Journal of Environmental Management 271 (2020) 110990

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

Soil erosion on mountain trails as a consequence of recreational activities. A comprehensive review of the scientific literature

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ARTICLE INFO

Keywords:
Soil
Erosion
Mountain trails
Land degradation
Measurements

ABSTRACT

This article reviews the scientific literature on trail erosion and the magnitude of the erosive processes that occur on mountain trails due to recreational activities, mainly due to hiking. This work is necessary as a result of the increase in hiking and biking in forest, scrubland and grasslands, and the soil and vegetation degradation induced by these activities. We analysed results that have been compiled in the scientific literature, as well as other issues such as the geographical and temporal distribution of the research, the methods applied, the journals where the research was published, the types and quantity of uses of the pathways and the measures undertaken for damage mitigation. This paper highlights that there is a need for harmonization of methods. The results show that soil erosion rates are highly variable, high, and non-sustainable. Trail erosion research is growing at a rate of 3 papers per year and is published in a small group of scientific journals. Six journals published 47% of the papers on trail erosion, which show a high concentration in environmental journals. There are few papers published in the soil science and geomorphology disciplines, although the research topic and the science background are in these two disciplines. Reported world soil losses from trails ranged from 6.1 Mg ha^{-1} y^{-1} to 2090 Mg ha^{-1} y^{-1}, all of which are not sustainable. Trail erosion has mainly been investigated in the USA and is a new topic in other regions of the world. There is a need to implement mitigation measures to avoid land degradation, and this should be researched in the near future as right now most of the research describes and quantifies the problem but does not provide solutions: mitigation, rehabilitation or restoration. From a pure scientific approach, we claim that there is a need to research the connectivity of flows and the role of the trails on runoff generation and then sediment yield at pedon, slope and watershed scales. There is a need to research the mechanisms of the soil erosion process in trails: trampling effect, wheel impact, factors and seasonal and temporal changes.

1. Introduction

Soil erosion has primarily been studied in agricultural land since the beginning of the 20th century and in range and forestland after disturbances such as forest fires (Smith, 1914; Bennet, 1928; Brevik et al., 2017; Antoneli et al., 2018). Most of the measurements carried out on agriculture land show high erosion rates due to ploughing and herbicides (Borrelli et al., 2018), and low soil erosion rates were found in rangelands due to the positive effects of vegetation (Wynants et al., 2018). Within both landscapes, soil erosion was also studied on trails, railways and roads embankments, and they show higher erosion rates than in the surroundings (Seutloali and Beckedahl, 2015; Navarro-Hevia et al., 2016). This is mainly due to the lack of vegetation and soil compaction (Gyasi-Agyei et al., 2001), which plays an important role in increasing runoff along the trails (Wallin and Harden, 1996). Soil compaction can affect other soil parameters such as soil organic matter and can result in a long-term degradation of the soil (Brevik and Fenton, 2012). One of those impacts is the nutrient losses caused by soil erosion and the plant development (Zheng et al., 2005; Pulido et al., 2017), However, soil compaction effect and hardening could provide also positive effects from the perspective of trail surface preservation such as Dixon (2017) highlighted.

The use of rangelands as leisure areas for trekking, biking and horse riding has become widespread in the last century. This is increasing trampling effects in many areas of the world and therefore soil erosion rates were enhanced (Deluca et al., 1998; Olive and Marion, 2009). The use of grasslands, forest and rangelands for sport activities results in soil degradation and soil erosion (Bryan, 1977; White et al., 2006), but little research has been conducted as most of the efforts were focussed on agricultural land and rangelands affected by forest fires (Cerdà et al.,

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https://doi.org/10.1016/j.jenvman.2020.110990
Received 12 July 2019; Received in revised form 8 May 2020; Accepted 17 June 2020
Available online 30 June 2020
0301-4797/

2017a,b; Keesstra et al., 2019a; Novara et al., 2019; Guadie et al., 2020).

Natural sceneries offer the opportunity to practice recreation in nature and an increasing number of people are participating in sports and leisure activities such as cross-country skiing, trekking, biking, horse riding or Nordic walking. The development of these activities induces a human pressure on these natural spaces, which implies environmental degradation that affects soil (Chapin and Shaver, 1981) and vegetation (Törn et al., 2009; Godefroid and Koedam, 2004) but also fauna and the landscape in general (Marion and Leung, 2011, Fig. 1). The importance of the trail erosion represents an impact of which we still know little, as it has developed substantially in recent years (Marion, 2016). On the other hand, and linked to the above, users generally underestimate the impact that can be caused (Graefe et al., 2019). Finally, and once again connected with the first point, new areas are being explored by users and are often environmentally sensitive areas (Hrnčiarová et al., 2018).

The impact of trails in rangeland ecosystems can be researched according to the ecological component affected: soil (e.g., compaction, loss of organic matter, soil moisture), vegetation (e.g., biomass, loss of coverage, introduction of exotic species), wildlife (e.g., habitat loss and alteration, modification of wildlife behaviour, displacement) and water (e.g., increased turbidity and nutrients inputs, altered water quality) (Leung and Marion, 2000). In short, all these disturbances interact together (e.g., soil compaction – runoff generation – loss of nutrients) and favour higher soil erosion rates on these mountain trails than those that existed previously. As an example of the magnitude of trail erosion, we can spot the work of López-Vicente and Navas (2009) who demonstrated that mountain trails accounted for only 2% of the surface area of a basin in the Spanish Pre-Pyrenees but represented up to 14% of the total erosion in the catchment. Likewise, Garland (1990) explained that trail erosion is one of the most serious and difficult to control problems in the Drakensberg Mountains in South Africa.

To improve the management of natural areas it is very important to know and understand the processes that lead to trail erosion (Tomczyk et al., 2016; Rodway-Dyer and Ellis, 2018) and thus, to be able to act accordingly to establish adequate trail designs and apply restoration and rehabilitation measures, especially if we consider that a significant loss of soil is seen as an irreversible impact (Marion et al., 2011) since soil is a non-renewable resource (Olive and Marion, 2009). Therefore, there is a need to understand soil erosion processes and quantify soil erosion rates to design and apply successful soil erosion control strategies.

There is a need to build a dataset of soil erosion research on trails in mountainous areas. Acceleration in scientific advances make it necessary to develop a comprehensive literature review to compile findings and achievements and to design future research to fill the gaps and flaws in the research already carried out. This work provides a review of soil erosion on mountain trails that will contribute to achieve sustainable management. Our objective is to review all the information related to erosion of mountain paths (i.e., trails located in natural and irregular areas, excluding those with artificial grounds as wooden walkways, asphalt, concrete, gravel treatments, or situated in urban areas) and analyse the different research topics in order to determine our current situation and discover where future research can be directed to address possible gaps in the thematic areas, thus contributing to the conservation and improvement of affected areas. This research is relevant within the framework of the role soils play in the Earth System under a changing climate (Brevik, 2012; Keesstra et al., 2018a,b; Visser et al., 2019).

2. Material and methods

A search was conducted in the Scopus bibliographic database (https://www.scopus.com) until 2018 with the criterion that the words "trail erosion" AND "trails erosion" were found in the title, abstract or in the keywords of the document type "article." The employed terminology is diverse as a result of the unclear nature of trail degradation processes. Then, works that did not conform to the theme of this study were discarded after carefully reading the whole paper. We found 299 articles that met the search criteria described in the methods section. Once all 299 articles were carefully read, a first selection of 127 articles was made that focused on erosion on trails from different types of use, and the other 177 were discarded as their topic was not related to the trail erosion we research here. Subsequently, 53 articles were selected that focused on recreational impacts on mountain trails, discarding studies that focused on fires, logging, animal trails or agricultural roads. The research papers were analysed and a set of tables with key data from each paper was extracted.

3. Results

3.1. The temporal evolution of trail erosion studies

Soil erosion on mountain trails as a consequence of human activities such as trekking, biking or horse riding are a new issue in soil erosion research. The pioneer research was carried out during the 1970's,

Fig. 1. Serious degradation effects in different mountain areas affected by intensive use of trails due to increased recreational activities. From left to right and top to bottom: Torla in the Pyrenees, Serra Grossa in Montesa (Barranc de la Fos trail, and Canals (El Portalet trail).

focussed mainly on an overview of human impacts on ecosystems (Willard and Marr, 1971). Those pioneering works on trail erosion were published 40 years after the pioneering research on soil erosion on agricultural land (Bennet, 1929). The Missouri Agricultural Experiment Station is generally given credit for the first soil erosion by water measurements with a project that started in 1915 (see Miller, 1946; Browning, 1977; and Meyer and Moldenhauer, 1985).

Although the use of trails for recreation (and transport of goods and people) is millennia old, their recreational use became popular after the 1960's. The pioneer period for the study of soil erosion on trails was between 1970 and 1995. This is the time when "recreational ecology" term emerges to refer to research on the ecological impacts of activities such as hiking (Coleman, 1981). During this period there was a sporadic publication of papers, usually less than 2 per year (three were published in 1984) and many years when no papers published. At this time, the scientific production of soil erosion research on trails was rare, non-continuous, and intermittent. From 1994 to 2011 there was a continuous increase in publications, with one to six publications related to the topic each year. In 2012 a new period was initiated that indicated a growing interest in soil erosion on trails that resulted in six to 10 papers published per year (Fig. 2). Those three periods can be called the pioneer (1970–1993), establishment (1994–2011) and spread (2012-today) periods. These periods are also characterised by geographical spread of the research. During the pioneer period research was focussed in the USA, during the establishment period research spread to other regions, and during the spread period research became global.

The general overview of the temporal changes in soil erosion research on mountain trails shows that most of the research was published recently: 50% after 2010 (Fig. 2). The acceleration in publications shows the general interest by scientific society to understand, quantify and control soil erosion along trails. The studies (53 papers) are distributed in 29 different scientific journals (Fig. 3), most of them related to the study of land degradation processes as well as the conservation and protection of natural ecosystems. A noticeable result is that only six journals published almost half of the papers and among them we can highlight Environmental Management with eight publications as well as Geomorphology and Journal of Environmental Management with four each.

3.2. Spatial distribution of trail erosion research

Research on the effects caused by recreational and leisure mountain trails was concentrated in the USA, covering 24 of the 53 works analysed (45%, see Fig. 4). Trail erosion research began in the USA in the 1970s with evaluation of the degradation of soil properties through the use of off-road vehicles (Webb et al., 1978; Stull et al., 1979) and of trampling by hikers and horses (Bratton et al., 1979). The first state-of-the-art review was also developed by USA scientists (Leung and Marion, 2000) and focussed on USA research.

Although far away from the intense research developed in USA, the Australians developed an excellent set of papers about trail erosion in Australia. In recent years this work has sought to assess the effect of mountain bikes (Goeft and Alder, 2001) and continued with the interest of researcher David Newsome who contributed to advancement of the science with several papers (Smith and Newsome, 2002; Randall and Newsome, 2008, 2009; Newsome and Davis, 2009). Finally, other countries with a considerable number of works are Poland and Spain, with some recent research such as those of Bodoque et al. (2017) and Ćwiąkała et al. (2017).

It is necessary to emphasize the small amount of work that exists in South America (Barros et al., 2013). We found the works of Farrell and Marion (2001a) in Chile and those of Harden (1992) and Walling and Harden (1996) in Ecuador. Something similar it is found in Africa where we only found the works of Obua (1997) who refers to the impacts of ecotourism on the Kibale National Park in Uganda, and the study of Garland (1990) focused on South Africa. Most of the research carried out in Africa was carried out by foreigners but one publication shows African authors. In South America all the research was carried out by foreigners, mainly scientists coming from the USA.

One of the results was that most of the works, 33 out of the 53 analysed (62%) were centred in natural environments that have high levels of protection (e.g., National Parks, Reserves or Natura, 2000 Network). This is because National Parks and other protected areas receive great attention from tourists, and even the simple appointment of the title "National Park" can significantly increase the trail network from one year to another (Galloway, 2002) at levels up to 180% higher (Arp and Simmons, 2012). However, sometimes too much effort may be focused on evaluating these areas, while there are others adjacent to them with similar anthropogenic pressure but without similar protection, meaning the risk of land degradation may be even higher

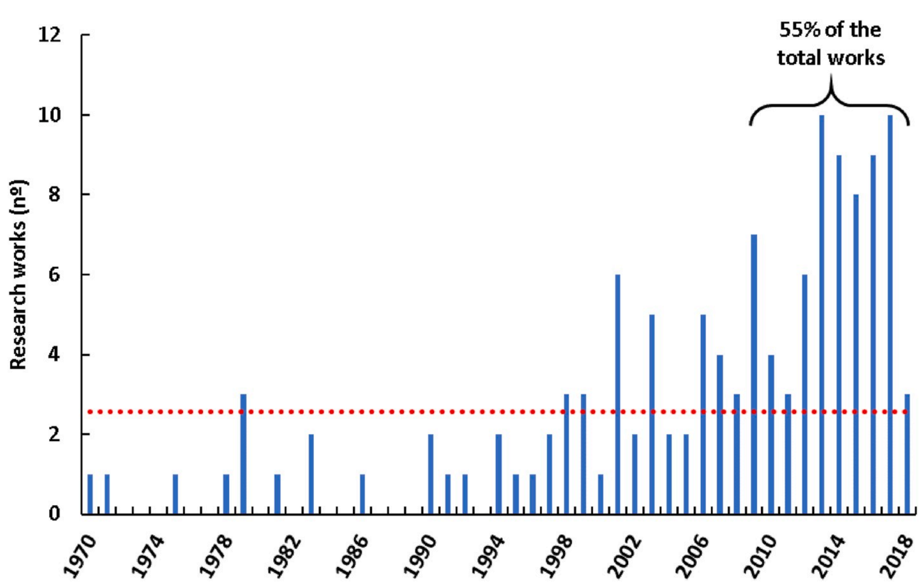

Fig. 2. Representation by year of the 126 works found that focus on the erosion and degradation of trails in general. The dotted line shows the average annual number of works published in the period 1970–2018.55% of the works published were in the period between 2009 and 2018.

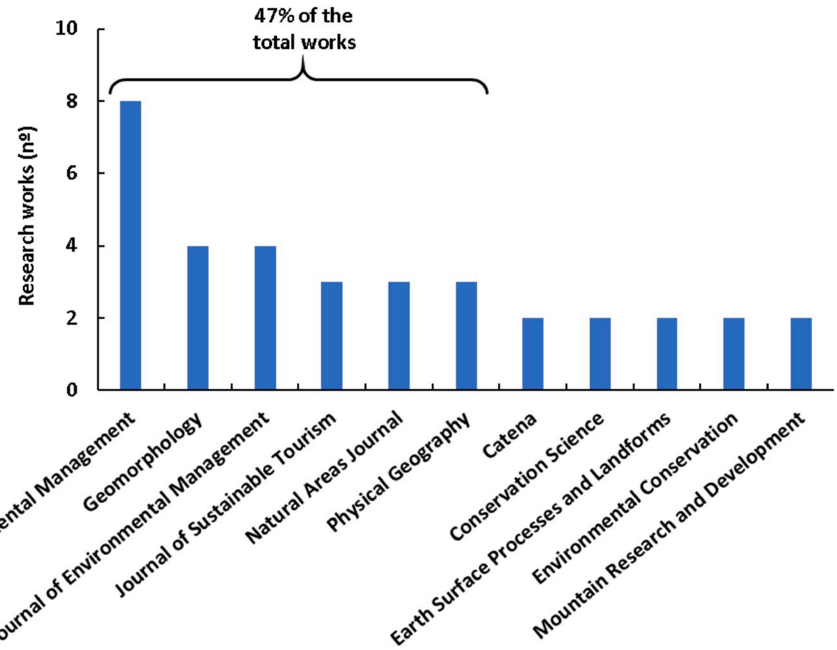

Fig. 3. Number of publications on recreational trail erosion by international journal. The first 6 journals cover 47% of the total number of articles published. Only those journals with more than one publication on the topic of trail erosion are shown.

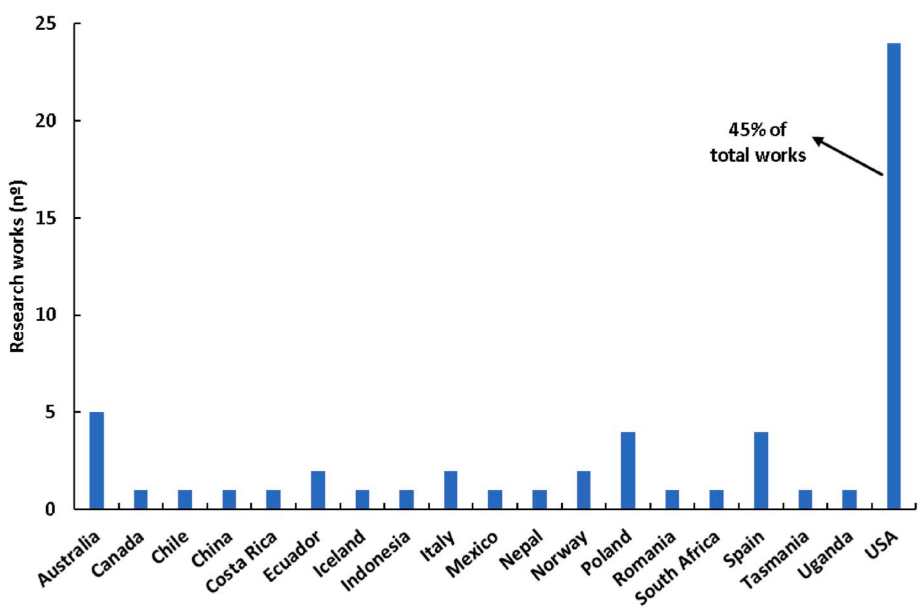

Fig. 4. Country of origin of the 53 studies analysed for erosion on mountain trails for recreational use. USA represents 45% of the studies published on the topic.

(Pickering and Hill, 2007). New investigations have sought to address this issue in Spain (Salesa et al., 2019).

The geography of the research is determined by environmental, social and economic constrains. An interesting question to address is whether levels of wealth and economic development affect trail erosion research. The main impacts on recreational trails are due to leisure activities (Geneletti and Dawa, 2009), so a higher socioeconomic level may imply greater pressure and degradation effects and simultaneously a greater investment of resources to explore this impact. This is probably why the USA scientists were the pioneers in trail erosion research. GDP (gross domestic product) is a measure of a country's economic performance so it can be employed as socioeconomic index. We have explored the impact of the GDP data related to the population of each country and its association with the number of papers that have been published. This relationship is shown in Fig. 5 and it can be seen that the richer a country is the more leisure activities that are carried out. One possible reason is that wealthier countries undertake more leisure activities or that wealthier countries have more funding to conduct this type of research. The analysis shown in Fig. 5 does not give cause and effect, it just shows that wealthier countries publish more papers. It would be interesting to know if within the same country the research is developed also upon the economic resources. The information in Fig. 5 also shows that some countries with a long tradition in mountaineering activities do not invest on research in trail erosion. France or Switzerland are countries where no research has yet been carried out on this scientific and environmental issue. In addition to the economic issues behind research on trail erosion, the interest by the scientists and the national scientific research programs in each nation also play a role.

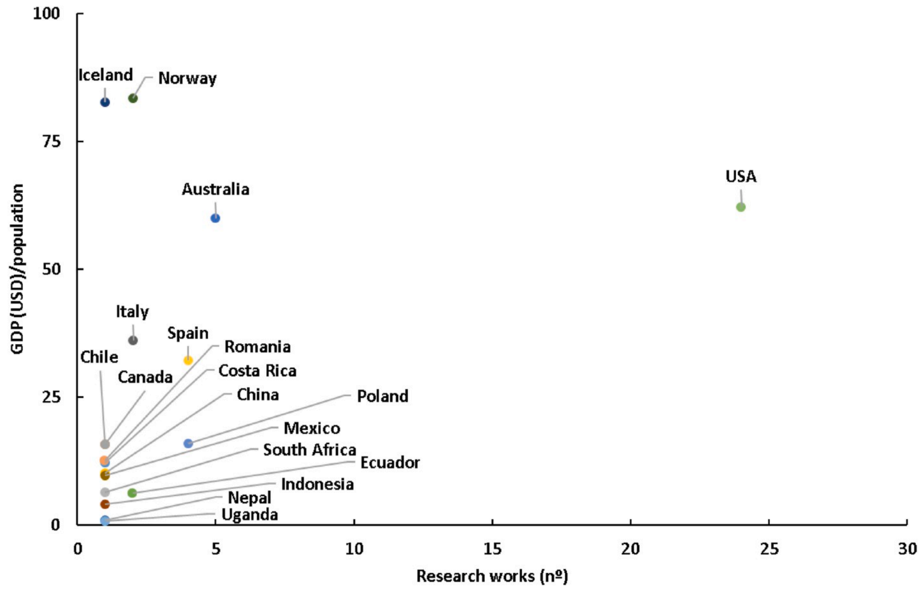

Fig. 5. Relationship between the number of articles analysed and national GDP (in US dollars and relative to the population) of the country where the research was carried out.

There are a wide range of studies that focus on the behaviour of walkers in different recreational activities, the existing social perceptions concerning various factors of trail degradation or surveys that try to find out how to improve trail management and avoid degradation (Morin et al., 1997; Symmonds et al., 2000; Lynn and Brown, 2003; Moore et al., 2012; Guo et al., 2015; Leung et al., 2016; Lin and Lee, 2019). This is a relevant issue for future research as the solutions to achieve sustainable management depend on how the stakeholders perceive the impacts we have on the trails. Furthermore, this interaction between user behaviour and management can also occur in the opposite sense. For example, good management decisions can influence visitor behaviour and minimize negative effects of trail widening (Meadema et al., 2020).

3.3. Methods to measure trail erosion

The methods used to quantify erosion on mountain trails are diverse. A good compilation of the methods can be found in Rodway-Dyer and Ellis (2010), and Marion and Leung (2011). There are sophisticated procedures such as terrestrial laser scanning to study the topography in great detail (Bodoque et al., 2017), the use of unmanned aerial vehicles to take photographs in remote areas (Ćwiąkała et al., 2007; Ancin--Murguzur et al., 2019), the use of devices that detect the transport of soil particles by the optically stimulated luminescence method (Muñoz-Salinas and Castillo, 2018) or even the use of artificial radionuclides to investigate soil particle transport (López-Vicente and Navas, 2009; Rodway-Dyer and Ellis, 2010). Methods such as these allow high precision and resolution, but they are expensive and only accessible to well-funded research teams.

Satellite and GIS technologies are widely used, especially digital elevation models (Cao et al., 2014; Bodoque et al., 2017) and LIDAR (Tarolli et al., 2013; Rodway-Dyer and Ellis, 2018), as they allow assessment of changes in the land surface, and methodologies have even been developed based on these techniques at a micro scale, such as the study by Tomczyk and Ewertowski (2013). Another method used by Tomczyk (2011) combined five different maps, three of them obtained from soil erosion models, together with a map of vegetation vulnerability and another of solar energy quantity. The use of aerial orthophotos is also commonly employed. Examples of this include the work of Trip and Wiersma (2015) and Mihai et al. (2009) who used satellite aerial imagery to check the infrastructure associated with trails and the impacts related to their use for tourism. Finally, we also have photogrammetry, which is based on the use of photographs to analyse different forms of relief. This method was developed many years ago to study path erosion (Johnson and Smith, 1983) but was only been observed again in the work of Warner and Kvaener (1998).

Other methods that involve more extensive work in the study area may be those that use tree root exposure as an indicator of erosion on mountain trails. For example, Bodoque et al. (2005) measured the vertical distance from the top of the root to the soil surface. Other similar methodologies measured the upper and lower growth of the root from the estimated time of root exposure with dendrogeomorphological analysis (Pelfini and Santilli, 2006; Bodoque et al., 2017).

Without a doubt, the most commonly used method in the field is to calculate the cross sectional area (Fig. 6) by estimating the volume of soil that has been lost (e.g., Webb et al., 1978; Fish et al., 1981; Cole, 1991; Goeft and Alder, 2001; Eaglestone and Rubin, 2013; Cao et al., 2014; Esque et al., 2016). This includes measuring the cross-sectional area after different intensities and types of use of the trails (Whinam et al., 1994). The precision and detail of this methodology varies greatly, with work being measured every 6 m along the trail and every 15 cm transvers to the trail (Sack and da Luz, 2003), every 10 m along the trail and every 20 cm along the transvers (Webb et al., 1978) or, for example, every 10 m along the trail and every 10 cm across the trail (Stull et al., 1979). Although the accuracy of this method compared to more advanced technologies is positive (Salesa et al., 2020), as it is a volumetric measurement, the trail width can have too much influence in the result obtained. Therefore, some authors consider it more appropriate to use the variable of maximum incision (Meadema et al., 2020).

Another method that is widely accepted among researchers is the problem assessment method (Leung and Marion, 1999). It is a categorical model that is repeatable and easy to carry out and that can be classified into different categories that determine the degree of erosion of a path (e.g., width, maximum incision, muddiness or root exposure). Examples of this method can be found in the works of Leung and Marion (1999); Farrell and Marion (2001a); Nepal (2003) and Randall and Newsome (2008).

Some researchers have employed innovative methods and designed new approaches to better understand the impact of soil erosion on trails. Tomczyk et al. (2016) included ecosystem services provided by natural environments in their work to demonstrate the benefits of sustainable trail management. Kidd et al. (2014) used surveys of aquatic

Fig. 6. Example of trail erosion measurement using the cross-sectional-area method. Measurements here are being made in the Serra Grossa El Portalet trail, Eastern Iberian Peninsula.

macroinvertebrate communities as indicators to check for changes in water quality due to sediment inputs from the trails. Padgett et al. (2008) monitored airborne particles from the trails after off-road vehicles passed by. In addition, various mathematical models have been designed to try to calculate different degradation processes such as soil loss due to runoff (López-Vicente et al., 2013), morphometric methods such as the relative path impact index (Tarolli et al., 2013), erosion estimation models such as USLE (Johnson and Smith, 1983) or modified versions of it (Tomczyk, 2011; Gaffer et al., 2008) have been used in some areas. Techniques to assess the risk of degradation of trails before their construction also have been developed (Garland, 1990).

As mentioned above, the diversity of methodologies used is high, which leads to a great diversity of results. Soil erosion is also a scale dependent process, and different mechanisms take place at different scales (González Hidalgo et al., 2012; Bagarello et al., 2018). These two issues make comparisons between studies difficult. Moreover, each trail has different characteristics: slope angle, parent material, climate, historical land use or vegetation, and traffic rates and patterns. Therefore, one option for the future in this field of research would be to establish a common criterion for measuring erosion on mountain trails, so that different research projects could complement each other by allowing straight-forward comparisons of the erosive processes that take place on the trails.

3.4. The need for harmonization of the measurements

Table 1 shows the maximum erosion rates that have been obtained by selected investigations that quantitatively expressed a specific erosion value for recreational trails. The results are very uneven and diverse due to the different methodologies applied and how the results

Table 1
Maximum erosion rates found in selected articles. Negative values show change in 2 different measurements periods. ORV (Off-Road Vehicle); WS (without specification).

Authors	Year	Type of use	Mg ha^{-1} y^{-1}	m^3 km^{-1}	CSA (cm^2)	Sediment detachment (g)	Maximum incision (cm)	Soil lowering (mm y^{-1})
Stull et al.	1979	ORV	540					129
Fish et al.	1981	Hike			−1070.7			
Johnson & Smith	1983	ORV	632		−618		102	140
Cole	1991	Hike			10230			
Harden	1992	WS				12.72		
Whinam et al.	1994	Horses			361			
Wilson & Seney	1994	Mixed				63		
Deluca et al.	1998	Hike & riding				110		
Farrell & Marion	2001	Mixed					21	
Smith & Newsome	2002	Hike		1.74				
Sack & da Luz	2003	Mixed	2090				5.3	
Bodoque et al.	2005	Hike & bike	170					11.3
López-Vicente & Navas	2009	WS	306.3					
Olive & Marion	2009	Mixed		143.9				
Randall & Newsome	2009	Hike		640				
Eagleston & Rubin	2013	Mixed			−37.8			
López-Vicente et al.	2013	WS	6.1					
Cao et al.	2014	Mixed		0.34	32000			
Kidd et al.	2014	Mixed	20.5					
Ramos-Scharrón et al.	2014	WS	81			60.5		6
Trip & Wiersma	2015	ORV					21.55	
Tomczyk et al.	2016	Hike					21.63	
Bodoque et al.	2017	Hike	151.3					19.5

are presented. Common means of reporting these values include lowering (mm y^{-1}), incision (cm), mass of soil detached (g), cross-sectional area of lost soil (cm^2), volume of soil lost (m^3 km^{-1}) and the traditional soil erosion rate measurement (Mg ha^{-1} y^{-1}). For example, we found erosion rates ranging from 6.1 Mg ha^{-1} y^{-1} (López-Vicente et al., 2013) to 2090 Mg ha^{-1} y^{-1} (Sack and da Luz, 2003) for off road vehicle use. We also found lowering values that ranged from 6 mm y^{-1} (Ramos-Scharrón et al., 2014) to 140 mm y^{-1} on steep segments (Johnson and Smith, 1983). The methodology applied determined the units that were used to present the data, and they are also controlled by the variety of environmental and anthropogenic conditions to which the different areas of study are subjected, the different uses of the mountain trails, and the difficulty of getting equipment to remote portions of these trails. A key issue identified through this review is sustainability. The need to understand and compute soil erosion sustainability is critical to understanding the problem of soil erosion along trails. Raw soil loss measurements cannot be used to determine sustainability and is also not particularly useful when comparing different study areas that are under different environmental conditions (Hancock et al., 2015). Each ecosystem has a different sustainable rate of soil erosion as the soil formation rate is variable (albeit slowly in all cases) and depends on the climate, parent material, slopes, vegetation cover and bioturbation as the pioneers of soil science established over a century ago (Brevik, 2013; Rodrigo-Comino et al., 2017).

Another key issue that arose during this review are temporal changes in erosion rates. Many of the works we analysed studied the erosive effects over short periods of time, as reported by Monz et al. (2010). Our research also found that long-term measurements are rare, although they do exist as Rodway-Dyer and Walling (2010) expose. Likewise, Randall and Newsome (2009) and Dixon et al. (2004) affirm that long-term data sets are preferable when dealing with trail erosion studies. Notwithstanding this, there is a wide variety of study periods found in the literature. We found works that studied trail erosion at a certain point in time (Harden, 1992; Nepal, 2003), changes that occurred over 2 months (Ćwiąkała et al., 2017), 1 year (Goeft and Alder, 2001), or 17 months (Fish et al., 1981), and changes over 50 years as documented by aerial photographs (Arp and Simmons, 2012). Although it has been demonstrated that the greatest changes and effects on pathways occur at the beginning of their use (Deluca et al., 1998; Nepal, 2003) or immediately after construction or restoration (Ramos-Scharrón et al., 2014), the erosion and degradation of soils is a dynamic process that involves long periods of time, and although it is a drawback, we encourage future research to consider this methodological issue to improve knowledge of temporal soil erosion on trails.

Our review concludes that the available data on soil erosion on mountain trails shows that there is a huge variability not only in the methods applied but also in how the results are shown. This results in some difficulties for the readers to understand and compare findings from different regions and scientists and contribute to dilute the importance of the problem. There is a lack of homogeneity in terms of the presentation of results of the erosion of mountain trails. On many occasions, the effects of leisure activities, such as lowering of the soil profile, maximum incision, percentage of change, affected surface, mass of soil displaced or even simply with qualitative methods are studied (e.g., excessive muddiness, high root exposure, presence of damage vegetation …). All this variety in the way the results are presented makes comparison between works difficult.

3.5. Effects of type of use

This review found that most of the research on soil erosion along recreational trails focuses on hiking, biking and off-road vehicles. Other activities which have been expanding in recent decades (Marion and Leung, 2011) are present along mountain trails to a lesser extent but can have high erosive effects on the trails (Wilson and Seney, 1994; Olive and Marion, 2009). There is also research that focuses on the environmental damage caused by the use of horses, cross-country skiing (Eagleston and Rubin, 2013), and even military training activities (Gaffer et al., 2008) or the behaviour and desires of hikers (Guo et al., 2015).

There are several research articles that have shown the highest rates of erosion on mountain trails are caused by the use of horses and ATVs. Deluca et al. (1998) found that horse traffic on trails resulted in a greater release of sediment than llamas or hikers after an episode of simulated rainfall. Wilson and Seney (1994) found that particle detachment in plots with horses was significantly higher than in control, hiking and cycling plots. As a final kind of trail erosion, we have found that an important source of erosion studies on mountain trails has been those caused by natural resources extractive activities of logging and the transport of such products. However, even this type of work has not been considered in our research as it is not recreational, this type of activities can cause similar adverse effects to those of recreational activities due to the induced erosion, such as the reduced quality of supply water caused by the sediment transport by runoff (Wenger et al., 2018). Mountain recreational activities involve different variations and ways to access the trails and paths. It is important to keep in mind what the trails are used for as it has been shown that the use of the trails is a much greater determinant of degradation than even the amount of use (Olive and Marion, 2009).

3.6. The impact of use

Another interesting topic in trail erosion is evaluation of the amount of recreational use which an ecosystem can tolerate without degradation. It is important to know the amount of tolerable use as there is threshold at which the vegetation needs a temporal period without disturbance to recover. This is relevant in the context of the opening of informal trails or the sudden increase in users that causes a trail widening at a certain moment and can involve temporary closure of trails which in turn could cause disturbances in users (Trip and Wiersma, 2015). This recommendation has also recently been proposed in informal trails to avoid changes in the functional composition of sensitive vegetation (Barros et al., 2020). Furthermore, see above the tolerable threshold results in difficult rehabilitation and restoration of the ecosystem, which can initiate degradation processes in a local scale (Fredrickson et al., 1998; Wenhua, 2004).

Sustainability concept in recreation ecology context implies a marriage between the quality of the user experience and the preservation of the natural surrounding (Marion and Wimpey, 2017). For achieve this purpose, the most influential determinants of soil loss on trails should be recognized. In this line, Farrell and Marion (2001b) found that the amount of use significantly influences the width of the trails, especially if the trails are only lightly used. This is consistent with Cole (1991), who found that the width of trails increases more than depth as use increases, although factors such as seasonal variation in precipitation or the surface rugosity also influence this variable (Dixon et al., 2004; Meadema et al., 2020). More comprehensive information about this issue can be found in Wimpey and Marion (2010).

Other authors like Rowe et al. (2018) found significant differences in soil crust (a key biological indicator of disturbance in arid environments) with medium and high use but not with a low amount of use when compared to a control area. A major case to consider is the one described by Arp and Simmons (2012). They found a feedback between the amount of off-road-vehicle traffic and the altered functioning of a watershed in Alaska.

Our review found that there is an asymptotic relationship between the damage caused and the amount of use. This means that great damage is generated with little use, but with greater use, the amount of negative impacts is stabilized (Leung and Marion, 2000; Monz et al., 2010). Salesa and Cerdà (2019) showed that in a short period of time and without a large amount of use the trails could be seriously damaged. By contrast, Obua (1997) did not find a relationship between the amount of trail use and the level of degradation. Similarly, Cole (1995) showed that the impact on soil properties was not proportional to the level of use in a study of campsites. Another example is the work of Rowe et al. (2018). They found unclear results when evaluating the relationship between level of use and degradation, and even considered that other factors (e.g., user behaviour, type of use, vegetation type or physiography) may have a greater influence on the physical and biological impacts on the trails. This is similar to that shown by Marion (2016), who establishes that at high amounts of use the relation with the impact is weak and is more successful to focus on reducing impact by modifying slopes, side-hill alignments or substrate types.

Considering all the above, it seems that there is a clear asymptotic relationship between the use and degradation of trails in some environments but not in others and regardless of the activity type in question. It therefore appears that there are some natural factors that have a significant influence on this relationship, so a future goal for research would be to understand what they are and how they affect the degradation and resilience of trails. In this context, it would also be useful to explore whether there is a difference in the degree of use-degradation according to the type of activity involved. The impact level is different depending to the kind of activity, but perhaps the response curve needs to be clarified with the environmental variables controlled. Finally, there are also other types of activities that have been less explored over time and should perhaps be valued in those areas where they are more common (horses, motorcycles or quads, skiing …).

3.7. Management recommendations and restoration measures

Trail-elements design influences how the trail will resist degradation over time (Eaglestone and Marion, 2020). To achieve sustainable management of recreational trails we must start with knowledge of the resistance of different environmental factors at the time of trail design (Leung and Marion, 2000) and identify the most influential elements on trail degradation that can be dealt by managers. Impacts due to trail use can be avoided or limited so that in an assumed restoration after the trail closure and preferably by using bioengineering techniques (Rangel et al., 2019), a lower accumulation of impacts would allow better recovery. In addition, lack of regulation and trail management can result in damage to vegetation and soil erosion (Barros et al., 2013). In most cases, it is more effective to prevent damage than to try to solve it. As Tomczyk et al. (2016) argued, "trail construction can therefore be seen as one of the solutions enabling park managers to avoid potential negative trade-offs related to the recreational use of designed protected areas". For this reason, some authors developed methods to prevent erosion risks on mountain trails and evaluate the areas of greatest risk, enabling the establishment of management measures or estimation of the tourist carrying capacity for walking trails (Somarriba-Chang et al., 2006). Such steps can also establish how suitable different lithological materials are for planning new trails (Lehtinen and Sarala, 2006) due to the large difference in runoff and sediment production that may exist between different parent materials (Rodrigo-Comino et al., 2018a).

Some authors have found that reducing the number of visitors can be a useful measure to reduce tourist pressure and erosive effects on trails. However, because the impact produced by the amount of use is not linear and there are other trail characteristics that are more effective to modify, this measure should only be applied when other options have not generated expected results (and better in higher impact activities than hiking) because it has major drawbacks such as intensive management interventions and only addresses one potential underlying factor contributing to trail impacts (Farrell and Marion, 2001b; Dixon et al., 2004).

Other management actions and recommendations have been discussed by various authors. One of the mechanisms that should be sought for optimal management of the trails is the reduction of water runoff, since it is the main agent that will trigger the erosive processes in the trails. For this purpose, Olive and Marion (2009) suggest that trail erosion can be minimized by avoiding "fall-line" alignments, steep grades, and valley-bottom alignments near streams, by installing and maintaining adequate densities of tread drainage features, applying gravel to harden treads, and by reducing horse and ATV use or restricting them to more resistant routes. Farrell and Marion (2001b) recommended that trail grades steeper than 10–15% are permissible for short sections as long as treads are tightened with large rocks and a trail maintenance program includes the installation and periodic cleaning of water diversion features to decrease soil loss. The trouble is that often the steepest trails are the ones that have been created by users (informal trails) and, therefore, lack any type of maintenance (Wimpey and Marion, 2011). As the severity of soil loss varies significantly with trail grade (Meadema et al., 2020), when steep slopes are present, a good mitigation measure can be the establishment of water diversion structures owing to its effectiveness in minimizing soil compaction (Jourgholami et al., 2018a, 2018b). Another measure that helps to modify the terrain ruggedness is that which suggest Mihai et al. (2009), who propose that adjacent vegetation to the trail should be restored by creating micro terraces on steep and degraded slopes.

Ramos-Scharrón et al. (2014) recommend that trail width should be kept as narrow as possible and trail braiding should be discouraged. In addition, they also argue that seeding and other measures to promote growth and revegetation in abandoned trails can be very effective at reducing erosion rates, a stance that is supported by Randall and Newsome (2008). An attractive method applied on other kind of trails could be the covering of abandoned trails with sawdust mulch, as the main objective of reducing runoff and sediment yield could be achieved (Jourgholami and Abari, 2017), although this should meet requirements such as avoiding steep slopes or supplying it with heavier material such as straw. Stemming this process of runoff will also help prevent the triggering of other related impacts (Liu et al., 2020). Straw mulch has been used in agriculture and rangeland and is a promising strategy (Cerdà et al., 2017a,b; Lucas-Borja et al., 2018).

On the other hand, Bratton et al. (1979) argue that the slope of a trail is the factor that most influences their condition, especially the percentage of roots exposed, and comment that a suitable conservation measure is to harden trails or to reduce traffic, or both. A final type of measure that can be utilized is education of trail users, which has been shown to be effective in changing user attitudes towards more environmentally sensitive (Hocket et al., 2017). As an example, Rowe et al. (2018) explain that a good measure to avoid the creation of informal trails is a combination of physical barriers along with educational campaigns. These informal trails are created by visitors' desires in short to access new sites, avoid tricky areas or shorten routes, but it is possible to discern up to seven different types of reasons (Wimpey and Marion, 2011). Therefore, addressing this concern must be a priority to support managers' decisions (Rodway-Dyer and Ellis, 2018).

3.8. Trail erosion in comparison to other human-related activities

Erosion rates on mountain trails should be compared with another activities in mountains to understand their real impact on soil degradation. A review of soil erosion rates in agriculture land, forest fire affected regions or due to logging activities will help to provide a holistic view. Total soil erosion from agricultural land in mountainous terrain is much higher than from trails due to the large area covered by agriculture. Another problem in mountainous areas is the increase in erosion after a forest fire. Elliot (2013) concluded that in the western USA, the greatest volumes of soil erosion are seen following infrequent wildfires, reaching up to 24.5 Mg ha^{-1} y^{-1}. In the Mediterranean basin, a review carried out by Shakesby (2011) found that post-fire erosion rates reached an average of between 45 and 56 Mg ha^{-1} y^{-1} in the first year after the fire. However, forest fire affected areas show short-term increase in soil erosion that is gradually controlled as vegetation becomes re-established, but enhanced erosion due to trails is long-term.

Another important source of erosion in mountainous areas is the extraction of wood resources. Logging increases erosion rates due to the large and heavy machinery that is used for log extraction, disruption of the soil surface, and clearing of organic cover from the soil surface. For example, Malvar et al. (2017) found that sediment yield rates were up to 3 times higher in logged areas than in unlogged control areas following salvage logging after fire, caused in part by soil compaction. Safari et al. (2016) concluded that significant differences exist in runoff, sediment yield and soil erosion rates in logging skid trails as compared to control plots.

With the above-mentioned data, we can agree that the rates of erosion on trails are not negligible among the sources of soil erosion in mountainous terrain. But we must also agree that trails cover a small area compared to many other land uses, and the connection of the flows coming from the trails to streams are not clear. This is a topic that needs more research as understanding the connectivity of the sediments and flows will allow us to more completely understand the effect of recreational trails on soil erosion, sediment yield, and associate processes (Keesstra et al., 2018a,b) such as has been done previously in vineyards to understand the runoff generation and sediment transport (Rodrigo-Comino et al., 2018b). Ecosystems must be understood as a whole, and their interrelationships understood as much as possible. The conservation of trails should consider not only the impact on the location itself but also how it may affect the rest of the environment and the possible synergies with other type of impacts. Therefore, scientific knowledge must also encompass this water and sediment connectivity caused by recreational trails because they can lead to ecosystem degradation by modification of landscape structure (Saco et al., 2019).

3.9. Implications

This review shows that the future of research on mountain trail erosion should establish a common way of reporting the findings. This is the main shortcoming we found in the scientific literature, and the current status has several drawbacks: i) comparisons between study sites are difficult, both in terms of the methodology used and the way in which results are expressed, even though we consider the last point to be of less concern since the development of technologies and knowledge will allow us to gradually change the way in which we obtain results; ii) soil erosion factors are different upon the methods applied to characterize the soil erosion rates; and iii) there is an urgent need to determine the thresholds to achieve sustainable management. In addition, criteria should be unified to establish which indicators are the most appropriate, reliable and sensitive to measure the degradation of trails. Being a multidisciplinary issue, these indicators must include relevant ecological, management and aesthetic considerations (Marion and Leung, 2011).

We recommend it would be advantageous to show erosion rates as Mg ha^{-1} y^{-1} as is common for other soil erosion studies (e.g., agriculture, forest fires, etc.), and in turn we would be able to compare soil erosion rates from trails with soil losses from other activities and land uses carried out in the mountains. However, a constraint to this approach is that trail erosion is a narrow linear process while soil erosion in agricultural land or after a forest fire often affects a much larger area.

Due to the number of factors that influence soil erosion on trails, conservation must be achieved with a holistic view (Bratton et al., 1979; Garland, 1990). Nevertheless, given the magnitude of the erosion rates described in this paper, we consider it necessary to compile some of the measures that appear to most effectively minimize the negative impacts of recreational activities based on the works we have reviewed. Proper trail management must begin with appropriate planning, integrating all aspects of the environment that influence soil loss and/or trail degradation: i) identify areas with dense and resistant vegetation cover that can prevent the widening or opening of informal trails, although this recommendation should be a support, not a basis for designing trails; ii) avoiding areas with soils, flora or fauna under threat due to their characteristics (weakness or singularity), and avoid stream crossings; iii) consider the selection of soils with good drainage and aggregate stability as well as the presence of rockiness that provides roughness; iv) consider the path's orientation to account for the amount of sunlight it receives; v) understand the climate conditions along the trail and all the factors that govern it (temperatures, rainfall events, insolation, drought periods …); vi) periodic maintenance if possible and properly implement of elements that divert or reduce the erosive energy of runoff such as tread grade reversals, but also water bars, drainage, dips and itching (Hesselbarth (1996) provides a good collection of these elements); vii) avoid excessive slope angles along the trail; and viii) account for the slopes around the path (avoid low side-slopes) and the angle of the trail with respect to them (avoid low trail alignment with the maximum-slope line. Once designed, it would be best to know the type of activity and number of users visiting the trails, to supervise the opening of new trails by users, to post messages that communicate good environmental practices, to consider closing some sections of the trail for certain periods (i.e., breeding periods and/or excessively wet periods), and to limit the size of car parking areas. Finally, if erosion damage is too great, temporary (or even permanent) closure of the path should be considered to allow the recovery of vegetation cover, some uses that lead to excessive erosion may be limited, and hydrological correction elements should be established to prevent continuity of the system and, in this way, reduce runoff and the detachment of soil particles, something such as steps in steep trail sections. In any case, generic measures should be avoided because they can often be unattainable (Eaglestone and Marion, 2020).

3.10. Research gaps

The research carried out on trail soil erosion is still very poor due to the initiation of the research in the 1970's and in comparison, to rangeland and agriculture land soil erosion research that was initiated much earlier (1920's) (Fig. 7). Nowadays, the situation has improved but not significantly (Marion, 2016). The lack of information on trail erosion is due also to the limited funding which leads to low scientific production in this field in comparison to any other soil erosion field. Another gap in the trail erosion scientific research is the lack of research in many mountainous regions of the world except in USA. There is also a shortage of information about the seasonal and temporal changes in soil erosion on trails that makes the progress of the scientific knowledge difficult. The mechanism of the soil erosion in trails are not investigated and topics such as the wheels, rock cover, competition events, trampling or weather conditions in soil erosion are not known. Regarding comprehensive landscape management, the upscaling of the soil erosion rates measured at trail scale to landscape/watershed scale is the main research gap in the trail erosion topic. To accomplish the challenge to up-scale the measurements developed at trail (pedon) scale we must apply connectivity indexes (Mekonnen et al., 2017; Keesstra et al., 2019b). This will enable us to understand a little more about the fate of the particles that have been detached from the trail and its impact on permanent waterways.

In addition, we do not know accurately the specific weight that soil compaction, particle displacement and erosion by natural mechanisms play in the joint of trail degradation. The reason for this is based on the fact that these three processes act in a mixed way in trail deterioration, but our role must be to properly understand each one of them separately in order to identify mitigation proceedings. Finally, there is no research to develop soil erosion control strategies on trails. All this research gaps should be covered in the next decade to achieve a sustainable use of the trails in the mountains and allow users to meet their recreational expectations.

4. Conclusions

Both society and science should share concern related to the use and abuse of trails and the increased soil erosion rates. A review of the soil erosion along recreational trails literature showed that scientists in the

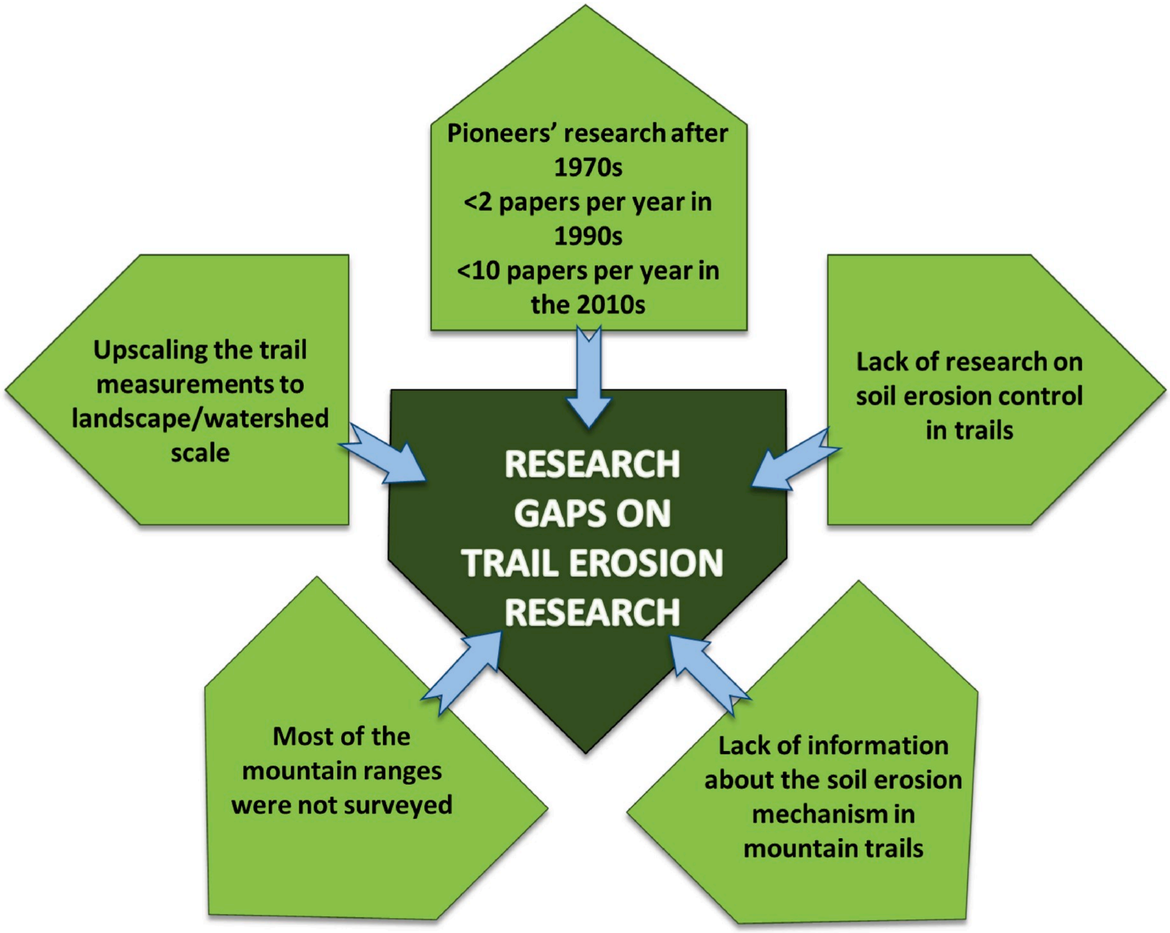

Fig. 7. Some examples of the most important gaps in mountain trail erosion research.

USA have led the way in researching this area. It also showed that very little research has been conducted in South America and Africa, and the research that has been done in these continents was conducted mainly by colleagues from developed countries. It should be highlighted that some developed countries with a tradition of mountaineering do not show any peer-reviewed publications on this topic. This review shows that soil erosion rates on trails are uneven and very diverse. This is because of a large variability in the factors involved and also due to the lack of a common methodology to assess soil erosion rates on mountain trails. In addition, most studies analyse trail erosion over short time periods; a long-term approach and the progression monitoring of trails after certain management interventions is needed to advance our scientific knowledge. Our review shows that six journals published 47% of the papers on this topic, which means that the diversity of researchers investigating this topic is likely low. Research should not be one-off work but should try to analyse long periods of time in order to precisely quantify the magnitude of soil losses. To effectively achieve a sustainable management, we have to integrate trails in the ecosystem functioning and planning, and to accept that right now the trail erosion rates are two orders of magnitude higher than the sustainable ones. A sustainable management is based in a proper design as control strategies are often difficult to implement. Nor should we forget that actions must also be directed at improving the user experience and allowing a sustainable human-nature connection From a pure scientific perspective, there is a need to research the connectivity of flows and the role of trails on runoff generation and sediment yield to fully understand the role that trails play in the mountain environment. The reduced number of papers and the delayed initiation (1970s) of the research is the main gap of the current investigations that results in the lack of information from most of the mountain ranges, the lack of information about the soil erosion mechanism in mountain trails and the erosion control measures to be applied.

Declaration of competing interest

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

Acknowledgements

This paper is part of RECARE-FP7 (ENV. 2013.6.2–4, http://recare-project.eu). This study was supported by the POSTFIRE Project (CGL 2013-47862-C2-1 and 2-R) and the POSTFIRE_CARE Project (CGL 2016-75178-C2-2-R [AEI/FEDER, UE]), financed by the Spanish Research Agency (AIE) and the European Union through European Funding for Regional Development (FEDER). We thank Eric C. Brevik for his review of the draft manuscript. Artemi Cerdà thanks the Co-operative Research programme from the OECD (Biological Resource Management for Sustainable Agricultural Systems) for its support with the 2016 CRP fellowship (OCDE TAD/CRP JA00088807).

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