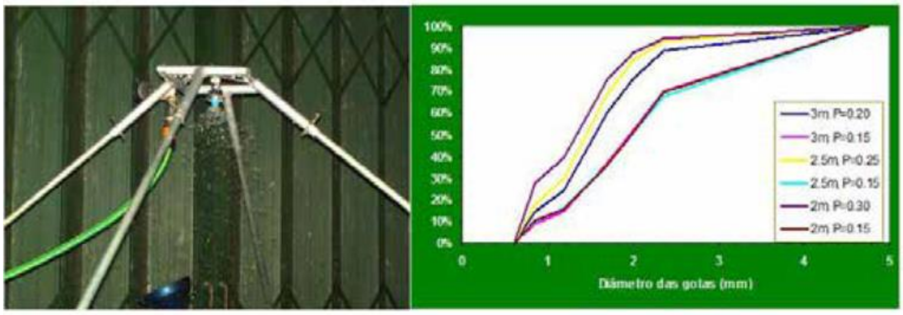

Figure 9. Portable single nozzle sprinkler-type rainfall simulator: calibration indoor and drop size distribution curves according to height and pressure (description in Ramos, 2009).

3.3. Rainfall simulators: types

Simulators can be classified by several criteria (Hudson, 1981; Morgan, 2005). They may be portable or fixed structures. The latter work indoor, meaning in a hangar or laboratory and may heavier or lighter structures according to purposes and material conditions to install them. They generally allow larger target areas, more accurate control of simulation conditions, eventually with extended capabilities that may comprise simultaneous rainfall, runoff and subsurface flow simulation and control, wind and moving storms effects, water quality regulation (Zheng *et al*., 2004; de Lima and Singh, 2003; Shainberg *et al*., 1991, respectively). Conversely, portable simulators are normally designed for field conditions, working over smaller target areas, generally with light structure, straight-forward operation, a short set of operational parameters or simple fixed ones, more concerned with water saving design and operation (Figure 10).

Besides, the main criterion for splitting simulators in two main types – drippers and sprinklers – is the drop forming process that sharply differs in the two cases and has important consequences for the characteristics of the simulated rainfall, as well as to operational conditions (Hudson, 1981; De Ploey, 1983; Morgan, 2005).

Figure 10. Portable single nozzle sprinkler-type rainfall simulator at work in NE Portugal: in a scrubland (left; description in Ramos, 2009, and Bompastor *et al*., 2009) and in micro-scale experiments using burnt soil samples (right, Alves, 2018 and Royer, 2019).

In drippers, drops form under low pressure (few centimeters equivalent water height), flowing out from a tank at kept at constant water head through narrow tubes (syringe needles, glass or plastic quasi capillary pipes, larger pipes with an axial wire or string fixed centrally). Water drops initial velocity is taken as zero and dropping frequency (mean total discharge from the tank) increases with water head, whereas drop size in determined by the drip device characteristics, namely the narrow tubes internal diameter. In drippers, water drops are very uniform and so the simulated rain shower represents only the D50 of the natural rainfall being simulated and not the range of sizes observed in nature. Furthermore, drops fall from each dripping device onto the ground always in the same position, meaning that some points are severely impacted while others are not at all impacted. To overcome this limitation, drippers should be moved during rainfall simulation runs, in a determined or random pattern, or the trajectory of the falling drops have to be disturbed, for instance by means of fans, or even the drops pass an intercepting mesh after leaving the dripping devices and are reworked to produce the actual simulated rain shower with a totally new drop size distribution (Alexandre, 1989; Bryand and De Ploey, 1983, respectively).

In sprinklers, drops are the result of rapid water flow under hydraulic pressure passing a nozzle where it is under atmospheric pressure. The spray produced includes a large range of drop sizes, therefore approaching natural rains drop size distribution. Nozzle characteristics, namely internal diameter and spray angle determine maximum discharge and the size of target area (also affected by simulation height). However, in sprinklers the set of operational parameters, and their interactions, affecting simulated rainfall characteristics is quite large. For example, besides nozzle characteristics, discharge is positively affected by pressure, meaning that intensity increases as pressure increases, but this induces a finer spray, meaning a decrease in the D50 of water drops. As so, sprinklers normally yield a low D50 of the water drops when compared with that of natural rainfalls with similar intensity, or, stated differently, when compared with natural rainfalls, rains simulated by sprinklers with a similar D50 of water drops have a much higher rainfall intensity than the natural ones (Tomás, 1997; Morgan, 2005; Bompastor *et al*., 2009). To overcome this limitation, typical of sprinklers, some models incorporate a rotating metal disk, with and an open window that intermittently allows the free jet flow, while during part of each rotation cycle the et is intercepted. This way, the intensity is lowered but the water drop characteristics are not changed (Hudson, 1981; Tomás, 1997). Multiple-nozzle sprinklers allow larger target areas but the problem of uniformity of drop distribution within the target area, normal in sprinklers, persists or it is even enhanced due spray cone interception (Hudson, 1981; Morgan, 2005).

In both types, kinetic energy of simulated rainfalls depends on water drops falling height, even though in sprinklers flow pressure in the hydraulic circuit promotes higher drop velocity than in the case of drippers. Only under laboratory fixed structures falling heights can allow approaching water drop terminal velocity, as so approaching natural rainfall conditions. Therefore, in most cases, simulated rainfalls have a lower kinetic energy than natural rainfalls for the same duration and intensity. In the most common cases both types of simulators perform similarly to this respect (De Ploey, 1983).

Outdoor simulations impose special concern about power supply to work pumps and ensure steady pressure in the hydraulic conditions (meaning the need of a fuel motorized power generator), water availability (water tanks) have to be transported to the field), feasible simulator height and appropriate positioning (to ensure a vertical water jet) and wind (the spray cone has to be protected in windy areas by means of a plastic curtain around the simulation area) (Bompastor *et al*., 2009).

4. Concluding remark

This overview on methods for assessing runoff erosion is expected to provide a consistent and comprehensive approach to the topic. However, in spite of the wish to cover the most essential cases that contributed to the development of erosion research, it was not meant to be a full review. As so, intentional or not intentional gaps may be found in this overview. Moreover, due the complexity of the object and of its dynamics, assessment methods require sometimes site specific solution to tackle with real world problems. Research innovative procedures are, therefore, ever present in erosion studies, while traditional methods keep their place in this field of knowledge, refining and consolidating protocols as well as adjusting their focus in terms of application conditions.

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