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Measuring, modelling and managing gully erosion at large scales: a state of the art

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Abstract

Soil erosion is generally recognized as the dominant process of land degradation. The formation and expansion of gullies is often a highly significant process of soil erosion. However, our ability to assess and simulate gully erosion and its impacts remains very limited. This is especially so at regional to continental scales. As a result, gullying is often overlooked in policies and land and catchment management strategies. Nevertheless, significant progress has been made over the past decades. Based on a review of >590 scientific articles and policy documents, we provide a state-of-the-art on our ability to monitor, model and manage gully erosion at regional to continental scales. In this review we discuss the relevance and need of assessing gully erosion at regional to continental scales (section 1); current methods to monitor gully erosion as well as pitfalls and opportunities to apply them at larger scales (section 2); field-based gully erosion research conducted in Europe and European Russia (section 3); model approaches to simulate gully erosion and its contribution to catchment sediment yields at large scales (section 4); data products that can be used for such simulations (section 5); and currently existing policy tools and needs to address the problem of gully erosion (section 6). Section 7 formulates a series of recommendations for further research and policy development, based on this review. While several of these sections have a strong focus on Europe, most of our findings and recommendations are of global significance.

Keywords: gully erosion, gully initiation, gully expansion, sediment yield, measuring, modelling, prediction, regional, continental, Europe, spatial data, policy

1. Introduction

1.1 The relevance of gully erosion

Soil erosion is globally recognized as the most dominant process of land degradation (e.g. Montanarella et al. 2016; Pennock, 2019). Most efforts to understand and quantify soil erosion by water have focussed on sheet and rill erosion (e.g. Renard et al., 1997; Montgomery, 2007; Maetens et al., 2012a; de Vente et al., 2013; Borrelli et al., 2017a). Nonetheless, numerous studies have highlighted the fact that also gully erosion is a key concern in many regions worldwide (Poesen et al., 2003; Valentin et al., 2005; Vanmaercke et al., 2011; García-Ruiz et al., 2017; Sidle et al., 2019). Overall, gully erosion is the formation and subsequent expansion of erosional channels in the soil as a result of concentrated water flow (Poesen et al., 2003). Gully dimensions can vary over several orders of magnitudes (e.g. Vanmaercke et al. 2016; Dube et al. 2020). However, conventionally a gully is distinguished from a rill based on a critical cross-sectional area of at least one square foot, i.e. the size of a channel that can no longer be erased via normal tillage operations (Poesen et al., 2003). An upper limit for gully dimensions has not been clearly defined yet.

Gullies are often associated with a wide range of on-site and off-site impacts. On-site impacts include the direct loss of land, trees and crops as well as reduced trafficability. These limit opportunities for agriculture and other land uses (e.g. Poesen et al., 2003; Valentin et al., 2005). Gullies can also cause significant damage to roads, buildings and other infrastructure. In severe cases, such destructions may claim significant numbers of casualties (e.g. Guerra et al., 2007; Makanzu Imwangana et al., 2015). In many regions, gully erosion contributes to significant soil losses and reduced soil quality (Poesen et al., 1996; 2003; Ionita, 2006; Haregeweyn et al., 2008; Xu et al., 2016; Hayas et al., 2017a), threatening the long-term sustainability of food production and other ecosystem services (e.g. Montgomery, 2007). Gullies can also significantly alter surface and subsurface hillslope hydrology. For example, their presence can lead to a more efficient water evacuation and, in some cases, lower water tables. In dry environments, this can result in significantly lower crop yields in areas bordering gullies (e.g. Frankl et al., 2016; Poesen, 2018) and reduced biomass production rates over larger spatial scales (e.g. Avni, 2005), contributing to desertification. In addition, gullies can initiate or aggravate other erosion processes, including soil piping (Bernatak-Jakiel & Poesen, 2018) and landsliding (e.g. Ionita et al., 2015a). As a result of such impacts, gully erosion can also become a significant driver of land use changes (e.g. Bakker et al., 2005; Valentin et al., 2005; Zgłobicki et al. 2015a). In extreme cases, gully erosion can even transform productive land into badland areas (Cánovas et al., 2017; Torri et al., 2018a).

Potential off-site impacts of gully erosion include changes in catchment hydrology, such as lower river baseflows and higher peak runoff discharges (e.g. Martineli Costa et al., 2007). Given their often high erosion rates, gullies can also be a major sediment source. Where they occur, gullies can easily account for 20-80% of the average catchment sediment yield (e.g. Poesen et al., 1996; 2003; Vanmaercke et al., 2012). Furthermore, gullies can indirectly contribute to sediment loads by increasing the runoff and sediment connectivity between upland areas, valley bottoms and river networks or lakes (Poesen et al., 2003). These higher sediment loads and increased connectivity can result in a plethora of problems, including (muddy) floods (e.g. Verstraeten & Poesen, 1999), reservoir capacity losses due to sediment deposition (e.g. Haregeweyn et al., 2006), channel aggradation (e.g. Benda et al., 2003) and reduced water quality (e.g. Owens et al., 2005). As such, gully erosion is a great concern in many regions worldwide (Valentin et al., 2005; Poesen, 2018). It is a key process of land degradation and desertification (Vanmaercke et al., 2011a), posing a significant threat to various ecosystems and ecosystem services (e.g. Kroon et al., 2012; 2016).

Given these impacts and concerns, land use and catchment management strategies are needed that allow the prevention and mitigation of gully erosion and its impacts (e.g. Poesen et al. 2003; 2018). Nevertheless, controlling gully erosion is often complex and costly and typically requires a catchment-wide approach (Golosov & Belyaev, 2013). Conventional erosion control measures aimed at reducing sheet and rill erosion on hillslopes are often insufficient and specific interventions, such as the installation of check dams or revegetation within the gully channel, are often required. Successfully implementing such measures is usually very challenging, due to their risk of failure, their need for maintenance, feedback mechanisms like the ‘clear water’ effect, but also their often high associated costs (e.g. Stokes et al., 2014; Frankl et al., 2016; Ayele et al., 2018; Lucas-Borja et al. 2018; Rey et al., 2019; Bartley et al., 2020; Frankl et al., 2021).

Nevertheless, it is worth noting that gullies can sometimes also create interesting opportunities and positive outcomes. When well managed, they can become productive and biodiverse hotspots that play a key role as ecological corridors (Romero-Díaz et al., 2019). Likewise, gully channels can become significant sediment traps and fill-up over time, especially when they are well vegetated (e.g. Vanwalleghem et al., 2005c; Lanckriet al., 2015; Molina et al., 2009). Furthermore, they can be of significant geo-archeological value, providing important insight into (pre-)historic land use and human occupation (e.g. Dotterweich et al., 2003; 2012; Vanwalleghem et al., 2003; Torri et al., 2018a; Maerker et al., 2019). As such, they are generally seen by the scientific community as a key landform to understand the environmental change and soil erosion risks and they can play an important role in raising general awareness about these issues (e.g. Poesen et al. 2003; Frankl et al., 2011; Zgłobicki et al., 2015b; 2019). Given their great visibility they can also help in raising awareness on erosion problems (e.g. Bielders et al., 2003; Zegeye et al., 2010). Because of their often great esthetical value or spectacular nature, several gullied areas and badlands even have large potential as geoheritage sites (Zgłobickiet al., 2018).

1.2. The challenge of assessing gully erosion at regional to continental scales

Developing appropriate gully erosion prevention and remediation strategies requires a thorough understanding of its dynamics and controlling factors. Gully erosion has already received a lot of research attention over the past century (Castillo & Gomez, 2016). This led to valuable insights on the formation and expansion of gullies, their contribution to sediment loads and their potential remediation. This research also demonstrated the sensitivity of gully erosion to land use/land cover (e.g. Prosser & Slade, 1994; Poesen et al., 2003; Torri and Poesen, 2014) and rainfall intensity (e.g. Vanmaercke et al., 2016; Hayas et al., 2017b). Globally ongoing land use/land cover changes that have a significant effect on sheet and rill erosion (Borrelli et al., 2017a) therefore probably also strongly impact gully erosion rates. Likewise, climate change and in particular increases in rainfall intensities (e.g. Polade et al., 2014) are likely to further intensify gully erosion rates (e.g. Nearing et al., 2004; Li & Fang, 2016; Vanmaercke et al., 2016; Panagos et al., 2017). In order to address these challenges, there is a need for tools and models that can quantify the current rates and impacts of gully erosion and assess the effect of potential climate and land use change scenarios (e.g. Poesen, 2018; Pennock, 2019). However, our ability to simulate gully erosion and its impacts remains currently limited (Jetten et al., 2003; Merrit et al., 2003; Poesen et al., 2011; Vanmaercke et al., 2016; Bennett & Wells, 2019; Sidle et al. 2019), particularly at regional to continental scales (e.g. de Vente et al., 2013; Poesen, 2018). Insights at these scales are essential for the development of adequate and targeted land and catchment management strategies.

These difficulties to simulate and quantify gully erosion at regional to continental scales arise from several causes. First, there is a wide variety of gully types and sizes (**Figure 1**). Examples include ephemeral gullies in cropland (e.g. Valcarcel et al., 2003), (pre-)historic gullies under forest (e.g. Dotterweich et al., 2003; Vanwalleghem et al., 2003), permanent gullies in rangeland (e.g. Gomez-Gutiérrez et al., 2009a), valley bottom gullies in alluvial planes (e.g. Amare et al., 2019), bank gullies (i.e. gullies forming in earth banks such as river banks, agricultural terraces, lynchets or sunken lane banks; e.g. Vandekerckhove et al., 2000; Poesen et al., 2003), large gullies in urban environments (e.g. Guerra et al. 2007; Makanzu Imwangana et al., 2015), sunken lanes (or road gullies; e.g. De Geeter et al., 2020) and gullies in badland areas (e.g. Nadal-Romero et al., 2015). Furthermore, the formation and expansion of gullies typically involve a range of subprocesses, including the initial incision of a flow channel by concentrated runoff and the formation of a gully headcut (e.g. Oostwoud Wijdenes et al., 1999), gully headcut retreat (Vanmaercke et al., 2016), gully widening and deepening (e.g. Hayas et al., 2019), mass movements (e.g. Zegeye et al., 2020), fluting (Poesen et al., 2002), piping or tunnel erosion (Bernatak-Jakiel and Poesen, 2018), sediment transport and sediment deposition (e.g. Vanwalleghem et al., 2005c). The relative importance of these subprocesses depends on the type of gully, its environmental conditions, but also on the age of the gully (e.g. Oostwoud Wijdenes et al., 1999; Sidorchuk et al., 2001; Poesen et al., 2006; Sidorchuk, 2006; Frankl et al. 2021). In addition, and as a result of these complexities, gully erosion is also characterized by an important degree of stochasticity (e.g. Montgomery & Dietrich, 1994; Prosser & Abernethy, 1996). While significant advancements have been made over the past decades, our understanding of these processes, their interactions and their numerous potential controlling factors remains limited (Poesen et al., 2011; de Vente et al., 2013; Vanmaercke et al., 2016).

From the aforementioned points it also becomes clear that the simulation of gully erosion at larger scales requires significant amounts of data. These include input data on relevant environmental controlling factors (i.e. topography, soil characteristics, climate/weather conditions and land use/cover/management) but also observations on gully occurrence, dimensions and erosion rates to calibrate and validate models. Although several studies have attempted to model gully erosion at local scales, applying these models over larger areas is mostly impossible due to data constraints (e.g. Poesen et al., 2011; de Vente et al., 2013; Poesen, 2018). Furthermore, the environmental factors that need to be considered can vary depending on the study area and gully type. For example, valley bottom gullies are often linked to the presence of dispersive soils or specific conditions in subsurface hydrology (Imeson & Kwaad, 1980; Brooks et al., 2009; Amare et al. 2019). In other areas, seismic/tectonic activity seems to exert an important control on gully erosion (e.g. Cox et al., 2010; Marden et al., 2018). Also farming practices like tillage or parcellation patterns can play a key role in the formation of gullies (Poesen et al. 1996; Gordon et al., 2008; Zgłobicki & Baran-Zgłobicka 2011). This large variation of controlling factors, subprocesses and their interactions further hampers the development and application of (process-based) gully erosion models at regional to continental scales. Finally, given its threshold-dependent nature, gully erosion is typically a highly erratic process, characterized by a very large temporal variability (e.g. Vandekerckhove et al. 2001b; Vanmaercke et al., 2016; Hayas et al., 2017b). Hence, identifying and constraining the key factors controlling gully erosion requires data on gully dynamics, land use, land management and weather conditions that are sufficiently detailed over long periods.

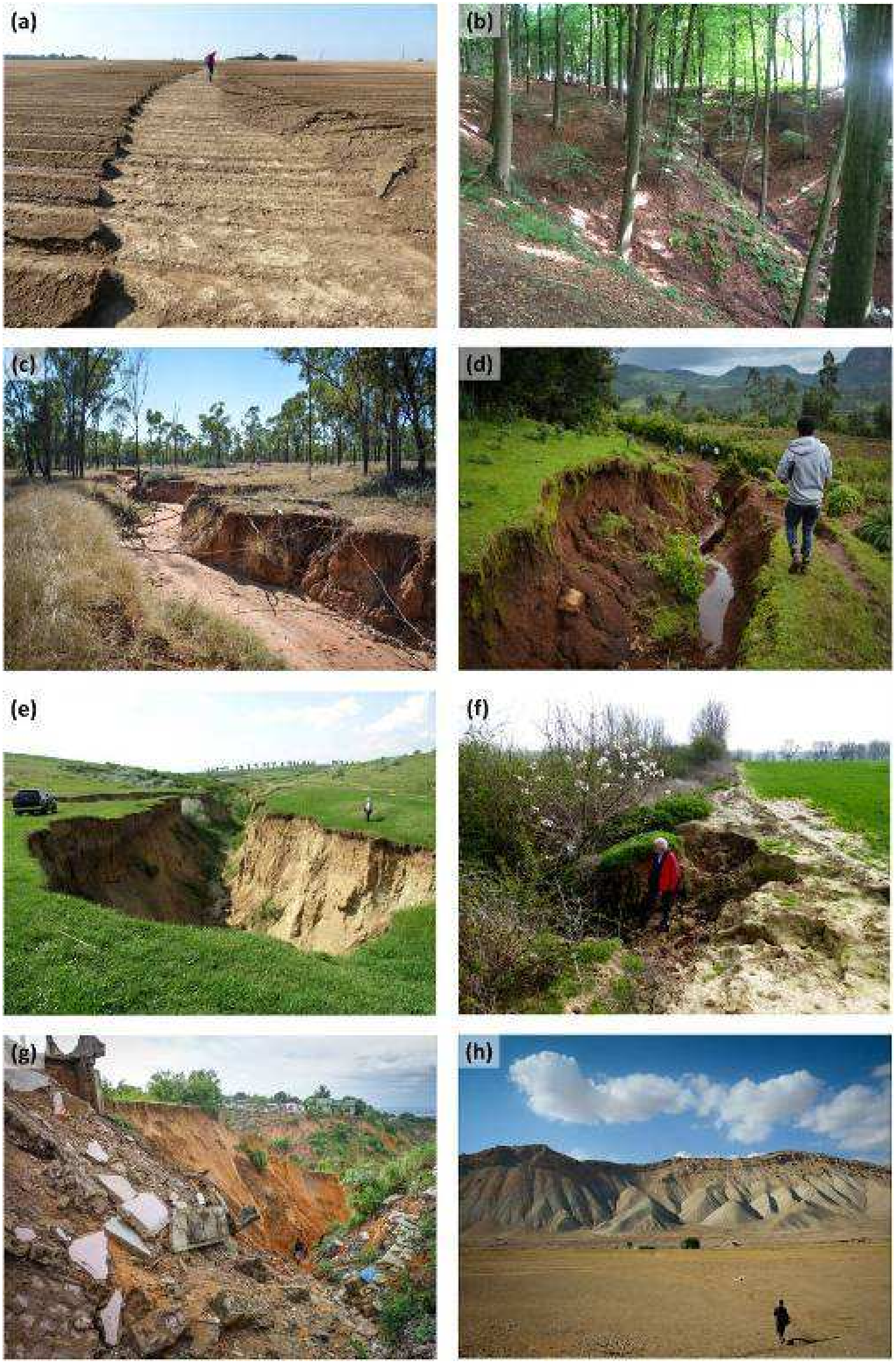

Figure 1: Illustration of different gully types across the world. **(a)** Ephemeral gully formed in a bare potato field with ridges and furrows (Neuville en Condroz, Belgium, May 2018; Photo: J. Poesen). **(b)** Historic gully under forest (Neigembos, Belgium, August 2013; Photo: M. Vanmaercke). **(c)** Permanent gully under rangeland (Burdekin catchment, Queensland, Australia, July 2019; Photo: M. Vanmaercke). **(d)** Permanent gully under grassland (Guder, Ethiopia, August 2017; Photo: M. Vanmaercke). **(e)** Permanent gully in a valley bottom (Moldova Province, Romania, May 2011; Photo: J. Poesen). **(f)** Bank gully formed in a sunken lane bank (Landen, Belgium, April 2019; Photo: J. Poesen). **(g)** Urban mega-gully that destroyed multiple houses (Kinshasa, D.R. Congo, November 2019; Photo: M. Vanmaercke). **(h)** Gullies formed in a badland area (near Quazvin, Iran, October 2014; Photo: M. Vanmaercke).

1.3. Scope and overview of this review

The previous subsections reveal that there is an important need for tools and models that allow quantifying and predicting gully erosion at regional (e.g. >10 000 km²), continental and even global scales. Presently, no approaches can do this. However, important advancements have been made in this regard. These include a better understanding of gully erosion processes, novel model approaches and mapping techniques and the development of new high-resolution datasets. The objective of this review is to provide a state of the art of our ability to monitor, model and manage gully erosion at regional to continental scales. From this we aim to identify key research and policy gaps, but also opportunities and pathways to address this problem. The main focus area of this paper is Europe. However, the scope and relevance of this paper extent to other continents as well.

Section 2 reviews remote-sensing and field approaches to measure and monitor gully properties and their dynamics. We discuss the limitations and potential of these methods with a focus on their application over larger areas. Section 3 provides an overview of past field-based gully-erosion research in Europe and European Russia. This to provide an overview of available data and observations that may be useful for further model development, but also to identify current research focuses and knowledge gaps. In section 4, we discuss modelling approaches used to simulate various relevant aspects of gully erosion (gully occurrence, gully expansion and the contribution of gullies to catchment sediment yields). Also here, our focus lies on the applicability of these approaches at regional to continental scales. Section 5 complements this objective by providing an overview of currently available GIS datasets that may be used as input for such models. We concentrate on datasets that are available for Europe or have a global coverage. Section 6 discusses to what extent environmental management policies and frameworks already account for the challenges posed by gully erosion (with a focus on Europe). Section 7 synthesizes our key findings into a list of key recommendations with respect to the monitoring, modelling and managing of gully erosion at larger scales.

2. Assessing gully erosion through monitoring

Observations on the occurrence of gullies, their dimensions and their dynamics are essential to quantify gully erosion rates, to identify the factors that control them and to develop and evaluate predictive models (cf. Section 4). In addition, such measurements are indispensable to assess the effectiveness of gully control measures (e.g. Frankl et al., 2013; 2021; Bartley et al., 2020). Here we review and discuss different methods to monitor the presence gullies (cf. section 2.1), their properties (cf. section 2.2) and their dynamics (cf. section 2.3), in particular at regional to continental scales.

2.1. Assessing the presence or absence of gullies

Especially at larger scales, time and labour constraints often limit the accuracy and level of detail of gully inventories. Nonetheless, inventories that simply record the ‘presence’ or ‘absence’ of gullies rather than their precise outlines can already greatly help in identifying problem areas and guiding policy decisions. Such approach has been followed in various regions, including Portugal (Vandaele et al., 1997), Belgium (Nachtergaele & Poesen, 1999), Ethiopia (Frankl et al. 2011), the USA (e.g. Bernard et al., 2010), Spain (e.g. Selkimäki and González-Olabarria, 2017), the European Union (Orgiazzi et al., 2018) and Australia (e.g. Hughes and Prosser, 2012; Darr and Pringle, 2017). This presence or absence can be assessed based on field surveys, aerial/satellite photo interpretation and/or remote sensing analyses. For the latter, the presence of vegetation or snow can hamper successful detection (e.g. Marzolff & Poesen 2009). Likewise, given that gullies can disappear or fill in over time, such inventories can be strongly time-dependent. This is especially a concern for ephemeral gullies, which are often filled in by ploughing shortly after the rain event that triggered them. Assessments based on infrequent surveys can thus severely underestimate the occurrence of ephemeral gullies (e.g. Nachtergaele & Poesen, 1999), and lead to high levels of error (Kuhnert et al., 2010). Furthermore, such inventories strongly depend on the size of the spatial units in which the presence or absence of gullies is recorded (e.g. parcels, catchments, grids of fixed dimensions).

Creating detailed inventories of gully presence at high resolution can be very labour-intensive (e.g. one person-month for a 3,000 km^2 area at a 100m pixel resolution; Darr and Pringle, 2017). Zhao et al. (2016) employed an alternative approach to estimate gully densities. Rather than systematically mapping entire areas, they assessed for a large number of random points whether or not the point was located inside a gully. The fraction of points located within a gully thus provides an estimate of the areal gully density. Such crude but fast proxy can be used for meaningful empirical analyses, e.g. to explore correlations between gully densities and catchment sediment yields (Zhao et al., 2016). Overall, complete assessments or random sampling procedures provide the advantage that mapping efforts are unbiased. In contrast, many existing gully occurrence studies focus on gully-prone areas and are therefore often unrepresentative at regional to continental scales.

A specific type of gully presence/absence inventories are maps that indicate the position of individual gully heads (e.g. Vandekerckhove et al., 1998; 2000b; Torri and Poesen, 2014; Hayas et al. 2017b). Since gully initiation and expansion are strongly controlled by local topographic and environmental conditions, such inventories are very useful for modelling purposes (cf. section 4). However, since their construction is often labour-intensive, they typically remains limited to local study areas (Torri and Poesen, 2014). Nevertheless, the growing availability of high-resolution remote sensing imagery and digital elevation models (cf. section 5) in combination with the development of (semi-) automatic gully detection procedures will likely increase the availability of such inventories at regional to continental scales.

2.2. Assessing gully properties

For some regions, more detailed inventories of gullies and their characteristics are available over large areas. An overview of such inventories for Europe is given in section 3. Examples outside Europe include parts of Queensland (Australia; e.g. Brooks et al., 2009) and South Africa (e.g. Mararakanye & Le Roux, 2012). Most of these inventories represent gullies as either linear features (e.g. Rysin et al., 2017a;b) or as polygons (e.g. Saxton et al., 2012; Shellberg et al., 2016). They are mostly constructed by manually mapping gully extent from (historical) monoscopic/stereoscopic aerial photographs (e.g. Knight et al., 2007). More recent examples made use of high resolution DEMs and/or high resolution remote sensing images in combination with classification procedures that are increasingly automated, accurate and computationally efficient (e.g. Thommeret et al., 2010; Castillo et al., 2014a; Shruthi et al., 2014; Fiorucci et al., 2015; Shabibi et al., 2019; Walker et al., 2020). Evidently, such gully inventories allow for more detailed analyses. Characteristics like gully-head locations (cf. section 2.1) may be extracted from them relatively easily (e.g. Hayas et al., 2017b). They also allow more precise assessments of the areal and/or linear gully density.

However, such inventories also come with limitations. Digitizing gullies from aerial photos or remote sensing products often involves significant uncertainties. For example, Maugnard et al. (2014) showed that mapping features of ephemeral gullies remains to a large extent subjective. Furthermore, their construction is generally very labour-intensive, resulting in important trade-offs between the size of the study area, the level of detail and the labour investment required (e.g. Mararakanye & Le Roux, 2012; Golosov et al., 2018). Key elements in this are the image resolution and/or the mapping altitude (i.e. the difference between the altitude of the camera and the surface elevation) used but also whether gullies are mapped as linear features or polygons. (Semi-)automatic detection procedures offer promising perspectives here. They are typically based on high-resolution multi-spectral images (e.g. Shruthi et al., 2011) and/or high-resolution digital elevation models (e.g. Thommeret et al., 2010; Shabibi et al., 2019; Walker et al., 2020). Such imagery has become increasingly available at regional to continental scales. Nonetheless, most of the current applications remain limited to relatively small scales. The potential of these techniques needs to be further explored. Another promising option may be to optimize sampling protocols to manually inventorize gullies. This can be done, by stratifying areas in terms of ancillary information such as slope, land use or soil type (e.g. Minasny and McBratney, 2006) or by using a (semi-)random sampling procedure of smaller sites to be mapped (e.g. Vanmaercke et al., 2020).

Also the widths, cross-sectional areas and, by extent, the total gully volumes are often of interest. Gully top-widths can typically be derived from aerial or satellite imagery (e.g. Nachtergaele et al., 2002a; Hayas et al., 2017a). However, gully floor-widths are typically hard to measure from such imagery (Giménez et al., 2009). The top-widths may be significantly larger than the gully floor-widths, especially for older gullies or gullies formed in soils with little cohesion (e.g. Hayas et al., 2019). Nonetheless, gully floor-width and hydraulic radius are often of greater geomorphic relevance as they relate more directly to the maximum runoff discharges passing through the gully (e.g. Nachtergaele et al., 2002a; Vanwalleghem et al., 2005b).

Also gully cross-sectional areas are difficult to quantify based on aerial photos or high resolution satellite images. Nonetheless, they are a key prerequisite to estimate the volumes of gully systems (Casalí et al., 2015; Castillo et al., 2019). Therefore they are often obtained through field measurements (e.g. Nachtergaele et al., 2001a;b). An uncertainty assessment by Castillo et al. (2012) showed that errors on individually measured cross-sections are overall relatively limited (3-15%). Extrapolating these cross-sectional areas to estimate gully volumes typically generates larger uncertainties. These depend on the gully length, its sinuosity and in particular the number of cross-sections surveyed. Quantifying gully volumes with an acceptable degree of uncertainty (10-20%) typically requires ten or more cross-sections per gully (Castillo et al., 2012). This can pose challenges when aiming to quantify gully erosion volumes over larger areas. Fortunately, gully cross-sectional areas are typically strongly correlated to their top-width (e.g. Frankl et al., 2013; Vanmaercke et al., 2016), which can be assessed via remote sensing. It is often feasible to develop robust empirical relationships between gully top-width and cross-sectional areas, based on a relatively limited amount of field surveys. These relationships can then be used to estimate gully volumes with acceptable uncertainties (e.g. Fiorucci et al., 2015; Hayas et al. 2017a). One concern with this approach is that the cross-sectional shapes evolve over time, e.g. from a rectangular to a more trapezoidal shape (e.g. Vanwalleghem et al. 2005b; Hayas et al., 2019). Hence, applying such a (time-specific) relationship to assess gully volumes over longer time periods may induce further uncertainties and biases.

The challenge to estimate gully volumes from 2D imagery is partly rendered obsolete by new techniques. Airborne LIDAR instruments, for example, allow mapping the morphology and volume of gully systems (e.g. James et al., 2007; Eustace et al., 2009; Perroy et al., 2010; Goodwin et al., 2017). The method, albeit expensive (Castillo et al., 2012), is relatively fast and typically allows to construct digital terrain models of gully systems with an accuracy of some centimeters to decimeters. Recently developed Structure from Motion (SfM) techniques offer a promising and cheaper alternative, with accuracies and precisions that are similar to LIDAR or in some cases even superior (e.g. Castillo et al., 2012; Gómez-Gutiérrez et al., 2014; Clapuyt et al., 2016; Koci et al., 2017). The photographic surveys required to construct a SfM-based digital terrain model can be conducted either from the ground or through drone flights. They can be made with standard photo cameras, while freely available software exists to process the photos into a 3D model (e.g. Koci et al., 2017). Nonetheless, vegetation cover can form a significant constraint for assessing gully properties via SfM. Also, as with LIDAR, data acquisition typically is labour-intensive and the computer resources required to construct such a 3D model currently remain considerable. Hence, most studies applying LIDAR or SfM to characterize gully systems cover only limited areas (e.g. Eustace et al., 2009; Perroy et al., 2010; Castillo et al., 2012; Kropacek et al. 2016; Koci et al., 2017). Increases in computational power and more efficient algorithms may make it feasible to apply these techniques at regional to continental scales in the near future (Bennett and Wells, 2019).

Apart from assessing gully dimensions, assessing whether gullies are stable or actively expanding is often of great relevance. While historic expansion of gullies is best assessed through repeated surveys (cf. section 2.3), this is not always possible. Furthermore, to target mitigation efforts, it is often required to identify the gullies that are currently active (e.g. Whitford et al., 2010). Some morphological characteristics can indicate whether a gully is likely active (Oostwoud Wijdenes et al., 1999). For example, (recently) active gully heads typically have sharp edges, a plunge pool, tension cracks, recently deposited sediments and flow marks. Stabilized gullies typically have smoother or rounded edges and vegetation re-growth on the gully head wall and at its foot (Oostwoud Wijdenes et al., 2000). However, such distinctions are not always detectable on aerial/satellite imagery. Several studies therefore assessed gully stability based on the vegetation cover inside the gully (e.g. Vanwalleghem et al., 2005c; Makanzu Imwangana et al., 2015; Golosov et al., 2018). While such morphological or vegetation criteria can provide strong indications, it is important to note that they are not a guarantee for gully stability. Extreme weather events or significant land cover changes may reactivate gullies that have been stable for many years (Vandekerckhove et al., 2001b).

Likewise, classifying gullies into types (e.g. permanent, ephemeral, bank gully, valley-bottom and valley-side gully) is generally useful, as this may help understanding the causing mechanisms, potential erosion rates and optimal remediation strategies (e.g. Amare et al., 2019; Bartley et al., 2020). Such classifications can be based on the dimensions, the landscape position and/or the land use type in which the gully occurs. However, while there is some agreement on different types of gullies (cf. section 3), no universal gully classification scheme currently exists. This limits the comparability of gully inventories and, by extent, gully erosion assessments at regional to continental scales. The development of systematic gully typologies, similar to those developed for landslides (e.g. Cruden and Varnes, 1996), may help address this issue.

2.3. Assessing gully dynamics

Various studies have assessed gully erosion rates through repeated field surveys or by determining the age of gullies through the analyses of tree roots, terrestrial photography, interviews, optical dating, sediment fingerprinting or other techniques (e.g. Vandekerckhove et al., 2001a; 2003; Martinez-Casasnovas et al., 2004; Ionita, 2006; Nyssen et al., 2006; Marzolff et al., 2011; Frankl et al., 2012; Portenga et al., 2017; Bernatek-Jakiel & Wrońska-Wałach, 2018). While such research can provide key insights, they typically require intensive fieldwork and are therefore generally limited to specific gullies or small study areas. Efforts to understand gully erosion dynamics over larger areas therefore mainly rely on applying the techniques discussed above over different periods (e.g. Nachtergaele et al., 2002b, Vandekerckhove et al., 2003; Vanwalleghem et al., 2005c; Marzolff and Poesen, 2009; Frankl et al., 2011; Yibeltal et al., 2019).

Such analyses based on available imagery typically face important limitations. A first one is the length of the observation period. Given its threshold-dependent nature, gully erosion is often a highly erratic process (e.g. Vandekerckhove et al., 2001b; Martinez-Casasnovas et al., 2004). For example, Hayas et al., (2017a) showed average gully erosion rates may vary up to a factor 60 over short (< 5 years) observation periods. A global review of observed gully headcut retreat rates indicated similar ranges of variability (Vanmaercke et al., 2016). Hence, average gully erosion rates derived from short observation periods are often subject to very important uncertainties. While these uncertainties generally remain poorly quantified, they may easily dwarf the uncertainties related to assessing gully properties (cf. section 2.2). These uncertainties are often asymmetric: gully erosion rates derived from short periods are more likely to underestimate the long-term average, but may in some cases result in severe overestimations (Vandekerckhove et al., 2003; Hayas et al., 2017a; Vanmaercke et al., 2016).

Apart from climatic variability, over- or underestimations strongly depend on the timing of the imagery. Permanent gullies often show the highest headcut retreat rates shortly after their formation, but then tend to stabilize over time (e.g. Nachtergaele et al., 2002b; Vanwalleghem et al., 2005; Sidorchuk, 2006; Whitford et al., 2010; Vanmaercke et al., 2016; Makanzu Imwangana et al., 2015; Rysin, 1998). When gullies are already present on the first image of a series, this poses large challenges in reconstructing the long-term average erosion rate (Vanmaercke et al., 2016). Furthermore, gullies can expand through widening and deepening (e.g. Martinez-Casasnovas et al., 2004; Marzolff and Poesen, 2009). Research suggests that these processes become relatively more important in the later stages of gully development (e.g. Sidorchuk, 1999; Sidorchuk et al., 2003; Sidorchuk, 2006; Hayas et al., 2017a). Nonetheless, few studies have focused on these processes. As a result, they remain poorly quantified and understood (Whitford et al., 2010; Hayas et al., 2019).

Finally, also the timing and frequency of the imagery greatly affects the reliability. Long periods between images make it difficult to accurately assess the initiation of gullies and may lead to biases. This is especially a concern for ephemeral gullies in arable land. As many ephemeral gullies are ploughed away shortly after their formation, assessing their erosion rate based on infrequent imagery can strongly underestimate the actual rate (Nachtergaele & Poesen, 1999). Ideally, imagery should be acquired shortly after every significant rainstorm event. However, that is rarely possible and especially hard for large areas. The rise of satellite imagery products with high spatial, temporal and spectral resolutions in combination with (semi-)automatic detection procedures (e.g. Shruti et al., 2014) may help address this gap.

In conclusion, assessing reliable gully erosion rates at regional to continental scales remains difficult, especially at high temporal resolutions. Methodological challenges in both the detection (cf. section 2.1) and characterization (cf. section 2.2) of gullies may induce significant uncertainties. New remote sensing products and (semi-)automatic detection procedures offer promising perspectives here. Nevertheless, especially the large temporal variability that characterizes gully erosion remains a major source of uncertainty. Accurately quantifying gully erosion rates therefore requires frequent imagery over sufficiently long time periods (e.g. decades). Historic (aerial) photographs can be crucial assets in this (e.g. Nachtergaele and Poesen, 1999; Frankl et al. 2011; Golosov et al., 2018). Nonetheless, such photographs are rarely available over large areas, are often difficult to access for scientists and their processing often remains very labour-intensive (e.g. Guyassa et al., 2018).

3. Measurements on gully erosion in Europe: an overview

As discussed above, field-based research is important for defining the locations, morphological characteristics, erosion processes, dynamics and controlling factors of gullies. To gain insights into the geographic distribution of field-based gully related research in Europe and European Russia, we conducted a detailed literature review. This review concentrated on research results published in peer-reviewed journals or in conference proceedings. Studies published in internal reports, MSc. or PhD. theses, or newspaper articles (i.e. grey literature) were not considered. As some research teams produced a large number of peer-reviewed papers about gullies in particular study areas, only the most relevant papers, considered to be representative for the study area, were selected. In total over 224 research papers have been selected (**Table 1**). **Figure 2** shows the spatial distribution of areas where permanent, ephemeral or bank gullies as well as gullies in badlands have been studied. Although a large number of papers report on various aspects of badlands, we only considered studies focusing on gully erosion in badlands.

Overall, gully erosion mainly received significant field-based research attention in some particular countries, i.e. Belgium, Germany, Italy, Spain, Romania and the UK. Most studies investigated permanent gullies in forests or rangelands (including badlands; **Figure 2a, Figure 2d**). Relatively fewer studies report on ephemeral gullies, which are typically observed after erosive periods in cropland. As ephemeral gullies are filled in by tillage or land leveling operations shortly after their formation, these gullies are also more difficult to study. Although quite common in rural areas with a rolling or steep topography, bank gullies forming at river banks, agricultural terraces, lynchets or sunken lane banks (Poesen et al., 2003) have also received less attention (**Figure 2c**).

Table 1: Overview of gully erosion research in Europe and European Russia.

Country	Ephemeral Gullies	Permanent Gullies	Bank Gullies	Gullies in Badlands
Austria	N.A.	Sass et al. (2012)	N.A.	N.A.
Belgium	Govers & Poesen (1988); Vandaele & Poesen (1995); Poesen et al. (1996); Vandaele & Poesen (1996); Vandaele & Poesen (1997); Desmet et al. (1999); Nachtergaele & Poesen (1999); Takken et al. (1999); Steegen et al. (2000); Gyssels et al. (2002); Gyssels & Poesen (2003); Vanwalleghem et al. (2005a); Evrard et al. (2007); Knapen & Poesen (2010); Maugnard et al. (2014a); Maugnard et al. (2014b)	Arnould-De Bontridder & Paulis (1966); De Ploey (1977); Langohr & Sanders (1985); Gullentops (1992); Poesen et al. (2003); Vanwalleghem et al. (2003); Vanwalleghem et al. (2005a); Vanwalleghem et al. (2005b); Vanwalleghem et al. (2005c); Vanwalleghem et al. (2006); Schotmans et al. (2015)	Poesen (1989); Poesen et al. (1996); Poesen et al. (2003); Frankl et al. (2015)	Gullentops (1992); Vanwalleghem et al. (2003); Vanwalleghem et al. (2006)
Bulgaria	N.A.	Malinov & Ilieva (2017)	N.A.	N.A.
Croatia	N.A.	Faivre et al. (2011); Gulam et al. (2018); Domazetović et al. (2019); Domlija et al. (2019)	N.A.	Gulam et al. (2018); Domlija et al. (2019)
Czech Republic	Báčová & Krása (2016); Dumbrovsky et al. (2019)	Tichavský et al. (2018)	N.A.	N.A.
France	Auzet et al. (1993); Cerdan et al. (2002); Souchère et al. (2003); Frankl et al. (2018); Patault et al. (2019)	De Foucault et al. (1997); Mathys et al. (2003); Rey (2003); Rey (2009); Erktan & Rey (2013); Rey & Burylo (2014); Taborelli et al. (2016)	N.A.	Mathys et al. (2003); Rey (2009); Erktan & Rey (2013); Rey & Burylo (2014)
Germany	N.A.	Bork & Rohdenburg (1979); Bork (1985); Bauer (1993); Semmel (1995); Bork et al. (1998); Dotterweich (2003); Dotterweich et al. (2003); Heine & Niller (2003); Schmidtchen & Bork (2003); Dreibrodt (2005); Stolz & Grunert (2006); Beyer (2008); Dotterweich (2008); Moldenhauer et al. (2010); Stolz (2011); Dotterweich et al. (2015)	N.A.	N.A.
Greece	Karydas & Panagos (2020)	Vandekerckhove et al. (2000)	N.A.	N.A.
Hungary	N.A.	Gabris et al. (2003); Jakab et al. (2011); Kertész & Gergely (2011); Kertész & Křeček (2019)	N.A.	N.A.
Iceland	N.A.	Hartmann et al. (2003)	N.A.	N.A.
Italy	Capra & Scicolone (2002); Poesen et al. (2003); Zucca et al. (2006); Conoscenti et al. (2013); Conoscenti et al. (2014); Fiorucci et al. (2015); Conoscenti et al. (2018); Conoscenti & Rotigliano (2020)	Battaglia et al. (2003); Strunk (2003); Clarke & Rendell (2006); Ciccacci et al. (2009); Buccolini & Coco (2010); Clarke & Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini et al. (2013); Conoscenti et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013a); Caraballo-Arias et al. (2014); Caraballo-Arias et al. (2015); Cocco et al. (2015); Bianchini et al. (2016); Bollati et al. (2019)	N.A.	Battaglia et al. (2003); Clarke & Rendell (2006); Ciccacci et al. (2009); Buccolini & Coco (2010); Clarke & Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013b); Caraballo-Arias et al. (2014); Caraballo-Arias et al. (2015); Cocco et al. (2015); Bianchini et al. (2016); Bollati et al. (2019); Bosino et al. (2019); Maerker et al., 2020

Latvia	N.A.	Zgłobicki et al. (2019)	N.A.	N.A.
Norway	Øygarden (2003)	Sønstegaard & Mangerud (1977); Erikstad (1992); Bogen et al. (1994)	N.A.	Erikstad (1992)
Poland	Maruszczak & Trembaczowski (1956); Teisseyre (1992); Janicki & Zgłobicki (1998); Janicki (2014)	Schmitt et al. (2006); Smolska (2007); Malik (2008); Rodzik et al. (2009); Schmidt & Heinrich (2011); Zgłobicki & Baran-Zgłobicka (2011); Dotterweich et al. (2012); Gawrysiak & Harasimiuk (2012); Superson et al. (2014); Zgłobicki et al. (2014); Kociuba et al. (2015); Zgłobicki et al. (2015a); Zgłobicki et al. (2015b); Bernatek-Jakiel & Wronska-Walach (2018)	N.A.	N.A.
Portugal	Poesen et al. (1996); de Figueiredo & Fonseca (1997); Vandaele et al. (1997); Vandekerckhove et al. (1998); Vandekerckhove et al. (2000); Nachtergaele et al. (2001a); Poesen et al. (2003)	de Figueiredo & Fonseca (1997); Vieira et al. (2014); Bergonse & Reis (2016); Martins et al. (2017); Martins et al. (2020)	Fernandes et al. (2017)	N.A.
Romania	N.A.	Motoc (1983); Motoc (1984); Ichim et al. (1990); Radoane et al. (1995); Ionita (2003); Ionita (2006); Mircea (2011) ; Niacsu & Ionita (2011); Boengiu et al. (2012); Ionita et al. (2015); Radoane & Radoane (2017); Nicu (2018)	N.A.	N.A.
Russia (European)	Litvin et al. (2003); Belyaev et al. (2005b); Belyaev et al. (2008); Platoncheva et al. (2020)	Bolysov (1987); Dedkov et al. (1990); Bolysov & Tarzaeva (1996); Rysin (1998); Litvin et al. (2003); Zorina (2003); Belyaev et al. (2004), Belyaev et al. (2005a); Yermolaev (2014); Vanmaercke et al. (2016); Rysin et al. (2017a); Rysin et al. (2017b); Gafurov et al. (2018); Golosov et al. (2018); Medvedeva et al. (2018); Rysin et al. (2018); Sharifullin et al. (2020)	Rysin (1998)	N.A.
Serbia	N.A.	Ristić et al. (2012)	N.A.	N.A.
Slovakia	Stankoviansky (2005); Stankoviansky & Ondrčka (2011)	Bučko & Mazúrova (1958); Stankoviansky (2003a); Stankoviansky (2003b); Papčo (2011); Stankoviansky (2003c); Dotterweich et al. (2013); Silhan et al. (2016); Mitusov et al. (2017); Nosko et al. (2019)	N.A.	Stankoviansky (2003a); Stankoviansky (2003b); Stankoviansky (2003c)
Slovenia	Zorn (2009a)	Zorn (2009b)	N.A.	N.A.

Spain	Vandekerckhove et al. (1998); Casali et al. (1999); Martinez-Casasnovas et al. (2002); Valcarcel et al. (2003); De Santisteban et al. 2006; Hayas et al. (2017a); Hayas et al. (2017b); Ollobarren Del Barrio et al. (2018); Hayas et al. (2019)	Donker & Damen (1984); Faulkner (1995); Poesen et al. (1996); Oostwoud Wijdenes et al. (1999); Nogueras et al. (2000); Oostwoud Wijdenes et al. (2000); Vandekerckhove et al. (2000); Canton et al. (2001); Vandekerckhove et al. (2001a); Vandekerckhove et al. (2001b); Martinez-Casasnovas et al. (2003); Ries & Marzolff (2003); Vandekerckhove et al. (2003); De Luna Armenteros et al. (2004); Faulkner et al. (2007); Lesschen et al. (2007); Menendez-Duarte et al. (2007); Gomez-Gutierrez et al. (2009a); Dóniz et al. (2011); Lucia et al. (2011); Marzolff et al. (2011); Campo-Bescos et al. (2013); Martín-Moreno et al. (2014); Stöcker et al. (2015); Caraballo-Arias et al. (2016); Ballesteros Cánovas et al. (2017); Hayas et al. (2017a); Hayas et al. (2017b); Selkimäki & González-Olabarria (2017); Castillo et al. (2018); Hayas et al. (2019)	Oostwoud Wijdenes et al. (2000); Vandekerckhove et al. (2000); Vandekerckhove et al. (2001a); Vandekerckhove et al. (2001b); Vandekerckhove et al. (2003)	Nogueras et al. (2000); Faulkner et al. (2007); Lucia et al. (2011); Martín-Moreno et al. (2014); Ballesteros Cánovas et al. (2017)
Sweden	Alström & Åkerman (1992)	Nordström (1984)	N.A.	N.A.
Ukraine	N.A.	Tsvetkova et al. (2015)	Tsvetkova et al. (2015)	N.A.
United Kingdom	Morris (1942); Howe (1955); Evans & Nortcliff (1978); Reed (1979); Boardman (1983); Boardman (1988); Watson & Evans (1991); Boardman et al. (1996); Boardman (2001); Clark & Vetere Arellano (2004); Watson & Evans (2007); Boardman et al. (2009); Boardman (2012); Boardman (2013); Boardman et al. (2020); Evans (2013)	Chiverrell et al. (2007); Rothwell et al. (2007); Evans & Lindsay (2010); Clay et al. (2012)	N.A.	N.A.

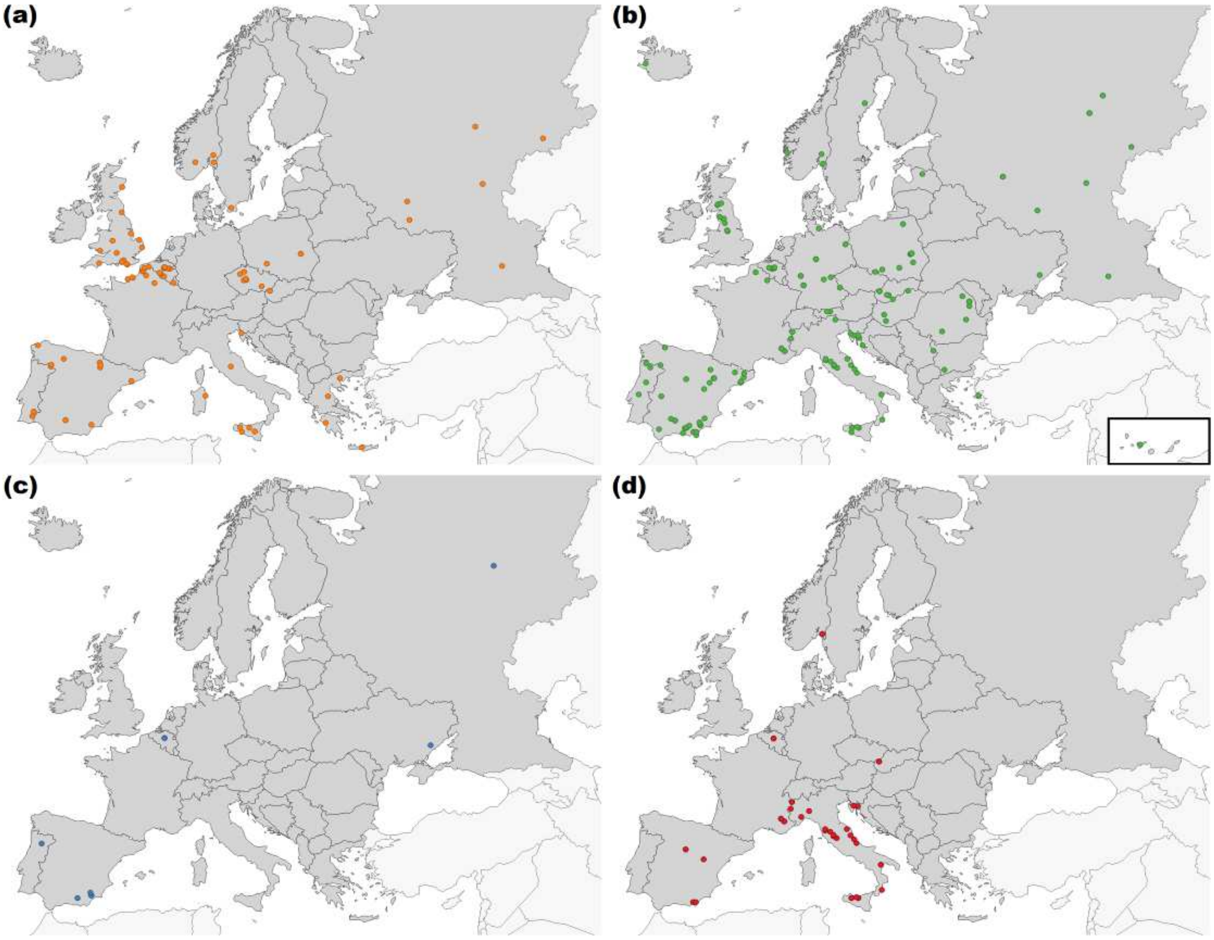

Figure 2: Overview of study areas in Europe and European Russia where field-based gully erosion research was conducted, sub-divided according to the investigated gully-type: **(a)** ephemeral gullies, **(b)** permanent gullies (inset shows the Canary Islands), **(c)** bank gullies, **(d)** gullies in badlands. References per country and gully type are listed in **Table 1**. Countries shaded in dark grey indicate the study area considered for this review.

Most studies focused on a single gully channel or on a limited number of selected gullies in a particular study area. However, a few studies provide gully inventories for extensive areas (> 10 000 km²) or even entire countries (**Figure 3**). More specifically, such studies exist for Slovakia (Bučko & Mazúrová, 1958), Poland (Józefaciuk & Józefaciuk, 1983), SE-Poland (Gawrysiak & Harasimiuk, 2012), East Romania (Radoane et al., 1995), Northern France (De Foucault et al., 1997), the Middle Volga region (Russian Federation; Golosov et al., 2018) and Hungary (Kertész & Krecek, 2019). These inventories are largely based on aerial imagery interpretation. They are often already relatively old and focused on larger, permanent gullies. Therefore it is generally difficult to assess their accuracy and completeness. Nonetheless, such inventories may be indispensible for calibrating and validating gully occurrence models at larger scales (cf. section 4.1).

It is beyond our scope to provide an in-depth review of all aspects of gully erosion that received research attention. Such thematic explorations have been conducted elsewhere (e.g. Poesen et al., 2003; Castillo & Gomez, 2016). Nonetheless, several major themes of gully erosion research in Europe could be identified. These include:

- Developing and testing gully measuring and monitoring techniques, such as high-altitude aerial photograph analysis (e.g. Nachtergaele & Poesen, 1999; Martınez-Casasnovas et al., 2002), analysis of high-resolution aerial photos taken by drones (e.g. Marzolff & Poesen, 2009; Stöcker et al., 2015), 3D-terrestrial image-based modelling (e.g. Frankl et al., 2015) and dendrogeomorphology (Vandekerckhove et al., 2001a; Malik 2008; Tichavsky et al., 2018).

- Dating of (pre-)historic gullies (e.g. Sonstegaard and Mangerud, 1977; Bork, 1985; Dotterweich et al., 2003; 2012; 2013, Schmitt et al., 2006, Vanwalleghem et al., 2006) and investigating the environmental conditions that lead to their initation and development (e.g. Bork, 1985; Faulkner, 1995; Dotterweich et al., 2003; Gabris et al., 2003; Nogueras et al., 2000; Stankoviansky, 2003a; 2003b; 2003c; Vanwalleghem et al., 2005b; Martin Moreno et al., 2014; Ionita et al., 2015b; Ballesteros et al., 2017).

- Investigating factors controlling the initiation and development of contemporary gullies, including soil profile characteristics (e.g. Vanwalleghem et al., 2005b), plant roots (e.g. Gyssels & Poesen, 2003), topography and topographic thresholds (e.g. Vandekerckhove et al., 1998; Souchère et al., 2003; Hayas et al. 2017a; 2017b; Torri et al., 2018b), snowmelt runoff (e.g. Oygarden, 2003; Ionita, 2006; Rodzik et al., 2009; Rysin et al., 2017a,b; Golosov et al., 2018), rainfall conditions (Hayas et al. 2017a; 2017b) and the role of piping (Bernatek-Jakiel & Wronska-Walachn, 2018).

- Exploring the conditions leading to the infilling of gullies (e.g. Erikstad, 1992; Vanwalleghem et al., 2005c).

- Evaluating the effectiveness of gully erosion control techniques, including geomembranes (e.g. Poesen, 1989), check dams (e.g. Castillo et al., 2007), grassed waterways (e.g. Evrard et al., 2008) and bioengineering structures (e.g. Rey & Burylo, 2014).

- Quantifying the contribution of gully erosion to catchment sediment yields (e.g. Bogen et al., 1994; Poesen et al., 1996; 2003).

This review also revealed some important research gaps with respect to understanding and quantifying gully erosion at regional to continental scales:

1) Most studies are clustered in specific study areas, while many other areas remain poorly or not investigated (cf. **Figure 2**). While these patterns may be partly caused by the absence of gullies, many regions probably remain under-researched.

2) Only few studies investigated gully occurrence on regional or country-wide scales (cf. **Figure 3**).

3) Relatively few studies monitored the evolution of gullies over extensive time periods (e.g. > 20 years). Given their potentially large temporal variability (e.g. Rysin, 1998; Nachtergaele et al., 1999; Martinez-Casasnovas et al., 2004; Vanmaercke et al., 2016; Hayas et al., 2017a; Rysin et al,

2017a,b; Rysin et al., 2018), this is critical to understand the long-term evolution and erosion rates of gully systems.

4) Relatively few studies have focused on testing or developing models that simulate spatial patterns of gully erosion. This is particularly the case for larger areas.

5) Evaluating the long-term effectiveness and efficiency of gully erosion control measures has received little attention, both at the scale of gully channels and catchments (Poesen et al., 2003; Bartley et al., 2020). Linked to that, our understanding of the conditions controlling the infilling of gullies is limited (Poesen et al. 2003).

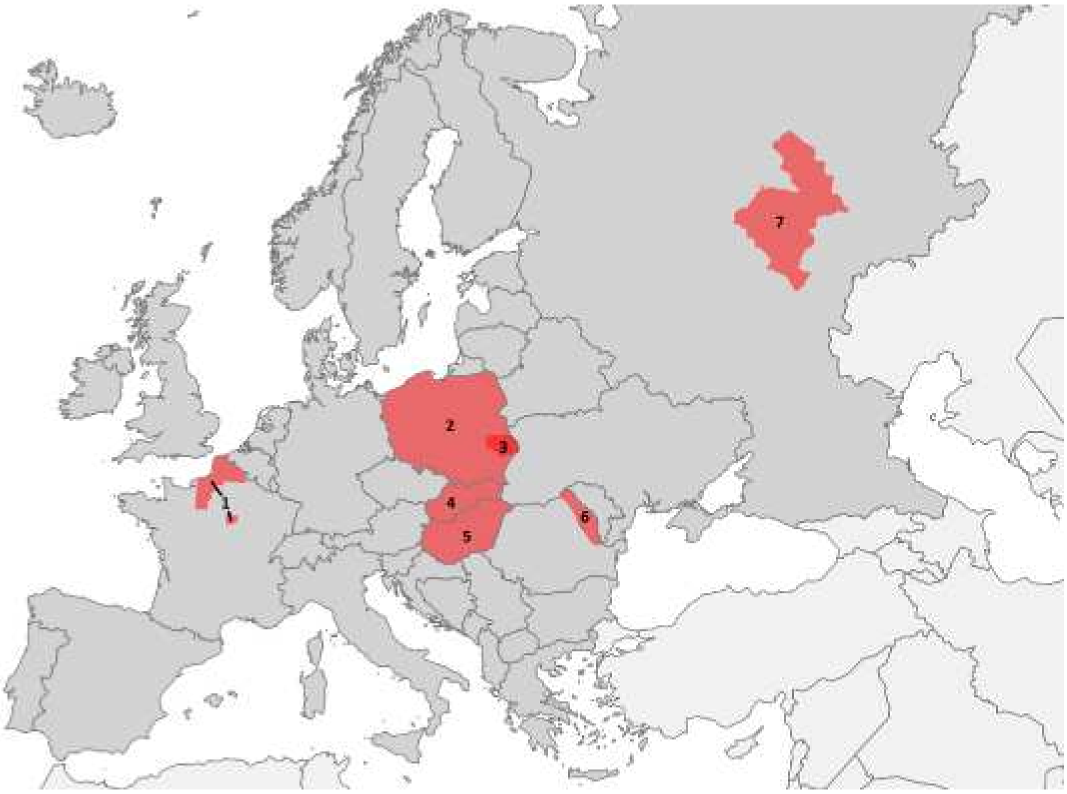

Figure 3: Regions and countries in Europe for which systematic gully inventories have been made. The mapped gully types, level of detail and completeness of these inventories may vary. 1: N-France (De Foucault et al., 1997), 2: Poland (Józefaciuk & Józefaciuk, 1983), 3: SE-Poland (Gawrysiak & Harasimiuk, 2012), 4: Slovakia (Bučko & Mazúrová, 1958), 5: Hungary (Kertész & Krecek, 2019), 6: E-Romania (Radoane et al., 1995), 7: the Middle Volga region (Russian Federation; Golosov et al., 2018). Countries shaded in dark grey indicate the study area considered for this review.

4. Assessing gully erosion using models

Predicting gully erosion rates and its impact on sediment loads encompasses several challenges. These include predicting: (i) where and why gullies occur, (ii) when and how these gullies expand, and (iii) to what extent these gullies contribute to catchment sediment yields. Numerous gully erosion models have been developed. However, no single model presently exists that addresses these three components. Furthermore, most modelling efforts have concentrated on individual gullies or local scales. Here we review and discuss different modelling strategies to simulate these different aspects of gully erosion. It is outside our scope to provide a comprehensive overview of all gully erosion models. Instead, we discuss which modelling strategies potentially can be applied at regional to continental scales, which future advancements may be expected and which research needs currently exist.

4.1. Predicting gully occurrence and density

Several modelling approaches exist to predict the occurrence of gullies in a landscape (e.g. Poesen et al., 2011). Overall, these can be characterized based on whether they aim to predict the initiation of gullies from process-based principles or whether they aim to predict their occurrence in a purely empirical or statistical way. Most of these involve a combination of both strategies.

In general, process-based approaches rely on the principle that gully initiation is a threshold-dependent phenomenon. Gully heads typically initiate where the shear stress of concentrated runoff exceeds the resisting forces, which mainly depends on local soil and vegetation conditions (Istanbulluoglu et al., 2003; Knapen et al., 2007; Knapen and Poesen, 2010). The most common approach to characterize these conditions is the topographic threshold concept. It builds upon the observation that gullies in a landscape typically form at locations where the upslope area (A) and local slope steepness (s) exceed a certain threshold (e.g. Begin and Schumm, 1979; Montgomery & Dietrich, 1994). Given that A provides a proxy of the potential flow discharge and s influences flow velocity, topographic thresholds directly relate to the critical flow shear stress principle. They are commonly expressed in the form:

$s=kA^b$ (Eq. 1)

where k and b are empirically fitted constants that depend on the environmental setting (Begin and Schumm 1979; Montgomery & Dietrich, 1994; Torri & Poesen, 2014). Such thresholds often allow fairly good identification of the positions of gully initiation within a study area and by extent their density (e.g. Desmet et al., 1999). However, their highly site-specific nature makes them unsuitable for applications at regional or continental scales. A meta-analysis by Torri and Poesen (2014) of 63 s-A relations for various areas worldwide indicated a very large variability in k- and b-values (cf. Eq. 1). Under the assumption that b-values are relatively constant, variations in k-values seem mainly attributable to differences in land cover. Nonetheless, generalizing these empirical constants remains difficult as also other environmental factors will play a role. For example, a main limitation of topographic thresholds is that they typically reflect the “integrated” result of different gully initiation episodes over time. Exact gully head initiation thresholds vary with rainfall intensity (e.g. Torri and Poesen 2014; Hayas et al., 2017b) and more specifically with the resulting peak flow discharge. Also spatial patterns of vegetation and soil characteristics within the contributing area can play a large role (e.g. Rossi et al., 2015a). Likewise, the upslope area can be modified by land management practices that are not resolved by DEMs, such as tillage furrows (Souchére et al. 2003), drainage ditches and stone bunds, all of which can affect the *k*-value (Monsieurs et al., 2015). Furthermore, gullies are not necessarily the sole result of (Hortonian) runoff. They can also form and expand as a result of saturation soil conditions and overland flow (e.g. Nachtergaele et al. 2001a; Tebebu et al., 2010; Amare et al., 2019).

Alternative topographic indices have therefore been proposed to better reflect landscape positions where gullies may initiate. For example, Moore et al. (1988) proposed an index that accounts for saturation overland flow. Istanbulluoglu et al. (2008) incorporated a probabilistic approach in order to account for uncertainties associated with these kinds of topographic relations. The AnnAGNPS model uses the Compound Topographic Index (CTI) to determine the location of potential ephemeral gullies (Taguas et al., 2012; Momm et al., 2012; 2013). This index is also based on contributing area and slope steepness, but aims to better reflect the potential effect of soil wetness conditions on gully initiation (Momm et al., 2015). Dagupatti et al. (2013) compared models based on four different topographic indices, i.e. CTI, slope-area (SA), topographic wetness index (TWI), and slope area power (SAP). Results showed that a SA-based approach predicted ephemeral gully occurrence better than the other models tested. Nevertheless, they also showed that CTI has potential for predicting gully headcut location and total gully length. Conoscenti & Rotigliano (2020) also tested CTI, SA, TWI and modified versions of the latter two (named MSPI and MTWI) which incorporate an index to reflect flow convergence/divergence. MSPI outperformed the other topographic indices, revealing that a convergence index may help in detecting hollows where gullies are more likely to form. However, local calibration is required (Dagupatti et al., 2013). This currently limits regional applications.

To account for factors other than topography (e.g. climate, land use/land cover, soil type) and their potential interactions, several process-oriented model approaches have been proposed. Overall, they aim to replace or complement the upslope contributing area (*A*) in Eq. 1 with better proxies of flow discharge, and by extent the flow shear stress, that can occur at a potential gully location. This could allow for more accurate and generalizable simulations of where and when gullies may form. Several approaches are based on the Curve Number (CN) method, a simple empirical model that allows estimating runoff based on rainfall, antecedent moisture, soil and land use conditions (e.g. Ponce & Hawkins, 1996). In principle, such approach allows making gully initiation conditions dynamic through time (e.g. Poesen and Torri 2014; Torri et al., 2018b). Likewise, combining a pixel-based CN approach with flow-routing algorithms makes it possible to account for the effect of spatial patterns of topography, soil conditions and land cover (Rossi et al., 2015a). An attractive element of the CN approach is that its simple nature enables its application at regional to global scales (e.g. Hong et al., 2007). Nonetheless, this also involves uncertainties and the risk of over-extrapolation as the CN approach remains an empirical model that was developed and tested for a relatively limited set of environmental conditions. Furthermore, such approach does not yet account for all relevant mechanisms and possible interactions with other erosion processes. For example, also the amount of sediments transported by the runoff from upslope areas will determine whether incision or aggradation will take place (e.g. Poesen et al., 2003).

Also several landscape evolution models are to some extent capable of simulating gully initiation, using a process-based approach (e.g. Tucker et al., 2001; Kirkby et al., 2003; Willgoose, 2005, 2018; Harmon et al., 2019). These typically define the threshold in terms of equilibrium between local sediment load or entrainment and sediment transport capacity; often conceptualized in terms of shear stress or stream power per unit flow width. Nevertheless, some empiricism remains. This mainly relates to the definition of critical flow shear stress and the long-term effects of temporal variations in environmental conditions.

Overall, process-oriented approaches offer significant promise to predict gully initiation as they aim to account for the actual driving processes in a conceptually transparent way. This can make them highly suitable for the evaluation of gully erosion risks in the context of climate or land use changes (e.g. Hancock et al., 2000; Sidorchuk et al., 2001; Sidorchuk et al., 2003; Rossi et al., 2015a). Furthermore, these models may generally allow for a more straightforward and correct coupling between gully initiation and expansion (cf. section 4.2). Several process-oriented gully erosion models already account for both components, and perform acceptably over study sites with reasonably uniform properties (e.g. Willgoose, 2005; Hancock et al., 2015). Nonetheless, the application of most of these models remains limited to theoretical considerations or small study areas (e.g. Rossi et al., 2015a). In many cases, these models also remain poorly validated (Poesen et al., 2011). A major reason for this is the relatively large data requirements (e.g. Kirkby et al., 2003; de Vente et al., 2013). This includes detailed information on the controlling factors, but also observations on gully initiation (e.g. knowing which gully head was initiated and when exactly for a sufficiently long observation period). For the former, the availability of new GIS data layers and products opens promising perspectives (cf. section 5). Nonetheless, the latter remains a critical point for applications at regional to continental scales (cf. sections 2 & 3). As with most geomorphic models, also error propagation is a critical concern. Accurate process descriptions of gully initiation typically require more input data. Errors and uncertainties on these input data can easily become more important than errors and uncertainties resulting from an inaccurate process description (e.g. Van Rompaey et al., 2002).

Empirical approaches to simulate gully occurrence and densities can offer a major advantage in this regard: they typically result in more robust predictions and are often less demanding in terms of data requirements (e.g. de Vente et al., 2013). Overall, a wide range of empirical approaches exist. To some extent, they can be classified in bivariate methods, multivariate methods, and machine learning approaches. An (non-exhaustive) overview of example studies is given in **Table 2**. Most of these procedures aim to predict the presence or absence of a gully on a given location. Their successful application results in a gully erosion susceptibility map (GESM), from which proxies of gully density can be derived. However, some approaches try to directly predict the gully density within a catchment (Zhao et al., 2016) or pixel (Kheir et al., 2007; Vanmaercke et al., 2020).

Bivariate statistical approaches (e.g. Conforti et al., 2011; Conoscenti et al., 2013) can be robust but reduce gully prediction to only one causal factor, typically leading to imprecise predictions. Except in simple situations or very data-poor regions, these approaches are therefore generally inferior to the other methods. Multivariate methods (e.g. Akgün and Türk, 2011; Lucà et al., 2011) analyse gully occurrence as a function of different causal factors and to some extent allow determining the relative contribution of each factor. Logistic regression (e.g. Vanwalleghem et al., 2008; Conoscenti et al., 2014; Dewitte et al., 2015) is the most commonly used multivariate approach. Its computational simplicity and ability to deal with both continuous and categorical explanatory variables are important advantages. However, its ability to fully disentangle the potentially non-linear role of different factors and their interactions remains limited. In this regard, machine learning methods offer great potential and have been increasingly used over recent years (**Table 2**). Especially techniques like random forests (e.g. Gayen et al., 2019; Rahmati et al., 2017; Hosseinalizadeh et al., 2019) can, at least in principle, better account for the fact that the role of explanatory variables may vary between different subpopulations of gullies and over different scales. They can also be used to spatially assess uncertainties on model outputs, thus guiding interpretation and targeting further data collection (e.g. Kuhnert et al., 2010; Vanmaercke et al., 2020).

Given their typically smaller data requirements as compared to process-oriented models, empirical approaches could be suitable to predict gully occurrence at regional to continental scales (e.g. Hughes & Prosser, 2012; de Vente et al., 2013). However, most empirical modelling studies focus on relatively small study areas (**Table 2**). Jurchescu and Grecu (2015) compared gully prediction performances with regression trees at different spatial scales. They report that predictions at the regional scale are affected by larger uncertainties as compared to predictions for smaller areas. A main limitation lies in the need for gully inventories at regional to continental scales in order to calibrate and validate such models. As discussed in sections 2 and 3, such inventories remain scarce as they are labour-intensive to compile. Another important constraint of such empirical models is that they generally remain 'black box' approaches. While they can provide some insight into the dominant factors controlling gully occurrence, the underlying mechanisms and interactions are generally less clear (e.g. Zhao et al., 2016). This may limit the potential of such empirical approaches for scenario analyses, especially in the case of machine learning techniques.

Models aiming to predict gully initiation and densities at regional to continental scales in the context of future climate or land use changes should therefore seek to strike a balance between a relevant and conceptually sound process description and feasible calculation and input requirements. Several studies already apply a hybrid approach between empirical and process-based gully occurrence prediction. For example, Dewitte et al. (2015) implemented a two-step procedure. First, potentially gully-prone areas were delineated based on the slope-area threshold concept. Next, logistic regression was used for a more detailed prediction of gully locations within those areas. Recent conceptual advancements that replace the slope-area threshold concept with more detailed description of expected runoff discharges (e.g. based on the CN-model approach; see above), also offer promising perspectives in this regard.

Table 2: Examples of empirical gully occurrence and gully density models

Method	**Sub method**[a]	**Authors**	**Scale (km^2)**	**location**
Bivariate statistical	Conditional analysis	Conoscenti et al., 2013	250	Italy
	Index of entropy	Zabihi et al., 2018; Arabameri et al., 2018b	15.44 - 416	Iran
	Information value	Lucà et al., 2011; Conforti et al., 2011; Al-Abadi and Al-Ali, 2018	26,74 - 30	Iran, Italy
	EBF	Al-Abadi and Al-Ali, 2018	26,74	Iran
	Frequency ratio	Al-Abadi and Al-Ali, 2018; Rahmati et al., 2016; Zabihi et al., 2018; Arabameri et al., 2018b	15,44 – 2.595	Iran
	Weights of evidence	Rahmati et al., 2016; Arabameri et al., 2018b; Zabihi et al., 2018	15,44 – 2.595	Iran
Multivariate statistical	Logistic regression	Akgün and Türk, 2011; Lucà et al., 2011; Conoscenti et al., 2014; Maerker et al., 2020	9,5 - 424	Italy, Turkey
Machine learning	AHP	Arabameri et al., 2018b	416	Iran
	ANN	Pourghasemi et al., 2017	2595	Iran
	BRT	Maerker et al., 2011, 2020; Angileri et al., 2016; Rahmati et al., 2017; Arabameri et al., 2018a	245 - 848	Iran
	CRT	Kheir et al., 2007; Geissen et al., 2007; Gomez-Gutiérrez et al., 2009b; Märker et al., 2011	26,4 - 3500	Spain, Turkey, Mexico, Italy
	FDA	Gayen et al., 2019	709	India
	MARS	Gomez-Gutiérrez et al., 2009b; Gomez-Gutiérrez et al., 2009c; Gómez-Gutiérrez et al., 2015; Arabameri et al., 2018a; Gayen et al., 2019; ; Conoscenti et al., 2018; Conoscenti et al., 2020	9,5 - 848	India, Spain, Iran, Italy
	Maximum entropy	Zakerinejad & Maerker 2014; Pourghasemi et al., 2017; Maerker et al., 2020	2595	Iran, Italy
	Random forest	Kuhnert et al., 2010; Rahmati et al., 2017; Arabameri et al., 2018a; Gayen et al., 2019; Bui et al., subm.; Vanmaercke et al., 2020	245 - 848	India, Iran, Australia, Horn of Africa
	SVM	Rahmati et al., 2017; Pourghasemi et al., 2017; Gayen et al., 2019;	245 – 2.595	India, Iran

[a] EBF: Evidence belief function; AHP: Analytical hierarchy process; ANN: Artificial neural network; BRT: Boosted regression tree; CRT: Classification and regression tree; FDA: Flexible discriminant analysis; MARS: Multivariate adaptative regression spline; SVM: Support vector machine

4.2. Predicting gully expansion

Total gully erosion rates over an area not only depend on the occurrence of gullies (cf. section 4.1), but also on their expansion rates. Actively eroding gullies generally produce sediment through headcut retreat and channel widening/deepening (e.g. Martinez-Casanovas et al., 2004; Marzolff & Poesen, 2009; Vanmaercke et al., 2016; Hayas et al. 2017a). In some contexts, piping can also contribute significantly to gully expansion (e.g. Valentin et al., 2005; Bernatek-Jakiel and Poesen, 2018).

Table 3 shows a (non-exhaustive) overview of models that have been developed to predict gully expansion. Gully headcut retreat is generally the best-studied expansion process and several process-oriented models have been developed to simulate this. Examples include CHILD for permanent gullies (Flores-Cervantes et al., 2006) or the module TIEGEM within AnnAGNPS for ephemeral gullies (Gordon et al., 2007). Both are based on a model simulating the hydraulics at the gully head by Alonso et al. (2002). While field validation of its predecessor, EGEM (Woodward et al., 1999), revealed important flaws, TIEGEM tends to show better model performances. Nonetheless, testing currently remains limited. Also evaluations of CHILD showed that it is capable of reproducing observed retreat rates relatively well, at least in some contexts (e.g. Campo-Bescós et al., 2013). However, its application requires several parameters that generally need to be obtained in the field (including the height of the headcut, the shape of the plunge pool and soil erodibility). This greatly limits its use at larger scales. This problem is not specific to the CHILD model, but affects most process-based gully headcut retreat models (e.g. Poesen et al., 2011). Another important limitation are the often high data requirements needed to accurately predict peak runoff discharges and flow velocities at the gully head. This is a common challenge for ungauged basins (Blöschl, 2006). More simplified approaches that predict headcut retreat based on (hydrological) model routines that require fewer and feasible parameters therefore show greater promise at larger scales but require further development and field validation (e.g. Dabney et al., 2015; Allen et al., 2018).

As with gully occurrence (cf. section 4.1), empirical models based on statistical correlations between observed headcut rates and environmental variables may offer an alternative (**Table 3**). Several studies proposed empirical equations predicting gully headcut retreat rates for specific study sites (e.g. Vandekerckhove et al., 2003; Marzolff et al., 2011; Poesen et al., 2011; Frankl et al., 2012; Li et al., 2015). These models differ strongly in terms of incorporated factors. However, a meta-analysis of >700 measured volumetric headcut retreat rates worldwide showed that the upslope contributing area (A) of the gully headcut and the rainfall intensity (expressed as the rainy day normal, i.e. the average annual rainfall depth divided by the average number of rainy days) are key factors (Vanmaercke et al., 2016). Combined, these two variables explained nearly 70% of the observed global variation in headcut retreat rates. As such, this opens promising perspectives to predict gully headcut retreat at regional to continental scales. Nonetheless, several important challenges remain. For example, applying this model to local or regional contexts can result in significant uncertainties. More accurate predictions will likely require the incorporation of land use and other controlling factors (Vanmaercke et al., 2016). Furthermore, its application requires knowing *A* and, by extent, the position of each headcut. Therefore, successfully predicting gully erosion rates at regional to continental scales will likely need the coupling of a headcut retreat model component to a module that simulates where these headcuts occur. Hybrid approaches that combine a simple hydrological model with empirical components are promising in this regard (cf. section 4.1).

Relatively fewer studies focussed on gully widening and deepening. Nonetheless, also they can contribute significantly to gully expansion (e.g. Martinez-Casasnovas and Poesen 2004; Hayas et al., 2017a). Some process-oriented models for gully-widening and deepening have been proposed (e.g. Sidorchuk 1999, Sidorchuk et al. 2003; **Table 3**). However, as with gully initiation (cf. section 4.1) and headcut retreat, their application at regional or continental scales is severely impeded by high data requirements. For example, Istanbulluoglu et al. (2005) present a model to predict gully widening by slab failures, but this requires knowing the slab geometry beforehand. Nevertheless, more simplified approaches applicable at larger scales are likely possible. For example, Crouch (1987) indicated the potential of gully sidewall to assess relative differences in erosion rates. Martinez-Casasnovas et al. (2004) successfully used logistic regression to predict gully wall failures in the Penedes region (Spain). Likewise, based on the analyses of gully widening rates in SW Spain, Hayas et al. (2019) developed a simple empirical model that relates gully widening to the upslope contributing area (A) and daily rainfall depth thresholds. This model shows strong similarities with the above-discussed global empirical model for gully headcut retreat rates (Vanmaercke et al., 2016). This suggests that developing relatively simple, integrated models of gully expansion should be possible. However, more research on the factors controlling gully widening and deepening across contrasting environments, as well as their associated time scales, is needed (e.g. Graf, 1977).

Also piping may contribute significantly to gully initiation and expansion, but no model currently exists that can predict the location and rate of this process, nor its contribution to gully erosion (Bernatek-Jakiel and Poesen, 2018). Furthermore, there is a large need for tools and models that can evaluate and predict how gully expansion rates will evolve in response to gully remediation and, by extent, assess the optimal spacing and dimensioning of such measures. This topic has received relatively little research attention (Bartley et al., 2020; Frankl et al., 2021). For example, some studies provide conceptual (e.g. Castillo et al., 2014b) or empirical (e.g. Pederson et al., 2006) strategies to determine the spacing of check dams. However, their applicability at regional to continental scales largely remains to be developed.

Table 3: Overview of process-oriented and empirical gully expansion models.

Type	Model name	References	Gully type[a]	Process modelled[b]	Main input parameters[c]	Field observations[d]
Process-Oriented	DIMGUL, STABGUL	Sidorchuk (1999); Sidorchuk et al. (2003)	PG	GHL, GW, GD	Ac, S, Q, K	Russia (n=1), Australia (n=1), Swaziland (n=1)
	EGEM	Nachtergaele et al. (2001a,b); Capra et al. (2005); Tekwa et al. (2015)	EG	GHL[f]	Aa, Ac, Pe, K, D	Belgium (n=116); Spain & Portugal (n=86); Italy (n=92); Nigeria (n=12)
	AnnAGNPS-TIEGEM[e]	Gordon et al. (2007)	EG	GHL[f]	Ac, M, Q, K, D	US (n=4)
	CHILD[e]	Flores-Cervantes et al. (2006); Campo-Bescós et al. (2013)	PG	GHL	Ac, M, Q, K, D	no; Spain (n=1)
	CHILD	Istanbulluoglu et al. (2005)	PG	GW	Aa, Ac, Pe, M, K, D	no
	-	Rengers and Tucker (2014)	PG	GHL	Aa, Ac, Pe, M, K, D	no
	LANDPLANER	Rossi (2014); Rossi et al. (2015a); Rossi et al. (2015b)	PG	GH, GA	Aa, Ac, S, Pe, Q, M	Italy
	EphGEE	Vieira et al. (2015); Dabney et al. (2015)	EG	GHL	Q, K	US (n=NA)
	SWAT-DEG	Allen et al. (2018)	EG	GHL[f]	Ac,Q, K, D	US (n=3)
Empirical	regression	Vanmaercke et al. (2016)	PG, EG	GHV	Aa, Pa	global (n=724)
	regression	Li et al. (2015)	PG	GA	Aa, Ac, S	China (n=30)
	regression	Frankl et al. (2012)	PG	GHV	Aa	Ehtiopia (n=18)
	regression	Marzolff et al. (2011)	PG	GHV	Aa, Pe	Spain (n=9)
	regression	Vandekerkhove et al. (2001, 2003)	PG	GHV	Aa	Spain (n=46, n = 12)
	regression	Burkard and Kostaschuk (1997)	PG	GA	Aa	Canada (n=44)
	regression	Radoane et al. (1995)	PG	GHL	Aa, Ac, Gl	Romania
	regression	Stocking (1980, 1981)	PG	GHV	Aa, D	US (n=66)
	regression	US SCS (1966)	PG	GHL	Aa, Pe	US (n=210)
	regression	Seginer (1966)	PG	GHL	Aa	Israel
	regression	Thompson (1964)	PG	GHL	Aa, S, Pe, K	US

[a] PG: permanent gully, EG: ephemeral gully.

[b] GHL: linear gully headcut retreat, GHV: volumetric gully headcut retreat, GW, gully widening, GD: gully deepening, GA = gully area.

[c] Aa: catchment area, Ac: catchment characteristics (slope, length, CN, etc.), S: local slope at gully head, Pa: average rainfall data, Pe: event rainfall data, M: gully headcut morphology, Q: flow discharge, K: soil data (e.g. critical shear stress, soil cohesion,…), D: (maximum) gully depth, Gl: gully length.

[d] for process-oriented models n refers to the gully validation years (i.e. number of gullies times the period over which they were evaluated); for empirical models n refers to the number of data points used for establishing the regression equation.

[e] based on Alonso et al. (2002) hydraulic "plunge-pool" model.

[f] the model simulates gully headcut retreat, however gully widening and deepening are estimated through empirical formula based on flow discharge.

4.3. Predicting the contribution of gullies to catchment sediment yield

Several studies already attempted to account for the contribution of gully erosion to catchment sediment yields (SY) via an empirical approach. These studies mostly rely on directly correlating observed SY to proxies of average gully densities (e.g. Zhao et al., 2016) or, alternatively, a semi-quantitative score describing the overall presence of gullies in the catchment in combination with other factors (e.g. de Vente et al., 2005; 2006; Haregeweyn et al., 2005). These approaches generally result in good model performances, while their relatively low data requirements make it feasible to apply them at larger scale. However, they also come with limitations. First, these are spatially lumped models that do not account for spatial patterns of gully densities. Second, they often depend on expert-based judgments of the presence and importance of gullies (e.g. de Vente et al., 2005; 2006) and therefore may not always be perfectly reproducible and objective. Third, factors controlling gully formation typically also control other erosion processes and sediment yields (e.g. steeper topography, erodible soils, limited vegetation cover; Syvitski and Milliman, 2007; Pelletier, 2012; Vanmaercke et al., 2014). Hence, it is often hard to tell to what extent observed correlations between proxies of gully density and SY are indeed attributable to the gullies or to inter-correlations with other factors. On the other hand, factors known to drive gully erosion (e.g. rainfall intensity; Vanmaercke et al., 2016; Hayas et al., 2017b) are not always incorporated in these models because they did not reveal a statistically significant correlation (e.g. de Vente et al., 2005; Zhao et al., 2016). These limitations make such empirical approaches often unsuitable for land or climate change scenario analyses or for developing detailed catchment management strategies (de Vente et al., 2013). Nevertheless, such models may be useful for predicting SY at regional to continental scales.

To address these shortcomings, several studies aimed to model the contribution of gully erosion in a more spatially explicit and process-oriented way. Some studies have adapted sediment yield models like SWAT or WATEM-SEDEM. They generally predict SY by estimating sheet and rill erosion rates and then accounting for sediment deposition between the hillslopes and river system (e.g. Van Rompaey et al., 2001; Vigiak et al., 2017). By changing some of the model assumptions or parameters, these models may partially account for gully erosion (e.g. Verstraeten et al., 2007; Easton et al., 2010). Nonetheless, such approaches remain difficult to parameterize and validate and are conceptually problematic, especially in the case of permanent gullies (e.g. de Vente et al., 2013).

Other studies have attempted to directly account for gully erosion by incorporating spatially explicit estimates of gully-prone areas in combination with other factors describing erosion and sediment transfers (e.g. de Vente et al., 2008; Haregeweyn et al., 2017). Identifying gully-prone areas is typically based on the slope-area threshold concept (cf. section 4.1; Eq. 1), while their contribution to SY is either based on an empirical estimate of typical gully erosion rates (Haregeweyn et al., 2017) or through model calibration with observed SY (de Vente et al., 2008). Apart from being spatially explicit, this may also avoid the problem of reproducibility mentioned above. Nonetheless, these approaches remain relatively rudimentary and scarcely applied. Wilkinson et al. (2009; 2014) developed a more elaborate strategy where detailed maps of existing gullies underpin estimates of the contribution of gully erosion to the sediment budget, based on the volumetric expansion rates of gullies over time. This approach incorporates ancillary information on the relative development stage of the gully networks and the fraction of soil textures likely to contribute to suspended sediment loads. However, the requirement for gully mapping limits easy applications at larger scales. One of the most complete models to date that allows accounting for the effect of gully erosion on SY is AnnGNPS (Momm et al., 2012). It can identify gully mouth locations semi-automatically with the APET tool. This could allow calculating the spatial contribution of gully erosion to SY and evaluating the effect of gully conservation measures at catchment scale. Nevertheless, its applicability over larger areas remains currently unknown.

An additional challenge lies in the fact that gullies not only directly influence SY by contributing sediments, but also indirectly by altering the runoff and sediment connectivity between hillslopes and river systems (e.g. Poesen et al., 2003; Martineli Costa et al., 2007; de Vente et al., 2008). They can significantly increase sediment connectivity (e.g. Ionita et al., 2015a) but also temporally store sediments (e.g. Taylor et al., 2018). Especially vegetated gullies can function as significant runoff and sediment traps (e.g. Zierholz et al., 2001; Rey et al., 2007; Molina et al., 2009). The same holds for check dams built in gullies (e.g. Castillo et al., 2007; Frankl et al., 2013; Guyassa et al., 2017). In addition, high gully densities may lead to more direct rainfall-runoff responses (e.g. Martineli Costa et al., 2007) and therefore potentially higher floodplain deposition rates, as riverbank overtopping may occur more frequently. While different modelling approaches for sediment connectivity already exist (e.g. Borselli et al., 2008, Vigiak et al., 2012), their suitability to deal with sediment transfers by gullies remains largely untested. Their application would also require information on the spatial extent of gully networks as well as on their vegetation cover and the presence of check dams or similar measures. As such, assessing both the direct and indirect contribution of gullies to catchment SY at large scales remains very difficult, in particular because the necessary data (e.g. inventories of gullies and gully control measures) remain mostly unavailable.

5. Model input data at the continental scale

Modelling gully erosion not only requires observations on gully occurrence and dynamics (cf. sections 2 and 3). It also requires input data on the environmental factors controlling gully erosion, more specifically the (i) topography, (ii) vegetation cover, (iii) land cover, use and management, (iv) soils and lithology and (v) climate and weather conditions. The availability and quality of input data condition the type of model that can be used (cf. section 4). Input data for small study areas can be acquired with field-based methods. Gully erosion modelling at regional to continental scale generally needs to rely on Earth Observation (EO) data. The spatial resolutions, revisiting times and level of detail of such EO data have significantly increased over the past decades (e.g. Belward and Skoien, 2015). Continental to global EO-derived datasets are also made increasingly publically available. Furthermore, an increasing number of cloud-based data processing platforms are developed in order to deal with the associated increasing demands for data storage and processing power. These include the Copernicus Data and Information Access Services (DIAS) launched by the European Commission in 2018 and the Google Earth Engine platform.

While datasets at the national level often provide higher resolutions and levels of detail, continental to global datasets have the great advantage of providing harmonized information. The use of national datasets for regional to global scale modelling is often hampered by their fragmentary availability, varying data acquisition and treatment methods and possibly limited data access (e.g. Höfle & Rutzinger, 2011; Lohani et al., 2018). Such lack of harmonization can introduce additional important uncertainties.

Hence, this review section aims to provide an overview of currently available harmonized (and ideally free) datasets that can be used for gully erosion modelling at regional to continental scales. We focus on data products that are available at a European or global scale. Based on our understanding of the factors controlling gully erosion and expansion, we discuss datasets describing the (1) topography, (2) vegetation cover, (3) land cover, use and management, (4) soil properties and lithology, and (5) climate. The datasets presented and discussed below were selected based on their relevance, up-to-datedness, accuracy, length of observation periods and frequency of updates. It is expected that with the increasing availability of EO data, additional datasets will become available in the near future.

5.1. Topography

Topographic variables play a key role in the prediction of both gully initiation and expansion. The most relevant factors are the local slope steepness and the topographic area draining to a specific point in the landscape (cf. sections 4.1, 4.2). Such information can be derived from digital elevation models (DEMs). Remotely-sensed DEMs for areas of limited spatial extent have been obtained from stereoscopic aerial image analysis or airborne LiDAR for decades. Numerous countries nowadays produce national DEMs based on airborne LiDAR surveys down to submeter pixel size (e.g. Lohani et al., 2018). Here we focus on DEMs having a (nearly) global or European coverage (**Table 4**).

Among the first near-global DEM datasets derived from spaceborne observations were the SRTM-C DEM (first released in 2003; Rabus et al., 2003), the ASTER GDEM (released 2009) and the improved ASTER GDEM2 (released 2011; Tachikawa et al. 2011) and ASTER GDEM3 (released 2019). While SRTM-C and the more recent TanDEM-X DEM (Krieger et al., 2007) are based on interferometric Synthetic Aperture Radar (SAR) image analysis, ASTER GDEMs and the ALOS DEMs (Tadono et al., 2014; Takaku et al., 2014) are derived from stereoscopic analysis of optical satellite images. All these global DEMs can be considered as Digital Surface Models (DSMs), i.e. the elevation values reflect the Earth's surface including objects such as vegetation and buildings. Furthermore, most of these global DEMs are based on observations collected over longer time periods. Only the SRTM data collection was conducted over only eleven days (in February 2000) and thus reflects the surface elevation at a fairly specific moment (Rabus et al., 2003).

As the data source documentation and various comparison studies indicate (see e.g. review by Alganci et al., 2018), the vertical accuracies of these DEMs strongly depend on the terrain characteristics. Among the publically available global DEMs with finer spatial-resolution (≤30m grid spacing), Purinton & Bookhagen (2017) found that STRM-C, ALOS World 3D and TanDEM-X provide the highest vertical accuracies (below 3.5m). This estimate was based on a large number of GPS reference measurements across a wide range of terrain types and elevations. Apart from freely available datasets, some commercial global DEMs have also been recently released (e.g. TanDEM-X, ALOS World 3D; **Table 4**). These generally have higher spatial resolutions. Based on the same GPS reference dataset, vertical accuracies of both datasets were assessed to be below 2m (Purinton & Bookhagen, 2017). Several authors have also assessed the suitability of these global DEMs for geomorphological and hydrological analyses in different landscapes (see e.g. Purinton and Bookhagen, 2017; Boulten & Stokes, 2018; Mondal et al., 2017).

Despite their lower spatial resolution and accuracies as compared to airborne LiDAR DEMS, these global satellite-derived DEMs (**Table 4**) remain the only consistent, harmonized datasets at regional to continental scales in almost all regions of the world. Among them, the TanDEM-X and the ALOS World 3D (AW3D5) are the best available products. However, their high cost and the computing resources required to use them may pose limitations to continental or global modelling efforts.

Table 4: Overview of global and European Digital Elevation Models and their key characteristics

Dataset/ product	Spatial extent	Satellite data acquisition period	Satellite sensor, type of DEM generation	Pixel spacing	Source	Data download	Reference
SRTM-C	global (60°N to 56°S)	11-22 February 2000	SRTM, single-pass C-band interferometry	30 m	NASA, public	https://earthexplorer.usgs.gov/	Rabus et al. (2003)
ASTER GDEM	global (83°N to 83°S)	2000 to 2010	ASTER, stereo-correlation of optical images	30 m	METI and NASA, public	https://asterweb.jpl.nasa.gov/gdem.asp	Tachikawa et al. (2011)
ALOS World 3D (AW3D5 and AW3D30)	global (82°N to 82°S, void-filled within 60°N to 60°S)	2006 to 2011	ALOS PRISM, stereo-correlation of optical images	5 m and 30 m	JAXA, 5 m product commercial, 30 m product public	AW3D30 (login required): http://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm	Tadono et al. (2014); Takaku et al. (2014)
EU-DEM	Europe	2000 to 2010	Hybrid product based on SRTM and ASTER GDEM data	25 m	European Environment Agency (EEA) under the framework of the Copernicus programme, public	https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem	Gonzalez (2015)
TanDEM-X DEM	global (pole-to-pole)	2010 to 2015	TanDEM-X, bistatic X-band interferometric SAR	12 m and 30 m	12 m commercial product available from Airbus Defence and Space as WorldDEM™; 12/30 m products available by research agreement from DLR	http://www.intelligence-airbusds.com/elevation-models/#worldem; products available by research agreement from DLR: https://tandemx-science.dlr.de/	Krieger et al. (2007)

5.2. Vegetation cover

Also vegetation is generally considered as a key controlling factor of gully erosion and its impacts on SY (cf. section 4). Overall, a negative relation between vegetation cover and gully density/erosion can be expected as (i) plant material at the surface can slow down flow velocities and reduce runoff shear stresses; (ii) below-ground biomass (in particular plant roots) can increase the soil cohesion; and (iii) vegetation can affect the soil structure and soil hydrological balance, leading to lower runoff production rates (e.g. Gyssels & Poesen, 2003; Knapen et al., 2007; Vannoppen et al., 2015).

Various indices exist to map patterns of vegetation cover from satellite imagery and several publically available, ready-to-use, datasets exist (**Table 5**). The most commonly used proxy for vegetation cover is the Normalized Difference Vegetation Index (NDVI). Various studies successfully used NDVI as a predictor for gully densities (e.g. Zhao et al., 2016; Vanmaercke et al., 2020). Nonetheless, also other indices may be useful for gully erosion modelling, e.g. the Soil-Adjusted Vegetation Index (SAVI) and the Modified SAVI. Bennari et al. (1995) and Barati et al. (2011) provide reviews of these different indices. While such indices provide proxies for plant biomass and productivity, biophysical variables like the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (FAPAR) and the fraction of green vegetation cover (Fcover or FVC) provide more physically-based descriptions of the vegetation cover. The latter is particularly relevant in the context of soil erosion susceptibility (Panagos et al., 2015; Borrelli et al., 2017b). It corresponds to the fraction of green vegetation, covering the ground as seen from the nadir direction. Similarly, Vegetation Continuous Fields (VCF) provides estimates of vegetation cover as the percentage of tree cover, percentage of non-tree vegetation, and percentage of non-vegetated area (e.g. Sexton et al., 2013). An important limitation of these EO-derived indices is that they only relate to the above-ground vegetation. Currently, information on below-ground biomass can only be indirectly estimated (e.g. based on above-ground vegetation characteristics, in-situ data and expert knowledge). Nevertheless, important progress has recently been made in this regard. For example, based on empirical modelling, Fan et al. (2017) provide estimates of maximum rooting depth at a global scale.

Table 5 lists a selection of publically available global NDVI and FCover datasets. They were selected because they are free, have a high spatial resolution (1 km or finer), are based on a sufficiently long observation period (at least several years) and can be considered representative for the current vegetation cover (i.e. their observation period includes recent years). Several of these datasets are regularly updated. Most of these selected datasets are derived from the analysis of MODIS, Proba-V, Spot Vegetation, and Landsat satellite imagery. They provide temporal coverages ranging from 8-day composites to annual composites. However, some of these series (especially monthly and sub-monthly Landsat composites) contain gaps due to cloud or snow cover. Datasets based on Landsat imagery currently provide the highest spatial detail, with 30 m grid spacing for continental to global products.

Table 5: Selection of global vegetation cover datasets (focusing on NDVI and FCover)

Dataset/ product	**Spatial extent**	**Sensor**	**Satellite data acquisition period**	**Spatial resolution**	**Temporal resolution**	**Source**	**Data download**	**Reference**
Fcover Copernicus Land Monitoring	global, 75°N to 60°S	Proba V, SPOT-VGT/ PROBA V	01/2014 to present, 1999 to present	300 m, 1 km	10 days composite	ESA, public	http://land.copernicus.eu/global/products/fcover	Smets et al. (2017); Smets et al. (2018)
MODV1 FCover	global	MODIS	2000-2016	1 km	monthly composite	ISPRA, public	Available upon request from the author	Filipponi et al. (2018)
MOD44B Vegetation Continuous Fields	global	MODIS	2000 to present	250 m	annual composite	NASA, public	https://lpdaac.usgs.gov/products/mod44bv006/	Dimiceli et al. (2015)
MOD13Q1 NDVI	global	MODIS	2000 to present	250 m	16-day composite	NASA, public	https://lpdaac.usgs.gov/products/mod13q1v006/	Didan (2015)
Copernicus Land Monitoring NDVI	global	PROBA-V, SPOT-VGT/PROBA-V	02/2016 to present, 04/1998 to present	300 m, 1 km	10 days composite	ESA, public	http://land.copernicus.eu/global/products/ndvi	Smets et al. (2016); Smets et al. (2018)
GEE NDVI	global	Landsat	1984 to present	30 m	8-day composite, 32-day composite, annual composite	USGS/ Google Earth Engine, public	https://earthengine.google.com/datasets/	Gorelick et al. (2017)
WELD NDVI	global	Landsat	1984-2001	30 m	monthly composite, annual composite	USGS/ WELD, public	https://lpdaac.usgs.gov/products/gweldmov031/ https://lpdaac.usgs.gov/products/gweldyrv031/	Roy et al. (2010)

5.3. Land cover, use and management

While vegetation cover refers to the quantity of above-ground biomass (see section 5.2), land use and land cover (LULC) datasets classify the land surface in categories describing how the land is used. Many of the currently existing modelling tools (e.g. CN-based approaches, cf. section 4) rely on LULC classes, rather than indices of vegetation cover. As such, LULC dataset can be an important asset for gully erosion modelling. Furthermore land cover, use and management encompass several other relevant elements that are not necessarily reflected by vegetation indexes. Examples include the shapes and sizes of parcels, parcel boundary characteristics, cropping cycles and tillage practices (e.g. Poesen et al., 2003; Valentin et al., 2005; Piccarreta et al., 2012). Also soil conservation measures often have a significant impact on runoff and sediment production (e.g. Maetens et al. 2012a, b). The effects of erosion-preventing or -reducing measures on gully erosion rates and sediment production can be large (for detailed reviews, see Bartley et al., 2020 and Frankl et al. 2021).

Several studies (e.g. Tsendbazar et al., 2015; Grekousis et al., 2015) provide comprehensive comparisons of available regional to global LULC datasets regarding their spatial and temporal resolution, accuracy and thematic coverage. Overall, the opening of the Landsat satellite image archive in 2008 and the launch of the Sentinel-2 satellites at 10 to 20 m spatial resolution in 2015 and 2017 lay the foundations for a new generation of high resolution global land cover products. The GlobeLand30 dataset was the first open-access global land cover map at 30 m spatial resolution (Chen et al., 2017). It comprises ten types of land cover for the years 2000 and 2010, extracted from more than 20,000 Landsat and HJ-1 satellite images.

Table 6 lists a selection of global and European LULC datasets. Similar to **Table 5**, datasets in this selection are freely available, based on sufficiently long observation periods, relatively recent and/or regularly updated. Overall accuracies of these products vary between 64 and 80% (Grekousis et al., 2015). Of this selection, CORINE Land Cover provides the longest temporal coverage (1990, 2000, 2006, 2012, 2018) and highest classification detail (44 land cover classes) at pan-European scale (Büttner et al., 2014). The S2GLC product based on the analysis of Sentinel-2 imagery currently provides the finest spatial detail at pan-European scale with a pixel size of 10 m. It distinguishes 13 land cover classes with an overall accuracy of 83% (Lewiński et al., 2019).

At global scale, the land cover product recently released by the Copernicus Global Land Service currently overall provides the highest level of detail. Besides a discrete classification with 22 land cover classes, this product contains fraction cover layers for ten base land cover classes (Buchhorn et al., 2019). It is worth mentioning, that the generation of a global land cover product by the ESA WorldCover initiative is in progress, aiming at a 10 m global land cover map with a minimum of 10 land cover classes and a minimum overall accuracy of 75 % (to be released in 2021).

Yet detailed information on land management practices and the implementation of gully control or other soil and water conservation measures remains largely lacking at (sub)continental scales. We believe this is a highly important research gap. It not only impedes the accurate prediction of gully erosion, but also the evaluation of prevention and mitigation measures at larger scales. Nonetheless, for Europe, several datasets were developed over recent years that can help assessing these aspects. Examples include the Copernicus Pan-European dataset on Small Woody Features (EEA, 2015) and the EU-wide assessments of the Crop Management factor of the Universal Soil Loss Equation (EU JRC, 2015). Also estimates of the effect of support practices (i.e. the P-factor in the Universal Soil Loss Equation) have become available at the EU level, based on extensive field surveys (e.g. Panagos et al., 2015e). However, these estimates remain subject to important uncertainties and relate to sheet and rill erosion rather than to gully erosion.

Table 6: Selection of global and European Land Use/Land Cover datasets

Dataset/ product name	Spatial coverage	Temporal coverage	Sensor	Spatial resolution	Classification scheme / no of classes	Source	Data download	Reference/ report
MODIS Land Cover Type/ MCD12Q1	global	2001-2018 (annual)	MODIS	500 m	IGBP scheme, 17 classes	NASA, public	https://lpdaac.usgs.gov/products/mcd12c1v006/	Friedl et al. (2010)
GlobCover GlobCover2005 GlobCover2009	global	2004 - 2006 2009	MERIS	300 m	FAO LCCS 22 classes	ESA, public	http://due.esrin.esa.int/page_globcover.php	Bicheron et al. (2008); Bontemps et al. (2011)
GlobeLand30 2000 2010	global	2000 2010	Landsat, HJ-1	30 m	10 classes	UN/ National Geomatics Centre of China (NGCC), public	http://www.globallandcover.com	Chen et al. (2015); Chen et al. (2017)
FROM-GLC	global	2010, 2015	Landsat	30 m	9 classes	Tsinghua University, public	http://data.ess.tsinghua.edu.cn/	Gong et al. (2013)
CCI-LC 2000 2005 2010	global	1998-2002 2003-2007 2008-2012	MERIS, SPOT VGT	300 m	FAO LCCS 22 classes	ESA, public	http://maps.elie.ucl.ac.be/CCI/viewer/index.php	ESA (2017)
CORINE Land Cover (CLC) CLC1990 CLC2000 CLC2006 CLC2012 CLC2018	Europe	1986-1998 1999-2001 2005-2007 2011-2012 2017-2018	Landsat, SPOT, IRS, Rapid Eye, Sentinel-2	100 m and 250 m (rasterized vector product,minimum mapping unit/width 25 ha/ 100 m)	44 classes	European Environment Agency (EEA), public	https://land.copernicus.eu/pan-european/corine-land-cover	Büttner et al. (2014)
Land cover 100m	global	2015	PROBA-V	100 m	FAO LCCS 22 classes	ESA, public	https://land.copernicus.eu/global/products/lc	Buchhorn et al. (2019)
S2GLC	Europe	2017	Sentinel-2	10 m	13 classes	ESA, public	http://s2glc.cbk.waw.pl/	Lewiński et al. (2019)

5.4. Soil properties and lithology

The formation and expansion of gullies is commonly influenced by particular soil characteristics and behaviour. However, the role of soil properties in explaining patterns of gully erosion remains relatively poorly understood (e.g. Torri & Poesen, 2014; Vanmaercke et al., 2016; 2020). One reason for this is that soil properties affect both the hydrological functioning of soils but also their erosion resistance during concentrated flow shear stresses (e.g. Knapen et al. 2007; cf. section 4). These effects may counteract each other in ways that currently remain hard to quantify. For example, clayey soils often have high runoff coefficients but can also be very cohesive. Furthermore, accurately quantifying soil properties is generally labour-intensive and therefore remains a big challenge at larger scales. This also impedes our understanding of their influence on gully erosion.

Nonetheless, there are several soil properties that are known to potentially influence gully erosion and are therefore worthwhile considering. Most of these can affect both the erodibility and hydrological functioning of soils. The most relevant properties are likely soil texture characteristics (e.g. percentage of sand, silt and clay), soil organic carbon content, the content and cover of coarse fragments (e.g. Poesen et al. 1999; Torri et al., 1997; Rieke-Zapp et al. 2007; Panagos et al., 2014; Borrelli et al., subm.). Also the water holding capacity, soil depth, bulk density and underlying lithology (or parent material) can play an important role in determining the occurrence and dimensions of gullies (e.g. Kheir et al., 2008; Hopp & McDonnell, 2009). Likewise, the presence of faults and joints can influence gully occurrence, as they are often associated with higher degrees of weathering. Finally, gully occurrence and dynamics can be affected by the presence of specific soil horizons, dispersivity (e.g. sodic properties), susceptibility to soil piping, etc. (e.g. Rienks et al., 2000; Nachtergaele & Poesen, 2002; Bernatek-Jakiel & Poesen, 2018; Bernatek-Jakiel & Wrońska-Wałach, 2018). Many of these properties remain difficult to assess in detail at (sub)continental scales. Nevertheless, qualitative soil maps can be very helpful when aiming to account for such context-specific aspects.

Table 7 provides an overview of relevant databases at European and global scales. The European Soil Database provides 73 attributes at 1:1 million scale or as a raster format with a 1 km resolution (Panagos et al., 2012). The dataset is mostly qualitative and mainly based on national soil data and maps from the period 1960-1990. Potentially relevant attributes include: the dominant and secondary parent material, depth to bedrock, soil structure, soil crusting and water holding capacity. Furthermore, the European Commission amended the LUCAS (Land Use/Cover) surveys of 2009/2012, 2015 and 2018 by including a topsoil survey to collect around 20,000 soil samples from all EU countries (Orgiazzi et al., 2018). The resulting LUCAS topsoil database includes measured data for soil physical and chemical properties. Based on a geostatistical processing of these data, a number of soil property spatial datasets were developed at a 500m resolution. These include soil texture (sand, silt, clay), coarse fragment content and available water capacity (Ballabio et al., 2016). Also datasets on chemical properties (pH, CEC, P, N, K) were also made available at 500m resolution for the EU (Ballabio et al., 2019). Likewise, building on the LUCAS database, the EU Joint Research Centre (JRC) developed high resolution soil erodibility datasets (Borrelli et al., 2014; Panagos et al., 2014). The latter are based on physical soil properties, taking into account the impact of stone cover. Other suitable sources for pan-European studies may be the 1:5 million Geological Map of Europe, which includes various lithological and geological attributes (Asch, 2005), or the Geo-LiM geo-lithological map for Central Europe (Donnini et al., 2019).

At global scale, the most comprehensive soil property datasets are the Harmonised World Soil Database v 1.2 (FAO, 2012) and SoilGrids (Hengl et al., 2017). The first provides a 30 arc-second raster database with over 15,000 different soil mapping units. SoilGrids is a collection of soil properties and classes. It is based on an automated soil mapping procedure using global soil profile data and various (EO) covariates. A ten-fold cross-validation of SoilGrids at 250m resolution indicated that the automated algorithms explain 61% of the overall variation. However, this performance varies strongly depending on the property considered (e.g. 56% for coarse fragments, 83% for pH; Hengl et al., 2017). With respect to underlying lithology, the GLiM (Global Lithology Map) by Hartmann & Moosdorf (2012) is currently one of the most detailed globally consistent products.

Table 7: Selection of global and European soil and geological/lithological datasets

Dataset/ product name	Spatial extent	Data acquisition period	Spatial resolution	Source	Data download	Reference
Harmonized world soil database v1.2	global, continental, regional	1971-2012	30 arc seconds	FAO/ UNESCO, public	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	FAO (2012)
LUCAS 2009 Topsoil physical properties for Europe	Europe	2009	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-lucas-topsoil-data	Ballabio et al. (2016)
LUCAS 2009 Chemical properties	Europe	2009	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data	Ballabio et al. (2019)
SoilGrids	global	2013-2017	250-1000m	ISRIC, public	https://soilgrids.org/#!/?layer=ORCDRC_M_sl2_250m&vector=1	Ribeiro et al. (2015); Hegl et al. (2017)
European Soil Database	Europe (and Eurasia)	1960-1990	1km	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/european-soil-database-v2-raster-library-1kmx1km	Panagos et al. (2012)
Soil erodibility dataset	Europe	2014	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe	Panagos et al. (2014)
1: 5 million Geological Map of Europe (IGME 5000)	Europe and adjacent areas	1990-2000	1: 5million	BGR, national geological surveys, public	https://www.bgr.bund.de/EN/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/International/Europa/IGME5000/IGME_Project/IGME_Projectinfo.html	Asch (2005)
Geo-lithological map for Central Europe (Geo-LiM)	Central Europe	1990-2010	1:1 million	CNR IRPI, public	https://zenodo.org/record/3530257	Donnini et al. (2020)
Global Lithology Map	global	unknown	1: 3750 000 (average)	University of Hamburg, (partly) public	https://doi.pangaea.de/10.1594/PANGAEA.788537	Hartmann & Moosdorf (2012)

5.5. Climate and weather conditions

Climate and weather conditions, and especially rainfall, are key drivers of gully erosion (cf. section 4). Rainfall can have short (i.e. triggering) and long term (i.e. conditioning) effects. On the short term, rainfall intensities and amounts are generally key parameters, as they will determine the runoff volume and hence shear stress exerted by the water. Numerous studies have demonstrated significant correlations between rainfall intensity and gully head initiation (e.g. Hayas et al., 2017b), headcut retreat (e.g. Vanmaercke et al., 2016) and gully widening (e.g. Hayas et al., 2019). Conversely, characterizing the effect of rainfall over long periods is more complicate. For example, rainfall controls the soil moisture, which may further condition the runoff response but also the soil resistance against erosion (e.g. Capra et al., 2009). Furthermore, climate over longer timescales can have significant indirect effects, e.g. through its influence on vegetation development and soil mechanical properties (e.g. Dunne et al., 1991; Sanchis et al., 2008; Fan et al., 2017). Complex relations exist among these different effects, making it difficult to define rainfall-related variables that accurately account for all relevant mechanisms. In some contexts, also snowmelt may be a key driver of gully erosion (e.g. Ionita, 2006; Golosov et al., 2018). While snowmelt runoff can already be modelled and monitored to some extent, its effects on gully erosion remain relatively understudied, especially at (sub)continental scales (e.g. Maltsev & Yermolaev, 2019).

Hence, the type and spatio-temporal resolution of precipitation data required will vary depending on the study region, but also in function of the purpose. Modelling exercises at short time scales (e.g. daily, event-based) require data of similar temporal resolutions. When aiming to understand mean tendencies and spatial variations, coarser data are already useful. For example, long-term average proxies like the rainy day normal can already serve as a useful predictor for average trends (e.g. Vanmaercke et al., 2016; Hayas et al., 2017b).

Table 8 provides a selection of available global and European rainfall datasets, building on an earlier overview presented by Sun et al. (2018). These gridded datasets are based on a variety of methods. Several are derived from rain gauge data, using different regionalization methods (e.g. Rudolf et al., 2009; Schamm et al., 2014). The accuracy of such datasets can be expected to depend on the gauge network density which may be limited, especially in Global South countries (e.g. Schneider et al., 2014). Despite their generally shorter time series, RADAR-derived products can provide an important alternative (e.g. Ashouri et al., 2015). RADAR-based rainfall observation networks are implemented in many countries. They measure rainfall rates, based on the analysis of the echoes generated by the interaction between active microwave signals and rain drops (Sauvageot, 1994; Wexler & Atlas, 1963). RADAR rainfall estimates are indirect and represent measures of rainfall far from the surface, which may be a limitation. However, their high spatio-temporal level of detail (e.g. estimates every 10 minutes at a 5×5 km resolution) allows measuring local, short and intense rainfall events. Overall, data from regional RADAR networks (and in particular historical RADAR data series) remain scarcely accessible and underused. Other gridded rainfall products are derived from satellite observations. In general, they are based on algorithms that combine passive microwave and infrared measurements from geostationary and low earth orbit satellites. Despite their often limited spatio-temporal resolutions, their main advantages are their global coverage and their easy accessibility. Hence, they offer great potential for gully erosion modelling at larger scales, especially in countries where other rainfall data are scarce. Nonetheless, also these satellite products generally rely to some extent on gauging station observations and can be subject to uncertainties (e.g. Monsieur et al., 2018). Finally, several datasets have been produced through reanalysis, in which meteorological modelling results are combined with rainfall observations (Gelaro et al., 2017). These products have diverse spatial and temporal resolutions that cover extended periods (**Table 8**).

At European scale, another relevant proxy worth mentioning is the rainfall erosivity dataset, which was produced with 30-minutes precipitation data from 1675 stations in the EU (Panagos et al., 2015). While this proxy was originally developed for simulating sheet and rill erosion rates, it may also be useful for gully erosion modelling.

Table 8: Selection of global and European rainfall datasets (based on Sun et al., 2018).

Dataset/ product	Spatial coverage	Spatial resolution	Temporal resolution	Period	Sensor and type of retrieval	Source	Data download	Reference
E-OBS	Europe	0.55°/0.50°/0.22° rotated/0.44° rot	Daily	1950-present	Gridded rain gauge	ECA&D	https://www.ecad.eu/download/ensembles/download.php#datafiles	Haylock et al. (2008); Cornes et al. (2018)
CRU	Global land	0.5° × 0.5°	Monthly	1901 -2016	Gridded rain gauge	CRU of the University of East Anglia	http://www.cru.uea.ac.uk/data	Harris et al. (2014); New et al. (2000)
GHCN-M	Global land	5° × 5°	Monthly	1900-present	Gridded rain gauge	National Climatic Data Center	https://www.ncdc.noaa.gov/ghcnm/v2.php	Peterson & Vose (1997)
GPCC-monthly	Global land	0.25° × 0.25°, 0.5° × 0.5°, 1.0° × 1.0°, 2.5° × 2.5°	Monthly	1891–2016	Gridded rain gauge	Global Precipitation Climatology Centre	https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2018_doi_download.html	Schneider et al. (2014)
GPCC-daily	Global land	1.0° × 1.0°	Daily	1982-2013	Gridded rain gauge	Global Precipitation Climatology Centre	https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-daily_v2018_doi_download.html	Schamm et al. (2014)
PREC/L	Global land	0.5° × 0.5°, 1.0° × 1.0°, 2.5° × 2.5°	Monthly	1948–2020	Gridded rain gauge	NCEP/NOAA	https://www.esrl.noaa.gov/psd/data/gridded/data.precl.html	Chen et al. (2002)
UDEL	Global land	0.5° × 0.5°	Monthly	1900–2017	Gridded rain gauge	University of Delaware	https://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html	Willmott & Matsuura (1995)
CPC	Global land	0.5° × 0.5°	Daily	1979–present	Gridded rain gauge	CPC	https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html	Xie et al. (2010)
GPCP	Global	2.5°	Monthly	1979–present	Satellite + rain gauge	NOAA/OAR/ESRL PSD	https://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html	Adler et al. (2003)
GPCP 1dd	Global	1.0°	Daily	1996–present	Satellite + rain gauge	NASA	https://rda.ucar.edu/datasets/ds728.3/	Huffman & Bolvin (2013)
GPCP_PEN_v2.2	Global	2.5°	Pentad	1979–present	Satellite + rain gauge	NASA	https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00933	Xie et al. (2003; 2011)
CMAP	Global	2.5°	Monthly, Pentad	1979-2016, 1979–present	Satellite + rain gauge	NCEP–NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html	Xie et al. (2003); Xie & Arkin (1997)
TRMM 3B43	Global (50°S–50°N)	0.25°	3 h/Daily	1998–present	Satellite	NASA	https://pmm.nasa.gov/data-access/downloads/trmm	Huffman et al. (2007)
GSMaP	Global (60°S–60°N)	0.1°	1 h/daily	2000–2014	Satellite	JAXA	http://sharaku.eorc.jaxa.jp/GSMaP_crest/	Ushio et al. (2009)
PERSIANN-CCS	Global (60°S–60°N)	0.04°	30 min/3, 6	2003–present	Satellite	Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California	http://chrsdata.eng.uci.edu/	Sorooshian et al. (2000); Nguyen et al. (2019)

PERSIANN-CDR	Global (60°S–60°N)	0.25°	Daily/monthly/yearly	1983–present	Satellite + rain gauge	Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California	http://chrsdata.eng.uci.edu/	Ashouri et al. (2015); Nguyen et al. (2019)
CMORPH	Global (60°S–60°N)	0.25°	30 min/3 h/daily	2002–2017	Satellite	Climate Prediction Center	https://climatedataguide.ucar.edu/climate-data/cmorph-cpc-morphing-technique-high-resolution-precipitation-60s-60n	Joyce et al. (2004)
GPM	Global (60°S–60°N)	0.1°	30 min/3 h/daily	2000–present	Satellite	NASA	https://pmm.nasa.gov/data-access/downloads/gpm	Hou et al. (2008); Hou et al. (2014); Huffman et al. (2015)
MSWEP	Global	0.1°/0.5°	3 h/daily	1979–present	Satellite + rain gauge	Princeton University	http://www.gloh2o.org/	Beck et al. (2017)
NCEP1	Global	2.5° × 2.5	Monthly/ Daily/6 hourly	1948–present	Reanalysis	NCEP/NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html	Kalnay et al. (1996)
NCEP2	Global	2.5° × 2.5°	Monthly/6 hourly	1979–present	Reanalysis	NCEP/NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.surface.html	Kanamitsu et al. (2002)
ERA 40	Global	2.5° × 2.5°/1.125° × 1.125°	Monthly/6 hourly	1957–2002	Reanalysis	ECMWF	http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/	Uppala et al. (2005)
ERA Interim	Global	1.5° × 1.5°/ 0.75° × 0.75°	Monthly/6 hourly	1979–present	Reanalysis	ECMWF	http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/	Dee et al. (2011)
20CRv2	Global	2.0° × 2.0°	Dailyaily/ 6 hourly	1851–2014	Reanalysis	NOAA	https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.pressure.html	Compo et al. (2011)
JRA-55	Global	60 km	Monthly/3 hourly/6 hourly	1958–present	Reanalysis	Japanese Meteorological Agency	http://jra.kishou.go.jp/JRA-55/index_en.html	Ebita et al. (2011)
MERRA	Global	0.5° × 0.67°	Daily	1979–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA/	Rienecker et al. (2011)
MERRA Land	Global	0.5° × 0.67°	Monthly/ Daily/1hourly	1980–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-Land/	Reichle et al. (2011)
MERRA2	Global	0.5° × 0.67°	Daily	1980–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/	Gelaro et al. (2017)
CFSR 38	Global	38 km	hourly	1979–2011	Reanalysis	NOAA	https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NCDC/Geoportal/iso/xml/C00765.xml&view=getDataView&header=none	Saha et al. (2010)
MSG CPP	Europe	3 × 3 km	15 minutes	2005-2011	Satellite	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	http://msgcpp.knmi.nl/mediawiki/index.php/MSG_Cloud_Physical_Properties_%28CPP%29	Roebeling et al. (2009)

6. Policies relevant to gully erosion: frameworks and current needs

At the global level, the issue of soil erosion receives significant attention (e.g. Montanarella et al., 2016). For example, the United Nations Convention to Combat Desertification (UNCCD, 2018) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Scholes et al., 2018) both stress the importance of human-induced soil erosion as a key driver of land degradation and expresses concerns about the potential impacts of climate change on soil erosion rates. Also several of the UN Sustainable Development Goals (SDGs) clearly identify soil resources as being of crucial importance. More specifically, Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-being), Goal 6 (Clean Water and Sanitation), Goal 13 (Climate Action) and Goal 15 (Life on Land) strongly link to the need to preserve soil resources in order to achieve these goals by 2030 (Keesstra et al., 2016; Bouma, 2019; Panagos & Katsoyiannis, 2019; Albaladejo et al., 2021). The Food Agriculture Organization has published Guidelines for Sustainable Soil Management (FAO, 2016), aiming to support countries in implementing actions for soil protection.

The European Union is a front-runner in attaining the SDGs and has committed to play an active role towards their realization. With respect to SDG 15 'Life on Land', the EU identifies 3 sub-themes: ecosystem status, biodiversity and land degradation (Panagos & Katsoyiannis, 2019). One of the indicators used to assess progress with respect to land degradation is soil erosion by water (Panagos et al., 2015a; 2015b). Overall, soil protection is not subject to a single, coherent legislation within the EU. Although a Soil Thematic Strategy (COM 2006.231) was proposed, the Commission withdrew this proposal to develop a Soil Framework Directive in 2014. Nevertheless, there is a strong commitment of the EU and its member states to conserve soil resources and several measures exist across different policies.

In the EU agricultural sector, the main active policy instrument to promote agro-environmental friendly agriculture is the Cross Compliance mechanism, which was introduced in the Common Agricultural Policy (CAP) in 2003. In 2009, the standards of Good Agricultural and Environmental Conditions (GAEC) were introduced in the CAP legislation framework (Common Agricultural Policy (CAP), 73/2009). One of the requirements in the GAEC is to limit soil loss by water erosion and to maintain soil organic carbon (Borrelli et al., 2016). For this, the GAEC standards include a set of practices, such as reduced tillage, crop residues management, cover crops, maintaining terraces, grass margins next to watercourses, contour farming and crop rotation. While most of these practices may have a beneficial effect on preventing gully erosion, the GAEC makes no explicit reference to the mitigation of existing permanent gullies, nor to the management of ephemeral gullies. Nonetheless, specific measures can be taken by individual member states to tackle (gully) erosion, using funds from the European Agricultural Fund for Rural Development (EAFRD), under the Council Regulation EU 1305/2013. For example, in the Spanish region of Andalucia, gully control measures were subsidized under this programme in 2009-2010. However, despite some initial successes, this programme was discontinued because of a shift in regional priorities. In Flanders (Belgium) municipalities can request subsidies for developing local erosion control plans and implementing small-scale erosion control measures like check dams or sediment control basins.

Also the new legislative proposal of the European Commission for the post-2020 Common Agricultural Policy (CAP 2021-27, COM(2018) 392) includes measures for soil conservation (e.g. cover crops) and maintaining soil organic carbon. Post-2020, soil protection will gain more importance through Eco-schemes as an integral part of the new Green Architecture design. In fact, effective soil management is one of the nine key objectives of the new CAP. While the post-2020 CAP is still being defined and will likely only come into force in 2023, it is clear that Member States will have greater flexibility in deciding on policy measures through the CAP national strategic plans. This may create opportunities to target gully erosion more specifically and to tailor the implementation of measures to particular farming contexts. However, apart from agriculture, also land use changes such as reforestation can have significant impacts on gully erosion. Presently, the European Union does not have a common forestry policy making it still primarily a national matter. Nonetheless, the CAP is the main funding source for forestry, with conversions of agricultural land to forest being supported by Rural Development funds.

In the area of European water policy, the Water Framework Directive (WFD, Directive 2000/60/EC) and the Nitrate Directive (91/676/EEC) set environmental targets that promote soil conservation actions. Under the WFD, EU Member States need to establish Programmes of Measures (PoMs) to achieve good ecological and chemical statuses of water bodies. Diffuse pollution from soil erosion in cropland is identified as a key pressure on water quality in many River Basin Management Plans across the EU (e.g. Heininger et al., 2015), thus erosion control measures should be adopted in PoMs to curb agricultural impacts on water bodies. Similarly, the Nitrate Directive requires implementation of good agricultural practices in nitrate vulnerable zones to reduce runoff, erosion, and nitrate losses. However, the WFD and the Nitrate Directive do not mention soil (or gully) erosion and its control explicitely.

Recently, the European Commission introduced the European Green Deal (EU COM(2019) 640) with the ambition to make EU the first climate-neutral continent by 2050. The EU Green Deal sets ambitious targets such as protecting 30% of the EU's land area, bringing back at least 10% of the agricultural area under high-diversity landscape features and plant more than three billion trees by 2030 (Montanarella and Panagos, 2021). Although those targets have not yet been translated in specific policy measures, it is clear that implementing the EU Green Deal will contribute to sustainable soil management, introducing more soil conservation measures, reducing land degradation and mitigating soil losses due to erosion.

In practice, a wide range of gully control practices exists and have been implemented in numerous areas (e.g. Evrard et al. 2008; Castillo & Gomez, 2016; **Figure 4**). The overall effectiveness of such measures has been recently reviewed (e.g. Bartley et al., 2020; Frankl et al., 2020). The most common conservation practices include increasing the soil erosion resistance in concentrated flow zones, protecting the headcut, diverting overland flows away from gullies as well as creating terraces, grassed waterways, check dams and water and sediment control basins (Casali et al., 1999; Poesen et al. 2003, Valentin et al., 2005). Also in the EU, such measures have been implemented. Nevertheless, measures that directly address gully erosion are not yet compulsory in EU policies. Also soil conservation measures such as reduced tillage are applied at a more limited scale in the EU (4% no till and 22% reduced tillage; EU Agricultural census, 2010; Panagos et al., 2015b) as compared to for example the USA (35% no till and 27% reduced tillage; Census of Agriculture, 2012). In terms of land management, this makes European arable land potentially more vulnerable to ephemeral gully erosion. Overall, soil erosion is clearly considered an important agro-environmental indicator to assess the effectiveness of EU policies such as the Common Agricultural Policy (e.g. Gobin et al., 2004; Zalidis et al., 2004). However, the CAP-induced soil conservation practices consider only sheet and rill erosion and do not account for gully erosion (Panagos et al., 2015a; 2015b).

The situation in the EU contrasts, with other regions. For example in the United States, gully control measures are more widespread. Measures to reduce gully erosion have been implemented as early as the 1930s in the USA, including those by the Civilian Conservation Corps (USDA, 2007). The development of handbooks on the formation and control of gullies by national agencies greatly contributed to this (e.g. USDA, 2007). Grade stabilization structures such as drop pipes were the most common conservation practice to control gully erosion (Wilson et al., 2008), but also extensive reforestation and reservoir construction programmes were implemented (e.g. Rhemtulla et al., 2009; Abbasi et al., 2019). In China, The Grain for Green programme strongly mitigated gully erosion in the Loess Plateau by implementing slope conservation measures and check-dams on a massive scale (Xiang-zhou et al., 2004; Sun et al., 2019). In some areas, the restoration of vegetation on hillslopes through the Grain for Green programme reduced gully erosion rates with up to 90% (Wang et al., 2016). Also in Australia, there are several large government-funded programmes focused on gully remediation (Wilkinson et al., 2019). They aim to reduce sediment and particulate nutrient loads that form, in combination with climate change, an important threat to the Great Barrier Reef (MacNeil et al., 2019). A variety of gully remediation approaches are currently tested in catchments draining to the Great Barrier Reef, ranging from low-cost erosion control structures to larger scale landscape remediation (Koci et al., 2021). Also Ethiopia has implemented several large-scale soil and water conservation programmes that included measures specifically targetting gully erosion (e.g. Haregeweyn et al., 2015).

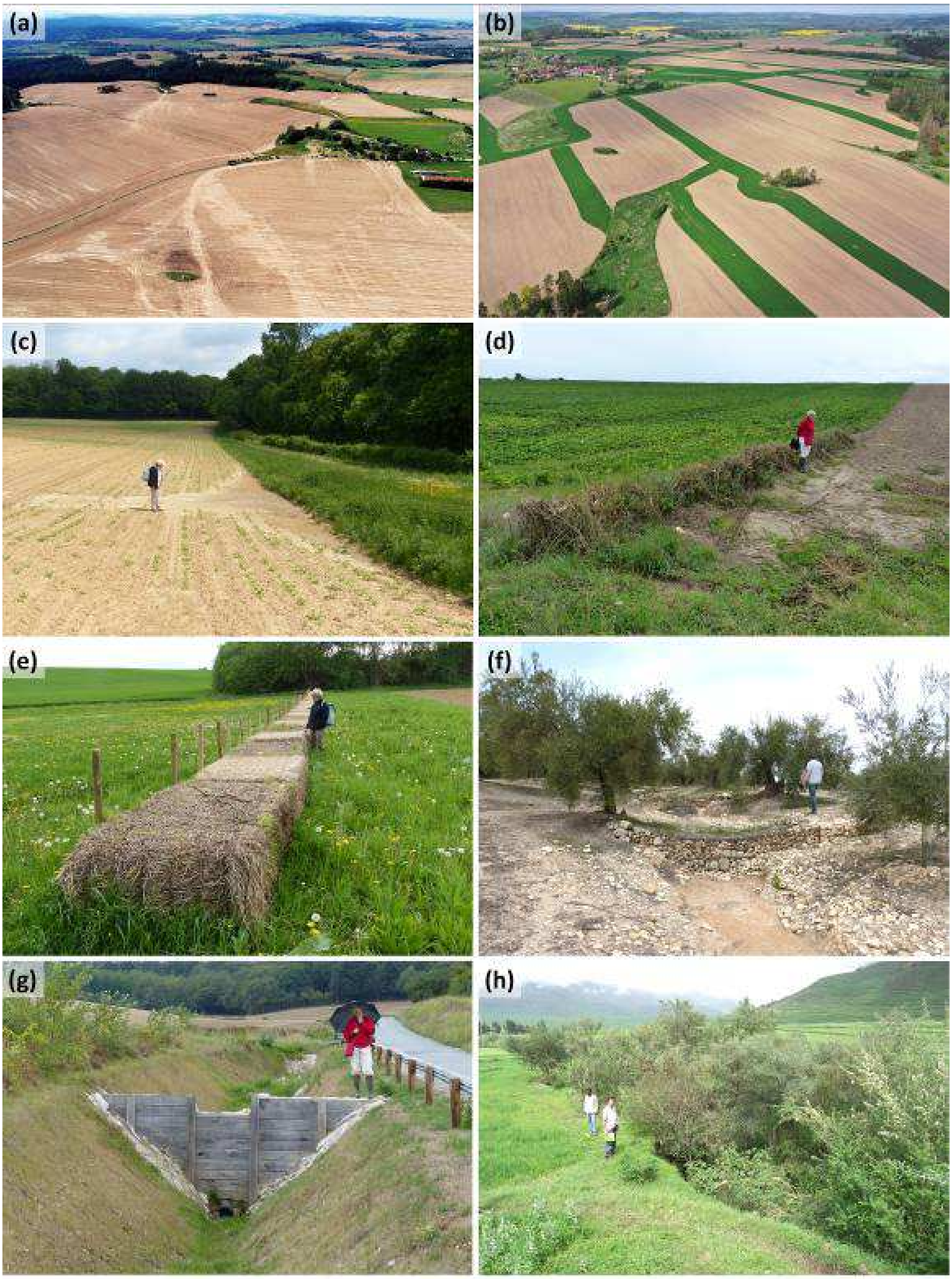

Figure 4: Examples of commonly applied gully control measures. **(a)** Cropland in Litichovice, Czech Republic with rill and ephemeral gully erosion (photo: J. Krása). **(b)** The same cropland area, treated with grassed waterways (foreground) and grass buffer strips to control sediment production and transfer by ephemeral gullying (photo: J. Krása). **(c)** Grass buffer strip installed at a parcel border to reduce the transfer of sediments originating in an ephemeral gully (Huldenberg, Belgium) (photo: J. Poesen). **(d)** Control of ephemeral gully erosion in the concentrated flow zone with a life vegetation barrier forming a hedgerow (Wisques, France) (photo: J. Poesen). **(e)** Control of ephemeral gully erosion in the concentrated flow zone with a dam made of straw bales (Huldenberg, Belgium) (photo: J. Poesen). **(f)** Control of a permanent gully erosion with a gabion check dam in the concentrated flow zone (Andalucia, Spain) (photo: J. Poesen). **(g)** Control of a permanent gully erosion in the concentrated flow zone with a wood/concrete check dam (Wisques, France) (photo: J. Poesen). **(h)** Revegetation of a permanent gully channel (Adi Shuhu, Ethiopia) (photo: J. Poesen).

In summary, the large number of policy initiatives at the European level (i.e. the Soil Thematic Strategy, the Common Agricultural Policy, the Water Framework Directive, and EU Green Deal) as well as global initiatives (Sustainable Development Goals, FAO guidelines, IPBES, UNCCD) show that soil erosion is widely recognized as a problem. Nonetheless, relatively limited attention is given to gully erosion. This likely results from insufficient awareness and understanding of this process. Developing adequate policies to deal with gully erosion requires reliable, spatially explicit indicators on where this problem occurs. Furthermore, it requires tools and data to assess the effectiveness and efficiency of soil conservation measures. This is especially pertinent since gully erosion generally requires interventions that are more drastic and expensive than for sheet and rill erosion (e.g. Valentin et al., 2005; Bartley et al., 2021).

Holistically addressing the problem of soil erosion and land degradation requires models that can simulate and assess all relevant erosion processes, as well as their impacts on catchment sediment budgets (e.g. Borrelli et al., 2018; Poesen, 2018). While detailed models and maps at the European and global level exist to assess sheet and rill erosion (e.g. Borrelli et al., 2017a) this is clearly not the case for gully erosion (cf. sections 3 and 4). Our current inability to quantify gully erosion and its impacts should not imply that this process should remain neglected in policies. Building on the already extensive scientific knowledge gained in several regions worldwide (e.g. USDA, 2007; Sabir et al., 2020), EU and national/regional agro-environmental policies should aim to address, prevent and mitigate gully erosion and its impacts. It deserves mentioning that the EU already makes important efforts in this regard, including through initiatives like the 'Land Use/Cover Area frame statistical Survey Soil' (LUCAS; e.g. Blum et al., 2004; Panagos et al., 2015b; Borrelli et al., 2017b; Orgiazzi et al. 2018) which aims at monitoring soil health in the EU. In the LUCAS 2018 campaign, a soil erosion module was introduced where different processes of soil erosion (including gully erosion) were assessed for more than 20,000 visited points across the EU (Borrelli et al., subm.).

7. Conclusions and recommendations

Gully erosion is an important land degradation process, leading to major on- and off-site impacts (cf. section 1). Climate change and land use/land cover changes may aggravate these impacts in many regions. Adequately addressing land degradation in a context of global change therefore requires strategies and policies that specifically account for gully erosion. However, the development of these is strongly hampered by our inability to accurately quantify and simulate gully erosion in relation to its driving factors, especially at larger (i.e. regional to global) scales. More specifically, we need tools and models that are capable of:

(i) identifying gully erosion hotspots;
(ii) quantifying gully erosion rates at different spatio-temporal scales;

(iii) assessing the impacts of gullies, including their (direct and indirect) contribution to catchment sediment yields; and
(iv) simulating the effects of land use/land cover changes, climate change, land management and conservation measures on gully erosion and its impacts.

While the development of such tools and models poses an important challenge, significant progress has been made over recent decades. Based on a review of over 590 scientific publications and policy documents, this article presents a state-of-the-art on monitoring, modelling and managing gully erosion at larger scales. Here we list our key conclusions and recommendations regarding these three aspects.

7.1 Gully monitoring

Monitoring the occurrence and dynamics of gully systems remains essential for better understanding and constraining rates and controlling factors of gully erosion. Especially datasets on the initiation and evolution of gully systems over large areas are a prerequisite for the development of models that can simulate this process at larger scales. Such datasets currently remain scarce. New remote sensing products can greatly help in addressing this gap. Nevertheless, monitoring gully erosion at larger scales remains highly labour-intensive and/or requires significant concessions in accuracy, completeness and level of detail (cf. section 2). Also the limited length of the observation periods and the coarse temporal resolution often form important constraints.

We make the following recommendations with respect to gully monitoring via remote sensing:

(i) Further research is needed to develop approaches that allow assessing the occurrence, properties and evolution of gully systems at larger spatial scales in efficient and accurate ways. Promising avenues for this are strategies that rely on monitoring gullies in large sets of small yet representative case study areas and the (semi-)automatic detection and characterization of gullies.
(ii) More studies are needed that provide data on the dynamics of gully erosion at high temporal resolutions across different environmental settings. This is particularly relevant for ephemeral gullies which may be formed and erased again over short time spans, potentially leading to significant underestimations of their erosion rates. Repeated analyses of frequent imagery, preferably taken shortly after every significant runoff event is likely the best way to address this need. The increasing availability of EO products at high spatio-temporal and spectral resolutions opens promising perspectives here.
(iii) Better insight and data are needed on the long-term evolution of gully systems. Gullies often form and expand over short time periods and then remain stable for many years. In some environments they may even be filled in again. Likewise, apparently stable gullies may be

reactivated as a result of extreme climatic events or land cover/use/management changes. Nonetheless, most of the available data on gully erosion rates cover relatively short time periods (i.e. a few years) and are not necessarily representative for long-term average erosion rates. Systematically assessing the evolution of both active and seemingly stable gullies over decadal timescales will help addressing this need. Historical (aerial) photos and early satellite imagery can be an important asset for this.

(iv) Methodological advancements are required that allow better quantifying the uncertainties associated with gully monitoring. Assessed gully dimensions and dynamics are often subject to considerable uncertainties as a result of mapping errors, observation biases, the large temporal variability of gully erosion and conversion errors (e.g. when deriving gully volumes from gully lengths or areas). We recommend more research that allows quantifying these different sources of uncertainty, as well as their combined effects on the total uncertainty. Linked to that, we recommend developing procedures that allow better comparisons of collected data. Classifying gullies according to a consistent typology across different studies will be an important element in this.

Apart from remote sensing, also field-based research in well-targeted areas will remain essential to understand gully erosion. Our overview for Europe (section 3) may serve as a starting point for future studies aiming to develop gully erosion models at regional to continental scales. However, it also uncovered shortcomings and gaps. For example, most studies focused on permanent gullies, while bank gullies and ephemeral gullies received considerably less attention. Nonetheless, their associated impacts can be very high. Other pertinent research needs include:

(i) studies that monitor gully densities and gully expansion rates systematically over larger areas;
(ii) studies that monitor gully dynamics (i.e. initiation, headcut retreat, but also gully widening, deepening and infilling) and related subprocesses (e.g. piping, mass movement) at decadal timescales, preferably at high temporal resolutions;
(iii) studies that evaluate the performance of different gully modelling strategies based on detailed field observations; and
(iv) studies that assess the effectiveness of different gully erosion control measures over sufficiently long time periods.

7.2. Gully modelling

There is an important need for models and tools that can simulate and predict gully erosion at regional to global scales. Various viable model approaches and concepts have already been proposed, but need to be further developed, upscaled and tested so that they can be applied at larger scales (cf. section 4). A major challenge is finding a good balance between an accurate process representation and feasible data requirements. The recent and ongoing development of new environmental data products at (sub)continental to global scales opens promising perspectives in this regard (cf. section 5).

More specifically, process-oriented model approaches can yield relevant insights into the factors and mechanisms driving gully erosion, as well as their interactions. As such, they can be important tools for scenario analyses. However, their generally high data requirements make it difficult to apply them, especially at larger scales. Empirical modelling strategies, and in particular machine-learning approaches, offer great potential. However, their overall ‘black box’ nature can impede clear insights into the actual drivers of gully erosion. Different modelling strategies will therefore need to be developed and combined.

We make the following recommendations with respect to modelling gully erosion and its impacts:

(i) Better insights are needed on the factors controlling gully erosion at larger scales and how the role of these factors can be translated into meaningful variables and proxies that can be derived from GIS/EO data. This is especially so for the effects of climate and weather conditions, vegetation cover, land use/management, soil and lithological properties.

(ii) While numerous modelling strategies have already been proposed, more work is required to scale up these approaches from case studies to larger regions. This is the case for process-oriented strategies (e.g. relying on a spatially explicit hydrological model) as well as for empirical (e.g. machine learning) approaches. Much of this work will revolve around finding optimal trade-offs between model accuracy and feasible data and calculation requirements.

(iii) The potential to couple and combine different approaches needs to be further explored and developed. Most efforts so far have focussed on simulating either gully initiation, density or expansion (mainly through headcut retreat), while little research has been conducted on how to integrate these different aspects into models that predict total gully erosion rates. Such integration will also need accounting for potential interactions between these different components of gully erosion and their controlling factors as well as with potential interactions with other erosion processes (e.g. sheet and rill erosion).

(iv) Additional research is necessary on accounting for the effects of land use and land management practices, and in particular soil and water conservation measures, on gully erosion and its impacts at larger scales. This will require further developing large-scale datasets indicating the presence of specific erosion control measures but also modelling frameworks that allow quantifying their effectiveness and efficiency.

(v) There is a large need for tools and model frameworks that allow better assessing and quantifying the diverse on- and off-site impacts of gully erosion, both at short and longer timescales. This includes the effects of gully erosion on hillslope hydrology, crop yields, biomass production and other ecosystem services of soils, but also downstream impacts (e.g. assessing the contribution of gullies to river sediment load and catchment hydrology). This will likely require coupling gully erosion models to available models, but also developing new model components (e.g. accounting for the impacts of gullies on sediment connectivity).

(vi) On a more general level, the potential of models to simulate gully erosion and its impacts for scenario analyses needs to be further developed and tested. A key element in this will be the thorough validation of these models, using reliable observations over a large range of environmental conditions.

7.3. Gully management

Overall, there is a significant and growing international interest to tackle the challenges of soil erosion and land degradation in the context of global change (cf. section 6). In Europe, numerous frameworks and policies help addressing the problem of soil erosion. However, very few of them explicitly account for (or even mention) gully erosion. More specific guidelines and recommendations to deal with this process are required. To a large extent, the absence of gully erosion in current policies is mainly due to our inability to accurately assess and quantify this process and its impacts. This hampers effective communication between scientists and policy makers on setting realistic targets and solutions. Nevertheless, our current state of knowledge does already allow accounting more explicitly for gully erosion.

We believe the following elements can aid in a better management of gully erosion at larger scales:

(i) Scientific initiatives that help to better quantify and understand gully erosion, allowing for more targeted policies, need to be further supported. Especially initiatives that help identifying (potentially) problematic areas and assessing the effectiveness, costs and benefits of prevention and control measures are needed in this regard.

(ii) Lessons learned from other policy implementations (e.g. with respect to sheet and rill erosion) as well as from regions where gully control measures are already implemented should be integrated in policies dealing with gully erosion.

(iii) Given that the formation, expansion rates and impacts of gullies strongly vary between regions, (future) policy instruments should accommodate for this diversity of contexts.

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