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Splash erosion: a review with unanswered questions

María Fernández-Raga[a]*, Covadonga Palencia[a] , Saskia Keesstra[b], Antonio Jordán[d], Roberto Fraile[a], Marta Angulo-Martínez, Artemi Cerdà[b,c]

[a] maria.raga@unileon.es Dept. of Physics, University of Leon, Spain

[a] c.palencia@unileon.es Dept. of Physics, University of Leon, Spain.

[b] saskia.keesstra@wur.nl Sustainable Land Management Department, Wageningen University

[d] a.jordan@us.es. MED_Soil Research Group. Department of Crystallography, Mineralogy and Agricultural Chemistry. University of Sevilla.

[a] rfral@unileon.es Dept. of Physics, University of Leon, Spain

[e] marta.angulo@eead.csic.es Estación Experimental de Aula Dei (CSIC)

[c] artemio.cerda@uv.es Department of Geography. University .of Valencia

* corresponding author: maria.raga@unileon.es Fax: +34 987 291546. Phone: +34 987 291000-ext 5342

Abstract

Soil erosion is a serious ecological and environmental problem, and the main cause of land degradation in many ecosystems at global scale. Detachment of soil particles by raindrop splash is the first stage in the soil erosion process. A review of the scientific literature published in peer-reviewed international journals (ISI) over the last decades on splash erosion research sheds light on the current scientific knowledge on this topic. In addition, it highlights the research gaps and unanswered questions in our understanding of soil erosion processes due to splash. In this literature review, a bibliographic search in Web of Science by the Institute for Scientific Information (ISI) database was carried out on August the 9st 2016, that returned 669 papers containing the words “splash erosion”. The research found was categorised according to a number of criteria: i) devices used to measure splash erosion, ii) advantages and disadvantages of these devices, iii) splash erosion studies by country, iv) date of publication of the first article, v) evolution of the number of articles published in each ten-year period, vi) concepts studied, vii) keywords, viii) authors, ix) number of citations, and x) most cited articles. After this review a synthesis of the information that the science has published about splash erosion was made in order to improve our understanding about splash erosion, by identifying the research questions that still remain unanswered today about the first detachment mechanism. From this review several issues were found important for the advancement of this research topic: a) further study of the known basic factors influencing splash erosion; b) description and quantification of sources of uncertainty about the measurement of different variables; c) to understand the influences that the chosen research approach by individual researchers will have in the final result; and, d) to study the impact of drivers or mitigation techniques that may affect splash erosion.

Keywords: splash erosion, bibliometric review; State-of-the-Art, rainfall, splash device, mechanism

1 Introduction

Soil erosion is responsible for land degradation in many ecosystems at global scale (Nowak and Schneider, 2017; Mekonen et al, 2015; Karlen et al., 2003). Soil erosion is a natural process that causes mobilization, transport and off-site sedimentation of mineral and organic soil particles, as well as associated chemicals and biota. Non-sustainable soil erosion rates (>10 Mg ha^{-1} y^{-1}; Wischmeier and Smith, 1978) are the result of human mismanagement and accelerated soil erosion processes, that, in turn cause the degradation of ecosystems (Novara et al., 2016; Mukai, 2016; Navarro-Hevia et al., 2016; Ochoa-Cueva et al., 2010; Prosdocimi et al., 2016a). On the other hand, in natural forest soils, scrubland soils or agricultural soils under sustainable management practices, the soil erosion rates are low and do not cause loss of ecosystem services (Keesstra, 2007; López Vicente et al., 2016; León et al., 2015; Prosdocimi et al., 2016a; Prosdocimi et al., 2016b). This is why strategies developed for control of soil erosion rates in bare soils (agricultural, mining, burnt or overgrazed areas) recommend afforestation or the use of mulches that will act as a forest soil litter cover, protecting soil against erosion (Cerdà et al., 2016; Prosdocimi et al., 2016a; Rodrigo-Comino et al, 2016a; Rodrigo-Comino et al, 2015) and improving soil physical properties (Jordán et al., 2010; Nzeyimana et al., 2017).

Understanding soil erosion processes is key for designing and applying soil management techniques that minimize and control soil erosion risk (García-Díaz et al 2017; Keesstra et al., 2016). According to Morgan (2005), soil erosion is a two-phase process that consists of the detachment of individual soil particles and their transport by erosive agents (water or wind). Detachment of soil particles by splash erosion may be considered the first step of soil erosion by water and this is why we must research the factors involved and the mechanisms that control splash erosion. Angulo-Martínez et al. (2012) define splash erosion as a complex process that causes the detachment of soil particles by raindrop impacts on the soil surface followed by short-distance transport of detached particles (Jomaa et al., 2012; Hudson, 2006; Kinnell, 2005; Morgan, 2005; Ryżak et al., 2015; Sempere-Torres et al., 1994). In addition, splash has an important role in the liberation of soil organic carbon because when the runoff flow forms, carbon-enriched particles previously detached by splash erosion are transported (Beguería et al., 2015).

Splash erosion can displace soil particles as high as 1.5 m vertically (Ryżak et al., 2015), and can reach horizontal distances of more than 5 m with the help of the wind (Erpul et al., 2009a and 2009b), depending on the soil. In addition, if raindrops impact on bare soil surfaces, they can contribute to increase the soil bulk density due to compaction and crusting (Terry and Shakesby, 1993). Although the crusting process usually results in a relatively smooth soil surface in the long term, the impact of raindrops and the resulting splash process can form miniature craters as a consequence of the redistribution of particles. This will result in an increase of the soil surface roughness. The size of these miniature craters depends on the type of soil, texture, structure and moisture (Ryżak et al., 2015). Crust hinders plant establishment because germination and seedling growth are inhibited, and infiltration rates decrease (Sharma et al., 1991). Limited infiltration may produce accumulation of water on the soil surface (Ruiz Sinoga, & Martinez Murillo 2009; Rodrigo-Comino et al, 2016b). Ponding, sheet and rill overland flow may protect the soil from raindrop impacts as it can act like a protective layer of mulch (Kinnell, 2005; Mermut et al., 1997), however these processes decrease infiltration rates and soil water availability for plant growth. In the same way, pre-detached soil particles may provide some ephemeral protection to the underlying soil. If the layer of pre-detached particles is too deep for raindrops to penetrate, only superficial pre-detached material is splashed (Kinnell, 2005).

Some strategies have been found useful to prevent splash erosion, such as vegetation cover or different mulch materials (straw, needles, leaves, litter, rock fragments or geotextiles) because those materials can absorb the impact of raindrops and protect the ground surface (Díaz-Raviña et al., 2012; Giménez-Morera et al., 2010 a; Ma et al., 2014; Robichaud and MacDonald, 2009). If the soil particles are not detached, they will not be transported by the sheet flow, and, consequently, sheet flow will not have potential enough to dislodge more soil particles from the bare surface. However, the intensity of splash erosion depends mostly on the resistance of the soil to erosion and the kinetic energy of the raindrops (Ghahramani et al., 2012). Another concern in splash erosion studies deals with the spatial and temporal variation of rainfall and its kinetic energy (Angulo-Martínez et al., 2012, 2016). The measurement of the kinetic energy of raindrops is difficult under field conditions (Scholten et al., 2011), especially in remote areas, in forest or in steep areas. Rain gauges do not provide the precise data needed for such studies, and other devices like disdrometers are difficult to use remotely (Erpul et al., 1998; Scholten et al., 2011).

As splash erosion is the first key mechanism of the soil erosion process, a State-of-the-Art review is needed and there is no bibliographic information about how much has been published and which topics were researched. This paper presents the key bibliographic information about splash erosion in order to determine the available scientific contributions, identify research gaps and propose future research objectives.

2 Data sources and analysis

Among the various existing bibliographic databases we have used the *Web of Science* ® by the *ISI Web of Knowledge* (hence *WOS*) published by *Thomson Reuters* ©. The present bibliometric study is an analysis of the current State-of-the-Art of the most relevant research papers on splash erosion. Out of the more than $5{\cdot}10^7$ scientific documents included in the *Science*

Citation Index Expanded (*SCI-EXPANDED*), from 1900 until present, the search engine retrieved 669 items with the words *splash erosion* in the title, abstract or keywords. Of these documents, 147 contain the word *splash** in the title, illustrating the relevance of splash in the publications. The search word *splash** included a wildcard to cover concepts such as splashed soil, splash erosion or splashed detachment. The bibliographic search was carried out on August 9th 2016 and results are shown in Table 1. After the 9th August a change in classification of document types in the data base has removed all the patents from the record, and the proceedings papers has been reclassified or as articles (they are repeated in both categories: articles and proceedings) or removed from the data base. Before 9th August, it can be seen that the vast majority are research articles (82.2 %) including some proceedings (14.9%). Other records are, in decreasing order, patents, reviews, editorial materials, notes, reports and abstracts. After August the presence of articles is even higher (96.5 %), but because of the reclassification. The rest of the paper we will analyse the data before 9th August 2016.

3 Results and discussion

3.1 Techniques to measure splash

The literature review revealed a generalised concern regarding the methodology when undertaking splash research and measurements. A key issue is which instruments are used to measure splash erosion. The type of materials is very diverse among researchers studying splash erosion, and the device type used influences greatly the results, making it difficult for comparisons. In addition, most of the equipment used to measure splash erosion is not commercially available and researchers manufacture themselves what is needed for their scientific purposes. These locally designed by researchers implies little standardization (Rodrigo Comino et al ,2016c; Iserloh et al 2013a; Stroosnijder, 2005). One of the objectives of this article aims at helping to standardized and homogenize the material and methods to be use in the future, making inter-comparisons possible. Also, it will help to understand the differences among different results from experiments due to their methodology.

The first concern is the accuracy and quality of splash erosion measurements. Ma et al. (2008) distinguish two terms: net splash amount (the mass of soil collected from the splash devices) and total splash amount (all particles hit by raindrops). Most of the splash erosion studies detect only the net splash amount. Indeed, measuring the total amount of particles hit by raindrops is not possible because some particles hit by drops will move to another position on the splash device, and in this case this movement will not be counted as splashed amount.

The methods and devices used to measure splash erosion are diverse (Figure 1). In general, these devices can be designed as a trap with a system for collecting soil or as a device with a known amount of soil or bounded surface to be splashed depending on the intensity of hits received from the raindrops. Additionally, some devices are designed to measure splash erosion in the field, while others are suitable for laboratory conditions. In total sixteen different types of device were found in literature, which were all developed for different research conditions. Main device types, properties and purposes are summarized in Table 2. Devices are classified in 16 different types attending to several characteristics: disturbance of the soil surface, possibility to measure the height that splashed soil particles reach for a given rainfall, possibility to determine the direction of the splashed soil particles and the possibility to calculate the rate of splash erosion.

Currently, there is no splash device yet that will be able to satisfy the four characteristics selected for classifying them. In order to facilitate the selection of the best available device to solve a specific research aim, we will describe one by one the splash devices following the classification in the explained four characteristics.

Some devices disturb the soil surface during installation in the field. When the splash devices are part of a nested setup of erosion measurements, these disturbances may condition the total sediment yield measurement of the larger plot or hillslope. Therefore it is important to be aware of differences in the design of the device that is chosen for a certain study, clarifying if results of two different studies are comparable (or not).

The nine first devices shown in Table 2 have a very low soil surface disturbance. In Figure 1, there is a representation of how they look like. Splash cup (Figure 1a) or funnel systems (Figure 1b), allow recovering the splashed soil using a removable filter paper on the top without extraction of the bottom part of the device, which is installed into the soil. On the contrary, bottles used for water and sediment collection (Figure 1c) need to be removed from the soil, causing great disturbance.

Other devices can also be installed at the field with a minimum disturbance on the soil, like the splash board (Figure 1d), the collection trough (Figure 1e) and the curtains (Figure 1f). All these systems are set on the ground, and only need to be washed to collect samples. In contrast, devices like the splash house (Figure 1g), the Morgan tray (Figure 1h) or the Leguédois tray (Figure 1i) produce a lot of disturbance, because they work or by extracting a soil sample (which will disturbed the soil area by leaving a hole after the extraction) or by being installed in the field removing all the area surrounding the soil sample to lower the surface. As an advantage, all these three systems allow to know exactly the exact contributing area, making it possible to calculate splash rates.

Only 5 of 16 device types allow to measure the distance or height that splashed soil particles can reach: the Leguédois tray (Figure 1i), the ink or radioactive tracers (Figure 1j), the sticks (Figure 1k) and the splash box with levels (Figure 1l). Among them, only the Leguédois tray and tracers allow to determine the contributing area.

Eight splash devices listed in Table 2 allow the determination of the dominant splashing direction, which is a possible objective in some experiments because it is related with the slopes and with the formation of new rills (Abrahams et al., 1991). The devices designed for detection of directional splash are the Morgan tray (Figure 1h) the splash box (Figure 1m) and the directional box (Figure 1n). The Morgan tray (Figure 1h) is used to analyze differences between upslope- and downslope-splash, while the directional box (Figure 1n) can determine if splashed particles move upslope, downslope or in other directions.

In Table 2 the splash devices are divided also between those which allow to obtain the rate of splashed soil (the contributing area is known) and those which do not allow it. This last type of splash devices includes the new splash cup (Figure 1o), which measures the loss of sand-sized particles splashed from a recipient that is located on top. Usually undisturbed soil is not used with this device, because it requires the use of homogeneous material (eg, sand) to simplify the comparison between different study sites by avoiding the differences within the soil samples. Finally, the movement of individual or groups of aggregates and/or particles can be measured using cameras (Figure 1p) or tracers (Figure 1j) or a combination of both (Darvishan et al., 2014). However, the drawback is that with these recordings the sediment is not collected. There is wide range of systems and devices depending on the studied factors and parameters of splash erosion (Table 3). Some devices listed in Table 3 are usually used under laboratory conditions (curtains, pictures, tracers) while other systems of splash have a wider use (cup, Morgan tray, etc.).

Summarizing, the selection of the splash instrument is based on meeting the maximum number of scientific goals and must also provide comparable results. Devices can be divided among those which measure the amount of soil material splashed from the soil surface to one target (unbounded splash traps), and those which measure the soil lost from the device (bounded splash traps). These are complementary measurements and are used upon the needs of the researchers, the objective of the research and the constraints of the environmental conditions. Then, a briefly discussion about the differences in using these both types of instruments will be done.

3.1.1 Unbounded splash traps

The splash devices can be divided into two main categories: [i] devices that collect sediment from an unknown area and [ii] devices that collect sediment from a well-known area. In the first group, it is not possible to measure soil erosion rates because the source area is not known and the calculation of sediments detached per each unit or every area is not possible. However, these methods usually do not cause great disturbances in the soil because the surrounding area is not altered during the setup. This factor makes these devices more suitable for studying degraded landscapes, like fire-affected forest areas, abandoned agricultural terraces or mining sites.

Probably, the first of these methods is the splash board (Ellison, 1944a, 1944b) which includes a vertical sheet of plastic or other material equipped with a tray in the bottom to collect the splashed particles (Figure 1d). Some years later this method evolved into splash boxes (Ghahramani et al., 2012; Van Dijk et al., 2003a). Basically, the apparatus consists of a tank or buried box, equipped with a tray that can be used both to quantify the dispersed particles and to collect surface runoff flow in sloped areas (see figures 1d, 1g and 1m, respectively). All of these methods are monodirectional. The same idea can be done recovering soil from any direction (see figures 1a, 1b, 1c, 1e and 1k), like the splash cup (Fernández-Raga et al., 2010; Morgan, 1978; Parlak and A, 2010), the bottle system (Bolline, 1975), the funnel system (Fernández-Raga et al., 2010; Terry, 1989, Jordán et al., 2016) or sticks (Fernández-Raga, 2012).

3.1.2 Bounded splash traps

The second type of devices is those that allow assigning the splashed soil to a known contributing area. These kinds of devices can be installed in the field or in laboratory for fully controlled conditions. The setup consists on an undisturbed amount of soil (eg, 3-5 mm soil aggregates; Leguédois, 2005) surrounded by a plastic cover tray located in a lower position that can collect the dispersed particles. The advantages are that all the captured soil particles can be recovered and the studied soil surface remains undisturbed. As the studied surface is known (eg, 18 cm^2; Leguédois, 2005), this type of experiments allows to determine the splash erosion rates (figures 1h, 1i and 1n). The setup requires removing or covering the surrounding soil making only possible the study of the splash and no other associated processes. Some researchers avoid this disadvantage by studying splash processes on soil samples under laboratory conditions. This implies that the soil sample may be disturbed during collection and transport. But depending on the goal of the research, this disturbation of structure of soil may not be an inconvenient. In some cases, sieved soil material has been used in order to obtain comparable measurements (Ryzak et al., 2015; Ma et al., 2014; Fu et al., 2011).

This type of devices include the design by Morgan (1981) which has been used most frequently (Nanko 2008; Angulo-Martínez,2012; Darvishan et al., 2014; Moghadama et al., 2015, Beguería, 2015), the Leguédoiss tray (Leguédois et al., 2005), and polyethylene curtains (Mermut et al., 1997). These techniques have some important limitations. First, splash traps are not recommended for well-structured or/and plant covered soils such as grasslands, forests or scrublands. However, when the research is developed on soils that are affected by intense ploughing, road and railways embankments, trampling areas and mine spoils, the use of disturbed samples does not influence the accuracy and quality of the measurements.

Second, interactions between splash and runoff flow are not considered, leading to poor estimation of field values (Mermut et al., 1997).

Bounded splash-trap experiments allow measuring soil erodibility of different soil materials or standardized sediments (eg, sand or model soils) by placing a known amount of sample in a splash cup and determining the difference in weight before and after a rainfall event (Figure 1g). When these systems are used with sand, the results are more comparable, but it is worth noting that these measurements will not reflect splash erosion, but only the result of the kinetic energy of the rainfall.

The most common device is the splash cup system (Ma et al., 2014), based on the first Ellison's model (Ellison, 1947). Several researchers have used special splash cup devices with some modifications in the size or design (Erpul et al., 2005; Fernández-Raga et al., 2010; Geißler et al., 2012; Poesen and Torri, 1988; Proffitt et al., 1989; Salles and Poesen, 2000) or splash curtains (Mermut et al., 1997).

The modifications done to the initial designs of splash cups try to solve the main three problems reported by Scholten (2011): rim effect, the size effect and the wash-off effect. The rim effect results from soil surface lowering in relation with the solid rim of the cup (Kinnell, 1974). With only 3 mm of decline of the sand surface inside the cup, underestimation may reach 9 % of the sand detached from the cup (Bisal, 1950). Larger-sized cups (above 10 cm in diameter) may help to minimize the rim effect (Poesen and Torri, 1988). The size effect depends on the characteristics of raindrops (velocity, frequency and angle of impact) and soil (particle size and aggregation). Thus, for a determined moisture content, an impacted sand particle will be shifted to more or less distance according to its size. Therefore, splash erosivity is worse estimated when bigger-sized cups are used (Leguédois et al., 2005; Poesen and Torri, 1988; Van Dijk et al., 2003c). Finally, the wash-off effect (Kinnell, 2001) refers to the impact of ponding and runoff flow. Slight modifications of the design (K-cups) were implemented by Kinnell (1974, 1982) to solve this problem.

3.1.3 Tracing splashed soil particles

The movement of splashed soil particles or aggregates may be quantified and traced (Cooper et al., 2012; Hoffman et al., 2013; Parsons, 1993; De Ploey, 1969). Tracing techniques allow individual determination of the trajectories that particles/aggregates run and directional analysis. On the other hand, they demand an objective photographic treatment and analysis, which increases costs and complexity of the study (Darvishan et al., 2014). The most common soil tracer is the isotope ^{137}Cs, but this method is very expensive and labour intensive. In contrast, potassium (K) has similar electrical, chemical and physical properties as Cs, and can be used instead. K content may be easily determined prior and after erosive events by infrared spectroscopy (Luleva et al., 2011), although it may lead to inaccurate results in fertilized soils or above certain moisture and clay content thresholds (Luleva et al., 2013).

3.2 Natural vs. simulated rainfall

Research under natural rainfalls contribute to understand the process but they are costly due to the long period necessary to measure splash erosion under different ranges of rainfall intensities and volumes. This is even more difficult in semiarid ecosystems, where rainfall is uneven and long drought periods are recurrent (Moghadama et al., 2015; Nadal-Romero et al, 2015; Ruiz-Sinoga et al 2011). Moreover, splash erosion experiments under field conditions do not allow controlling the factors involved. Although rainfall simulation results are not directly comparable or extrapolable to natural rainfall experiments, controlled conditions improve the accuracy of results and they can be repeated in the laboratory or in the field (Dunkerley, 2008; Iserloh et al., 2013a; Iserloh et al., 2013b).

Even though rainfall simulators are able to reproduce high rainfall intensities over a representative period of time, they cannot simulate series of rain intensities nor simultaneously produce raindrops of different size, each raindrop impacting the soil with its real terminal speed and its natural kinetic energy. Therefore, rainfall simulation is not completely efficient (Cerdà, 1996; Cerdà, 1997; Lassu et al., 2015). Arguably, this is not seen as a problem in general as most researchers are only interested in low-frequency high-magnitude rainstorms that trigger overland flow and associated erosion processes. Although rainfall simulators can produce representative rainfall drop size distributions (DSD) (Ries et al., 2013), it is difficult to reproduce raindrops with kinetic energy as high as that observed during a natural storm (Parsons et al., 1991; Wainwright et al., 1999; Parsons and Stone, 2006;). In rainfall simulators, the kinetic energy reached by raindrops at the time of impact on the soil surface is conditioned by the height at which nozzles or drip systems are located. Although the terminal velocity can be modified slightly by modifying the height, the kinetic energy increased is less than that observed during natural storms (Iserloh et al., 2013a). By applying pressure, satisfactory velocities can be achieved at the time of impact. However, this also produces too small sized drops and unnatural DSD (Goebes, 2014). In both cases, natural rainfall cannot be perfectly reproduced (Cerdà, 1996 and 1997; Lassu et al., 2015).

The characteristics of simulated rainfall, the type of devices and the amount of measurements depends on the aim of the research. If the objective of the research is to determine rainfall erosivity, or variability of soil erodibility under different land uses and managements, most researchers use rainfall simulation to reproduce similar storms at different points (Foot and Morgan, 2005; Fox et al., 2007; Legout et al., 2005; Salles and Poesen, 2000; Salles et al., 2000). Although the results are not usually extrapolable, it is possible to make comparisons between points with different characteristics (Rodrigo-Comino et al, 2016d). However, if the objective of the research is to characterize soil erodibility of a region, it is necessary to take measurements under natural rainfall conditions.

Rainfall simulation is a technique that can be used in both field and laboratory conditions. Measurements taken in the field guarantee that the sample is not disturbed. In contrast, laboratory experiments imply that the soil sample must be collected, transported, stored, possibly pretreated and redistributed. All these processes may alter the sample and strongly influence the final measured result.

3.3 Main literature review findings

The review of the publications on splash erosion allow us to highlight the main findings and the current knowledge: i) the amount of detached particles increases with rainfall intensity (Ma et al., 2014; Mermut et al., 1997), but in any case, the most important parameter that affects the splash erosion is the kinetic energy of raindrops (Fernández-Raga, 2012; Fernández-Raga et al., 2010); ii) recurrent storms in a short time cause a progressive decrease of splash erosion. This effect is more pronounced at higher rainfall intensities. This effect can be influenced because soil moisture has a significant negative relation with the intensity of splash erosion (Mermut et al., 1997); iii) for experiments under laboratory conditions, most researchers use dry and sieved soil (>2 or >5 mm are the most common used sieve fractions) or use only sand fractions (Fu et al., 2011); iv) although there is some controversy, most authors have suggested that intensity of splash erosion increases with slope (Abrahams et al., 1991). However, upperslope and lateral splash decrease at higher slopes, and is virtually disappears at slopes steeper than 35% (Fu et al., 2011); v) although the study of directional splash is extremely important, the diversity of techniques and devices used has produced data that are not comparable (Fu et al., 2011); vi) the study of splash erosion in relation to water and sediment connectivity is a current gap in literature (Van Dijk, 2005). Bracken and Croke (2007) wrote a well cited paper which deals with the concept of hydrological connectivity and puts forward an evaluation system called “the volume to breakthrough” to quantify changing connectivity between different environments and catchments. This system has later been applied by other authors (Geißler et al., 2012b). Connectivity is a growing issue in soil erosion research and is powering the papers on this issue to be highly cited (López Vicente et al., 2016; Masselink et al., 2016; Marchamalo et al., 2016).

3.4 Bibliometric analysis of splash erosion

Bibliographic search allows researchers to access scientific knowledge focused on a specific topic. It also provides key authors' names and allows to analyse the evolution, the trends and the changes in the research. But, mainly, it also allows to identify new lines of investigation. Papers focusing on splash erosion have been published in 177 different journals (Table 4), but mostly in *Catena* (53 papers) and *Earth Surface Processes and Landforms* (44). Both journals are devoted to soil science, hydrology and geomorphology research, which are the areas where splash erosion research is included. There is also a great variety of journals where the articles on splash erosion are published. There are 122 journals that published at least one paper on splash erosion and 22 published 2 articles, and 10 journals published 3 articles (see Table 4 for more information).

3.4.1 Splash erosion studies over the world

A geographic analysis of these articles was carried out to identify the regions of the world where more scientific research papers on splash erosion are produced. From the 77 countries (Table 5) that published papers on splash erosion, USA dominates clearly with 159 articles, followed by the United Kingdom (57), China (84), France (42), Germany (55) Australia (39), and Belgium (39). Next come Japan (35), the Netherlands (32), and Spain (33). Figure 2 represents the countries with studies on splash erosion cited in the bibliographic sources employed. Regarding the language used for the publications, 97% of the articles are written in English. The number of articles in other languages are 7 in Chinese, 4 in Korean, 3 in Portuguese and in German and 1 in each of the following languages: French, and Turkish. However, this research is based in the ISI Web of Knowledge dataset, which is biased towards journals published in English, and there are other journals that have published papers on splash erosion in other languages. However to list them will be difficult and their impact on the science of today is scarce.

3.4.2 Keywords

The keywords in the articles on splash erosion were searched and Table 6 shows the main ones found, the number of articles in which they appear, and the main concepts treated in those articles. The most common keywords are actually *splash* and *erosion,* which occur in 527 and 518 papers, respectively. Many keywords refer either to rain or soil properties (including *runoff, rainfall*, *soil properties*, *soil topography, erodibility).* The articles deal with different aspects related to splashing, either on the base of theoretical models developed for modelling, or measuring the transport with an empirical approach, the impact caused, the stability of the aggregates, or the rain infiltration. Some of the keywords are, for example, *model, simulated rainfall, impact, transport or infiltration*.

Only very few authors have included the study zone among the keywords. It was found that regions with Mediterranean, semiarid and arid climates are the ones arising more interest in the study of splash erosion. Most of the research is carried out in the region where the research teams are located. For example, Bochet et al. (2000; 2002; 1998) have carried out studies in Spain, and Molina et al. (2008) in the Andean mountains, Van Dijk et al.(2003) in Indonesia.

3.4.3 Chronological study and evolution

The articles on splash erosion have also been classified according to publication dates. Figure 3 shows the countries ordered by the year of publication of the first articles on splash erosion, indicating also the number of documents published before 1980. The first results were published in the second half of the 1960s, but there are several articles that are not included in the ISI of Knowledge data (Ellison, 1944a, 1947).

Although splash erosion is traditionally included into soil science, this topic has been deeply treated also in meteorology journals because of the relationship between the splash erosion and the drop size distribution of the rainfalls and also the kinetic energy of the raindrops. There is a continuous increase in the number of articles about splash erosion, especially in the last decade. As this increase can be noticed also in the articles about other related science topics, an analysis of the evolution of the number of articles in splash erosion, in soil science and in meteorology areas has been carried out.

The number of published articles on meteorology and atmospheric sciences was already relatively large when the first splash publications appeared (Figure 4A). During 1967, when the first splash publication appeared (Mutchler, 1967), 1973 articles on meteorology were also published, and the number of publications continued increasing in the following years (Bakker et al., 2012; Barchyn and Hugenholtz, 2012; Fernández-González et al., 2011; Fernández-Raga et al., 2009; Fraile and Fernández-Raga, 2009; Mehta et al., 2012). During the 1990s there was a “boom” in the number of publications on splash erosion and on soil erosion (Figure 4B), both growing in number at a similar rate.

In order to normalize the number of publications on splash erosion to the categories in which they are included, two indices were computed as the quotient between the publications on splash erosion and the publications on meteorology/atmospheric sciences and soil erosion (Figure 5). The proportion of articles on splash with respect to meteorology/atmospheric sciences has increased significantly after the boom of the 1990 whereas the number of splash erosion articles related with soil erosion remains approximately stable.

An overview of the evolution of the publications reveals that the first article on splash erosion is by Mutchler (1967), after the invention of the disdrometer in the 1960s. It is a specialized article on a number of factors influencing the physical geometry of raindrops and which must be taken into account when studying splash erosion. Later, in 1968 two articles are published about the type of clouds in relation with splash erosion (Moldenha and Koswara, 1968), and radioactivity-based methods to detect this particular type of erosion (Coutts et al., 1968). In the 1970s we find 7 articles on the description and properties of splash erosion (Luk, 1979), indices (Yamamoto and Anderson, 1973), measurement techniques, such as the cups method (Kinnell, 1976), and splash erosion in relation to animal activity (Imeson, 1977; Imeson and Kwaad, 1976). In the 1980s there are 11 publications, most of which focus on the modelization of splash erosion (eg: Kinnell, 1982; Park et al., 1982), and others on its impact on agriculture (Osuji, 1989).

It is not until the 1990s that the study of splash erosion clearly expands and diversifies, with a much higher number of publications (138). The topics studied are diverse and include modelization (Nearing et al., 1990; Morgan et al, 1998a), fertilization (Siegrist et al., 1998; Yadav, 1990), stability of aggregates (Amezketa et al., 1996; Le Bissonnais, 1996; Torri et al., 1998), rainfall simulations (Kincaid, 1996; Wainwright et al., 1995), infiltration (Abrahams and Parsons, 1991a; Agassi et al., 1994; Agassi and Levy, 1991; Wainwright, 1996), interception by vegetation (Bochet et al., 2000, 2002; Ghidey and Alberts, 1997; Gyssels et al., 2005), disdrometers (Salles and Poesen, 1998), runoff (Agassi et al., 1994; Grosh and Jarrett, 1994; Le Bissonnais and Singer, 1993; Roth and Helming, 1992; Wainwright, 1996), and the effect of the wind on splash erosion (Erpul et al., 1998; Pedersen and Hasholt, 1995).

In the first decade of the 21st century, the increase in the number of publications on splash erosion has been impressive, growing by 65%, with 238 documents, and another 248 from

2010 to 2016. These articles complement and develop research areas started in previous years, and the study of splash erosion becomes fully fledged for scientific applications in a number of fields. The topics studied include disdrometers (Begueria et al., 2015; Fernández-Raga et al., 2010; Meshesha et al., 2016; Sanchez-Moreno et al., 2012; Van Dijk et al., 2002), modelization (Erpul et al., 2013; Ma et al., 2008; Marzen et al., 2015), stability of aggregates (Arthur et al., 2011; Jomaa et al., 2012; Le Bissonnais, 2016; Mahmoodabadi and Sajjadi, 2016; Mataix-Solera et al., 2011; Wakiyama et al., 2010), rainfall simulations (Chaplot et al., 2011; Fox and Bryan, 2000; Katuwal et al., 2013; Mahmoodabadi and Sajjadi, 2016; Wei et al., 2015), infiltration (Lei et al., 2006; Nanko et al., 2010), interception by vegetation (Geißler et al., 2012; Hoffman et al., 2013; Negishi et al., 2006; Van Dijk et al., 2003a), runoff (García-Díaz, et al, 2017; Rodrigo Comino et al, 2017; Dong et al., 2013; Ghahramani et al., 2011a; Van Dijk and Bruijnzeel, 2003; Van Dijk et al., 2003b,). Some of the new topics are soil protection by mulching (Bhattacharyya et al., 2010; Gholami et al., 2012a; Smets et al., 2008; Van Dijk and Bruijnzeel, 2004; Van Dijk et al., 2003b; Van Dijk et al., 2003a), interception by vegetation canopy (Furbish et al., 2009; Geißler et al., 2012a; Geißler et al., 2013), and the use of ions to determine erosion (Insepov et al., 2008), hydrophobicity (Ahn et al., 2013) and the effect of the wind on splash erosion (Cornelis et al., 2004b, 2004a; Erpul et al., 2008, 2009a).

3.4.4 Number of citations

The impact of research on splash erosion, measured as the number of citations, has increased exponentially since the 1960s (Figure 6) shows the number of published articles and citations over the years. Different behaviours have been observed in the 1990s. The articles published in the 1990s are cited, on average, from the 5th year after publication. In contrast, the number cited papers and citations increased rapidly since 2006.

The most widely cited article on splash is Le Bissonnais, Y. (1996), a revision about aggregate breakdown, crusting and water erosion, describing three different treatments for measuring of aggregate stability. The next most cited article is about EUROSEM, an erosion model (Morgan et al., 1998b) which is able to simulate interill and rill flow; analysing also information about the effects of plant cover interception, stone cover on infiltration, flow velocity and splash erosion.

4 Main gaps in splash erosion research

Since 1960, splash erosion has been studied as an important part of erosion processes (Parsons et al., 1994; Wainwright et al., 1995), but it has not become a main topic of research because of the difficulties of getting an accurate data with reliable methodologies. Another difficulty is the high variability in space and time that is intrinsically joined with the splash erosion process. These problems, together with the tendency of individual researches to create new instruments to measure splash in every study, increases the variability of results and makes it difficult to compare results.

Some unanswered questions regarding splash erosion are how it interacts with other processes such as infiltration, soil water repellency or how soil structure and composition change in relation with raindrop impacts. This lack of understanding contributes to the limited knowledge we have about the full cascade of erosion processes and how they interact with one another.

More research is required in four areas within splash erosion research (Figure 7): a) further study of the known basic factors influencing splash erosion, b) description and quantification of sources of uncertainty about the measurement of different variables, c) to understand the influences that the chosen research approach by individual researchers will have in the final result and d) to study the impact of drivers or mitigation techniques that may affect splash erosion.

4.1 Factors influencing splash erosion and uncertainty in splash erosion measurements

A complete study on splash erosion should include all the factors that might influence splash erosion including the consequences of splash erosion over other factors and soil properties. The literature review reveals that the rainfall factor is avoided in terms of its discrete character. DSD and kinetic energy are left out the research, which is mainly focused on rainfall intensity. This is a source of uncertainty and can cause wrong measurements since the main process triggering splash erosion is the impact of the raindrops on the soil and their kinetic energy. Only the measurement of rainfall intensity cannot provide a proper understanding of the rainfall physics behind precipitation and this should be included when undertaking splash research. The main reason for the lack of a accurate characterization of precipitation is that most experimental sites are in places where a disdrometer, that can measure raindrop sizes and velocity, cannot be installed. Without a disdrometer, the only possibility is to work with theoretical DSDs. But theoretical models do not consider changes in the speed of the raindrops produced by wind or the interception by vegetation. Furthermore, there are some studies that warn for an overestimation of kinetic energy when theoretical DSDs are used (Angulo-Martínez et al., 2016).

Other typical parameters of rainfall are the intensity and the quantity of rainfall, which both need to be evaluated as time data series. It has been reported that, under constant rainfall intensity, three phases can be differentiated during a storm (Roth and Helming, 1992; Martínez-Zavala and Jordán, 2008). During the first phase, the rate of splash increases, with no runoff observed. In the second phase, runoff and sediment yield rates increase sharply, along with a continuous increase in the splash rate, until a maximum is reached (Chaplot and Poesen, 2012). At that time, a peak the sediment transported by the runoff can be observed. Later, the proportion of detached and transported particles decreases as the surface soil layer becomes saturated. Finally, during the third stage (steady state), runoff and soil loss rates reach equilibrium. Nevertheless, rainfall intensity is not constant during natural storms, and runoff flow or depth of ponded water may condition splash erosion rates (Ghahramani et al., 2011b). It has been reported that soil detachment rate decreases as runoff depth increases (Torri et al., 1987; Dunne et al., 2010), but there is a need to develop modelling approaches that rely on relevant data obtained under well-controlled flow depth and velocity conditions (Kinnell, 2012). Strong intensity periods may produce ponding water that protects the soil against splash erosion. Furthermore, rainfall parameters tend to be very variable spatially and temporally (Enmmanuel et al., 2012), which is important to know in order to upscale splash erosion either over space or time.

The type of soil and its physical characteristics (moisture, organic matter content, infiltration capacity, texture, structure, etc.) are the second most important parameter to understand splash erosion potential. The lack of detailed information on soil characteristics compromises greatly the comparison of results from different authors. As an example, some studies about soil moisture content have been carried out, finding an influence on splash (Ryzak et al., 2015), but there is scarce information about other parameters like infiltration capacity and soil structure or stone cover (Abrahams and Parsons, 1991). Soil texture and chemistry can determine not only aggregate stability, but also other changes like porosity, infiltration capacity or other reactions of soil to water or fire. A high organic matter content is related normally with larger aggregates, which is a sign of stability (Besalatpoura et al., 2013; Canasveras et al., 2010). The size and the weight of aggregates will determine the threshold of kinetic energy that a drop will need to move a particular aggregate (Guerrero, 2001; Leguédois et al., 2005; Salles and Poesen, 1999; Salles and Poesen, 2000; Salles et al., 2000). Only some researchers have touched this topic. Salles et al. (2000), for example, calculated a threshold of 1 mm of diameter for a raindrop to be able to detach and transport particles by splash. Van Dijk et al. (2002) found a threshold of 0.8 mm h^{-1} to move aggregates. Processes such as fires, capable of drastically reducing the soil organic matter content, may cause destruction of aggregates (Mataix-Solera et al., 2011), increasing the strength of splash erosion. Also the analysis of specific mineral elements which are preferentially affected by the splash erosion is a topic that should be incorporated in splash erosion research as it may become the main process in the movement of carbon (Hu and Kuhn, 2014) and nutrients (Dong et al., 2013) at the surface.

Although the influence of the slope on splash erosion is a recurrent topic in literature, the scientific community has not reached an agreement about the importance of this influence (Fu at al 2011; Torri and Poesen, 1992) probably because of the poor analysis of the influence of wind on slopes in the splash experiments described in these studies (Erpul et al., 2008).

Literature review shows also a lack of studies relating splash erosion with subsequent sealing and crust formation and its influence in infiltration. This topic needs to be more researched because although splash erosion is one of the main mechanism of aggregate breakdown, and the measurements of aggregate breakdown is used frequently to asses soil crustability and erosion risk, the evolution of crusts between rainfall events is complex and sometimes independent of aggregate stability (Le Bissonnais, 2016).

4.2 Research approaches

As with any other research methodology, the outcomes of a research are affected by the approach that is chosen when the measuring scheme was set up. In splash erosion research there is a lack of standardization in both, approaches and methodologies. Either because of a different choice of device, or a different strategy in terms of the use of soil, i.e. the choice of laboratory *vs.* field study, or natural *vs.* simulated rainfall. Both reasons make it difficult to compare different experiments and the results obtained, so that general conclusions cannot be achieved. Taking into account the diversity in the methods, it can be concluded that there is a need for establishing appropriate and inter-comparable methodologies, either by providing a catalogue of standard devices depending on the variable to study and/or the type of measurement to carry out, or by providing a protocol of system selection to ensure comparable splash erosion data. A broad catalogue of different devices for measuring splash erosion-related variables has been compiled (Table 2). The selection of the device without a deep knowledge of splash behaviour is sometimes cumbersome and the development of a standard measurement method is highly recommendable. Also the treatment of the soil samples (i.e., sieving) has to follow a strict protocol since it can affect deeply the results.

The spatial upscalling is another topic that can make comparisons difficult. Changes in the test surface exposed to raindrops may affect the ability of the displaced particles to fall back into it or into the device. This is also works for changes in the rainfall properties. Poesen and Torri (1988) reported the influence of the size of the splash device in the reception of sample, but few experiments have been carried out to clarify which device size fits best for splash research. There are devices with a square meter of test surface (Fu et al., 2012), others with a couple of squared centimetres (Salles and Poesen, 2000; Van Dijk et al., 2003b, Geiβler et al., 2012, Nanko 2008) and others even with unbounded test soil surfaces. And also there are larger differences in the recovered splash soil over plots of 1 m^2 (Van Dijk et al, 2003 a) or 3 cm^2 (Scholten et al., 2011). Major efforts in designing scalable devices have still to be done. This will allow to calculate the actual influence of splash in the total erosion of any surface and to compare results from different studies. Comparative studies should analyse also the spatial influence on measurements of splash in height (Fernández-Raga, 2012), in distance (collection trough by Jomaa et al., 2010) and in several points or plots. Splash production is a complex process, which results from the interaction of water and soil. On its own, the impact of raindrops does not have to produce detachment and transport of particles, but soil conditions (moisture, structure, porosity, etc.) do play a key role that needs further investigation

The time interval between events, together with the time that it is raining over the samples is also impacting the outcomes. The effects can also build up over time, and the distribution of rain and the duration of every rainfall event should be also measured. The influence of the temporal evolution of splash rate need exploration, as a storm with a heavy rainfall intensity in the first few minutes does not necessarily have to produce the same erosion as another with a similar but delayed intensity. There are rainfall variations within and between natural rainfall events that influence how splash erosion occurs which should be reproduced in simulated rainfall. Usually, splash particles are attributed to the entire rainfall event, which allows differencing between events with different genetic mechanisms (Fernandez- Raga et al., 2010). Some studies have taken splashed samples after 30 (Ma et al., 2014), 60 (Fu et al., 2011) or 120 minutes (Mermut et al., 1997). As a conclusion, a deeper and better understanding of splash process needs to account with the temporal dimension also.

4.3 External drivers impacting splash erosion

Stated all of these gaps, the last column in figure 7 are the drivers or special conditions and factors which influence splash erosion. Land cover management is a way to prevent splash, because mostly all authors confirm bare soil as the most erosive soil (Gyssels, 2005), although some studies have pointed out that an increase in splash can occur due to larger drops that fall on the soil surface from dripping points coming from leaves (Ma et al., 2014).

Other authors have found the absent of influence of the form of the leaf in splash (Foot and Morgan, 2005), but there is very little information about the influence of several related characteristics: plant height, species, leave size/shape or morphology of canopy. Mulching cover is another method to prevent erosion which should receive a deeper study from the point of view of the splash, because currently there are only two articles using wood-chip-mulch (León et al., 2015), eight using straw mulching (Cerdà et al., 2016; Edwards et al., 2000; Gholami et al., 2012a; Haider, 1989; Harmon and Mayer, 1978; Lang et al., 1984; Lattanzi et al., 1974; Prosdocimi et al., 2016b), one for rice straw mulch (Glolami et al., 2012b), one for geotextile (Bhattacharyya et al., 2010; Giménez-Morera et al, 2010 b), one recommending the use of straw mulch (Liu et al.,2015) and other with organic mulching (Smets et al., 2008) . The study of different potential types of vegetation that could be used to protect against splash would be very useful for applying in restauration plans for avoiding soil detachment. Furthermore, splash erosion needs to be analysed in terms of crust formation and the effect this may have on vegetation establishment, as the impacts of drops may disturb small seedlings and the crusting may inhibit seeds to germinate.

But the influence on splash erosion is not only related to plants. Soil fauna can make a great influence on splash erosion (Imeson, 1977; Imeson and Kwad, 1976). They can be the responsible of huge quantities of soil movements. In general the relation between soil, fauna and erosion has received little attention in literature so far (Cerdà and Jurgensen, 2011; Hancock et al., 2015), and splash erosion is not an exception.

The management of the soil is another way that can lead up to splash erosion, and the land movements for constructions of roads, terraces, tillage, mulching and drainage lines need special attention in future studies about erosion. Specially in activities that produces bared soil, the splash erosion is an important process that will continue till the stablishment of plants. The design of new patterns of drainage systems may slow down the splash process over engineering structures and embankments. New terraces change the roughness and slope, and the influence of this changes is unknown. The last humankind influence in splash is due to fire, which can change the aggregates size (Providoli et al., 2002), the infiltration capacity and the cover (Keesstra et al., 2014), and need to be studied from a perspective of recurrence and severity. But also the ash and charred litter leaved after the fire can reduce the susceptibility to rain splash erosion (Zavala et al., 2009).

For future topics that should not be forgotten, another proposal is to study how splash erosion fits into conceptual approaches like connectivity (Parsons et al., 2015). How splash erosion changes their ecosystem and influence in other processes. And once the influence in other processes is determined, a complete model may be developed which allows to estimate the soil loss per splash erosion. Several authors have tried to explain the physical processes of splash (Torri and Poesen, 1992;) but only Ma et al. (2008) have developed a theoretical representation of the splash erosion process. More studies are needed to validate this model by applying it to another similar places or to develop new models.

5 Conclusions

A complete reviewed revision of the main advantages and disadvantages of the different methods that exists to measure the splash erosion, and the recommendations of use under certain condition were better performed. It can be noticed the need of a new high-precision device to minimize the problems associated to the measurements, which make so difficult the quantification of the total loss of soil due to the impact of raindrops.

From the first indexed article published on splash erosion in 1967, a total of 669 publications on the topic have been counted. A particularly drastically increase in the number of publications has been observed from the 1990s onwards, reaching a maximum in 2015, with 50 articles per year. In addition, the number of citations of the articles has grown exponentially. There is no single author who stands out with a high number of publications. The United States is the pioneering country in the study of splash erosion, and also the one with most articles: 159. Most articles have appeared in 2 journals: *Catena*, with 53 and *Earth Surface Processes and Landforms*, with 44 articles. In most articles, splash erosion is treated as a complementary issue of the main topic of the paper. The most frequent keywords are *splash* and *erosion,* with 527 and 518 papers, respectively. Other common keywords are related to rain or soil properties (for example, *runoff, rainfall*, *soil properties*, *soil topography, erodibility).*

From the literature review several key research gaps have been defined: i) there is a need about studies of the texture, structure, composition and physics characteristics of the soil related to splash; ii) to make a more in-depth analysis of the threshold in kinetic energy of the rain, depending on the sizes of aggregates; iii) create a calculation of the main minerals which are preferentially moved by splash; iv) measure the impact of the cover of vegetation and the animals behaviour in splash; v) develop a methodology to calculate how human interventions can influence splash erosion in mines, terracing or unpaved roads. Also the influence of fire recurrence and severity on splash erosion is a poorly studied issue; vi) determine the size influence of the device to measure splash erosion, and designing of a model which better represent the complexity of the splash process is another issue which demands a larger improvement; vii) to develop a standard methodology and decide on a clear research approach to measure splash erosion to be able to compare splash data.

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Table captions

Table 1. Document types on splash erosion found in Web of Knowledge (WOS) with the words “splash erosion” in the title, abstract or keywords between 1900 to 2016.

Table 2. Summary of the different device types found in bibliography, original sources, articles reporting application of each device and different characteristics (yes/no): disturbance of the experimental soil surface, possibility to measure the height or distance that splashed soil particles reach during natural or simulated rainfall (height/distance), possibility to determine the direction of the splashed soil particles (direction) and possibility to calculate the splash erosion rate (splash rate).

Table 3. Summary of different measuring systems used and their general characteristics.

Table 4. Journals with published papers on splash erosion (1900 to 2016).

Table 5. Countries with studies on splash erosion cited in the Web of Science (1900 to 2016). The number of documents is shown between brackets.

Table 6. Keywords in the articles published on splash erosion.

Table 1. Document types on splash erosion found in WOS with the words “splash erosion” in the title, abstract or keywords between 1900 and present.

Document types	**Records before august 2016**	**%**	**Records after august 2016**	**%**
Articles	550	82.2	557	96.5
Proceedings papers	100	14.9	50 (proceedings removed from conferences not contrasted enough)	8.6
Patents	51	7.6	patents extracted form database	
Reviews	11	1.6	11	1.9
Editorial materials	5	0.7	5	0.9
Notes	2	0.4	2	0.4
Reports	1	0.1	1	0.1
Abstracts	1	0.1	abstract extracted form database	
Total with repeated documents	**721**	**107.7**	626	**108.5**
	In two categories		**In two categories**	
Article + Proceedings papers	52	7.7	50 (all the proceedings included are also included as articles)	8.6
Total documents	**669**	**100**	**577**	**100**

Figure captions

Figure 1. Samples of measurement used for splash: a) splash cup (Ellison, 1947), b) funnel (Gorchichko, 1977), c) bottles cup (Sreenivas et al., 1946), d) splash board (Ellison, 1944), e) collection through (Jomaa et al., 2010), f) splash curtains (Mermut et al., 1997), g) splash house (Proffitt et al., 1989), h) Morgan tray (Morgan, 1981), i) Leguédois tray (Leguédois et al., 2005), j) ink or radioactive tracers (Coutts et al., 1968), k) sticks (Fernández-Raga, 2012), l) splash box with levels (Van dijk et al., 2003), m) Splash runoff box (Ghahramani et al., 2011a), n) directional box (Van dijk et al., 2003b), o) T cup (Scholten et al., 2011) and p) camera (Darvishan et al., 2014).

Figure 2. Countries with studies on splash erosion cited in the bibliographic sources employed.

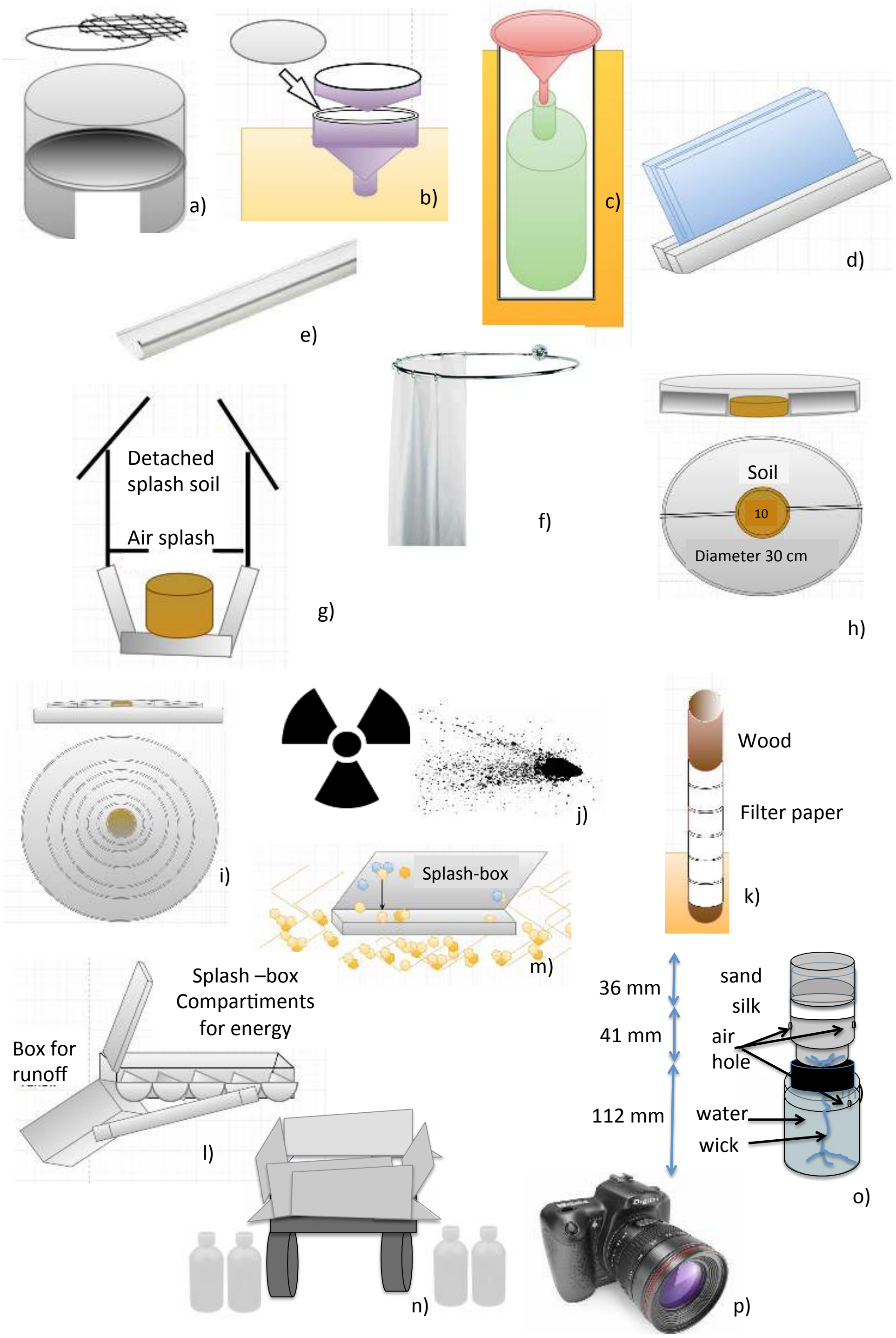
Figure 3. Countries and number of articles published before 1980 on *splash erosion* and year of the first publication.

Figure 4. Annual evolution of the total number of publications on splash erosion compared with a) publications on meteorology and atmospheric sciences and b) publications on soil erosion.

Figure 5. Ratio between papers focused on splash erosion and other areas: A, splash erosion/soil erosion papers; B, splash erosion/meteorology and atmospheric sciences papers.

Figure 6. Annual evolution of the number of publications on splash erosion and the number of citations.

Figure 7. Scheme explaining the gaps in the study of splash erosion organized by groups.



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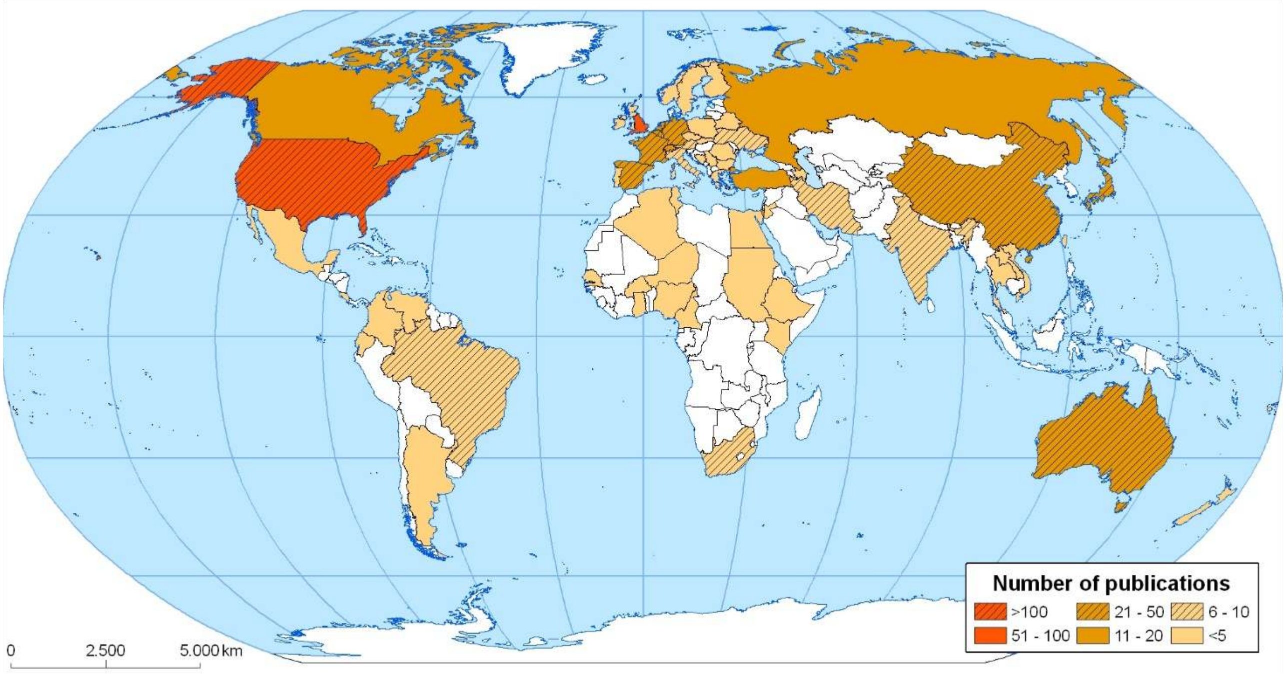

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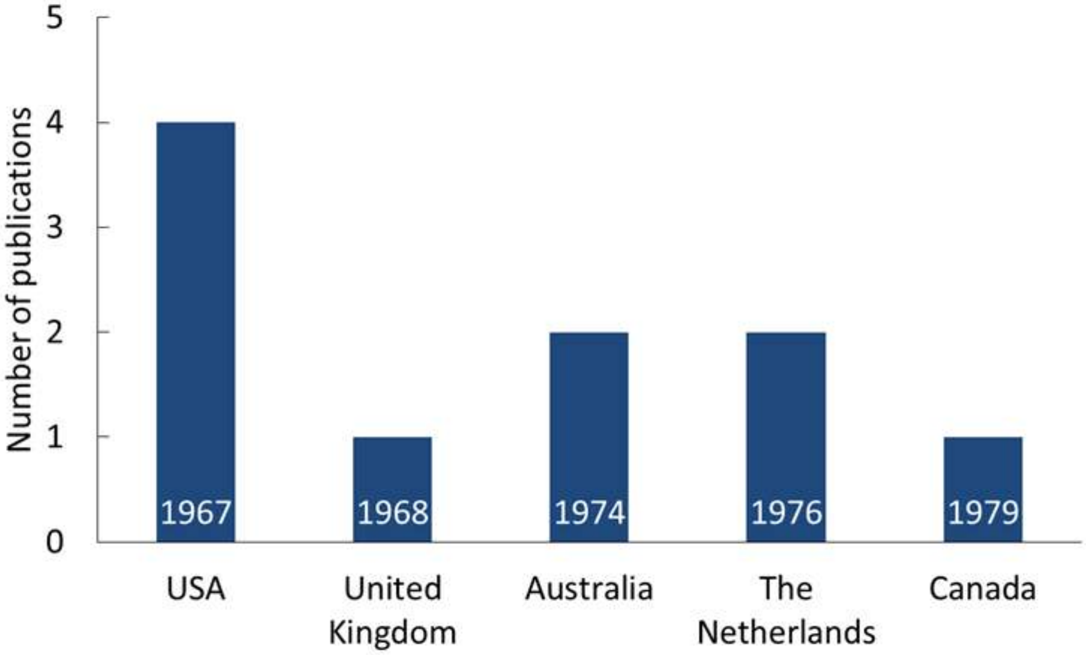

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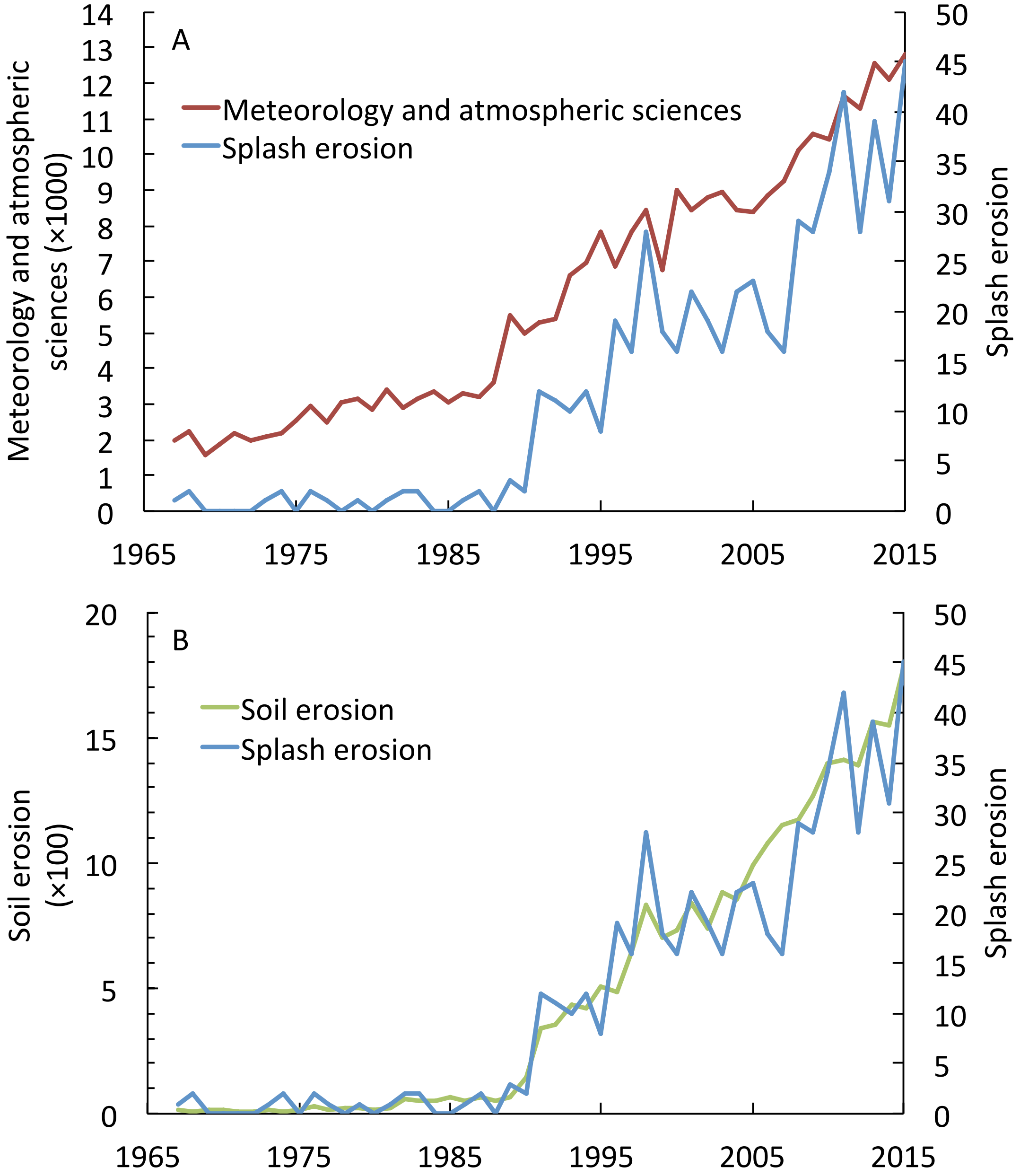

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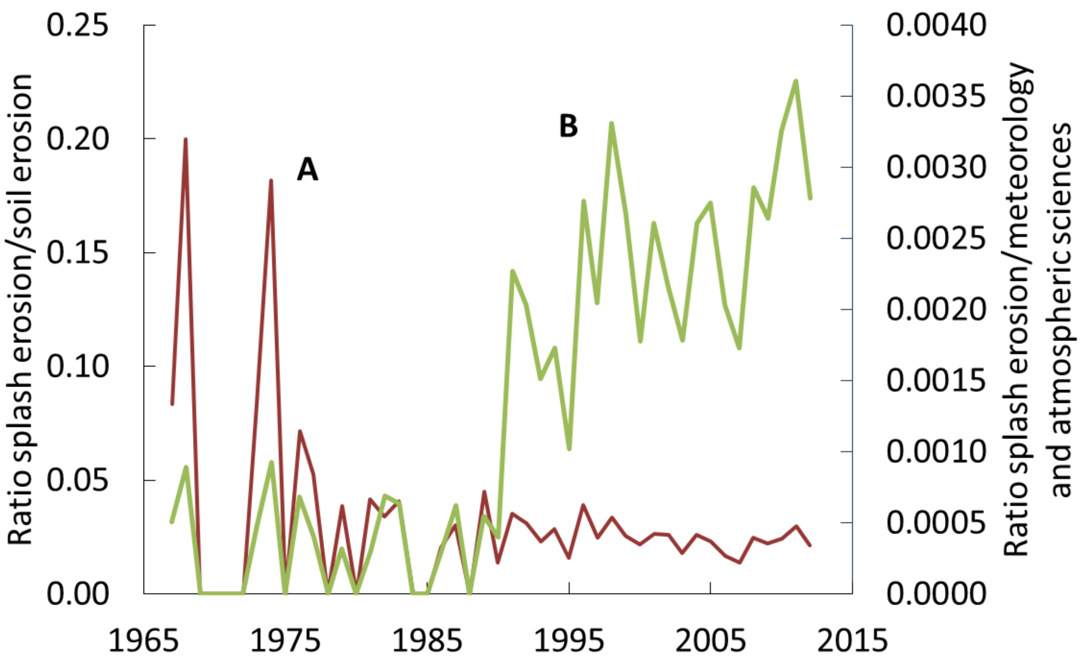

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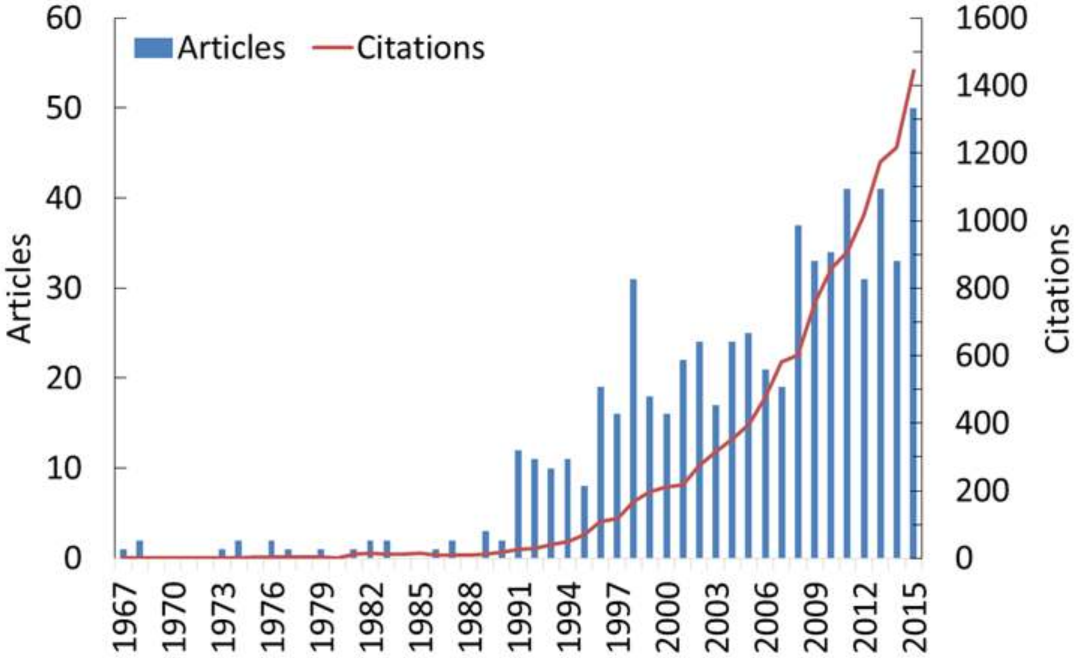

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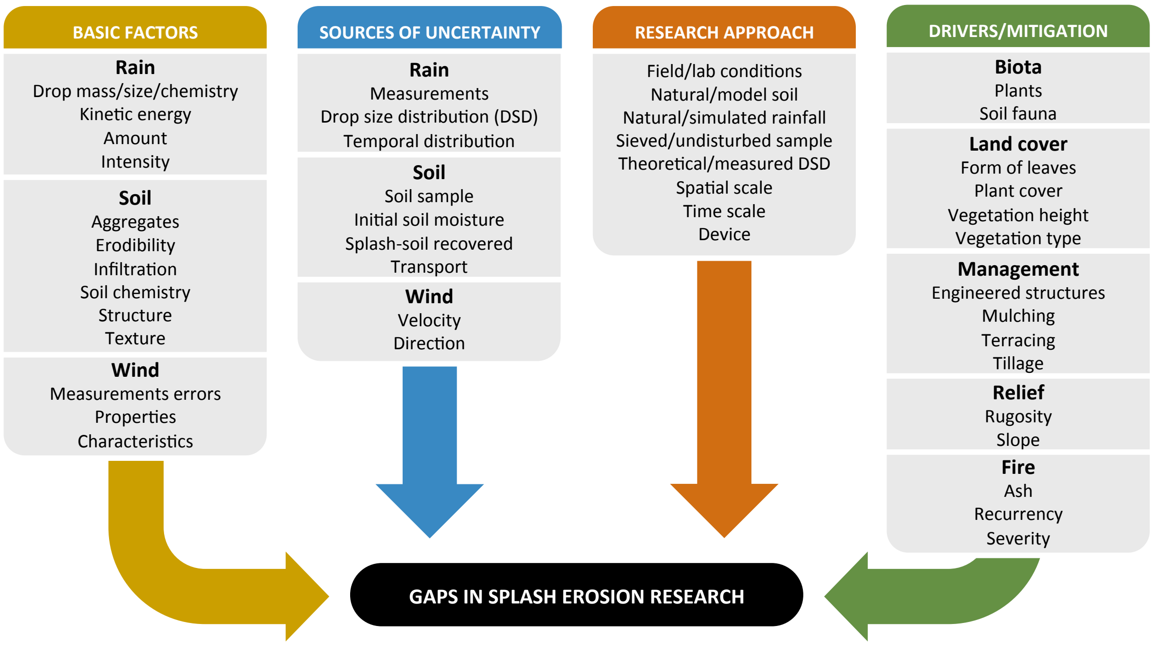

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