Agriculture, Ecosystems and Environment 348 (2023) 108443

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Review

The role of grassland for erosion and flood mitigation in Europe: A meta-analysis

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ARTICLE INFO

Keywords:
Grassland
Erosion
Ecosystem services
Flooding

ABSTRACT

Permanent grasslands are widely recognized for their role in protecting the landscape against soil erosion and flooding. However, this role has not yet been comprehensively quantified. Also, the degradation of grasslands is accelerating at an alarming pace, leading to erosion and runoff generation. This study aims to (i) quantify the erosion and flooding mitigation effect of permanent grasslands in the EU and the UK, compared to other land uses; (ii) review all soil erosion and runoff generating processes on permanent grasslands. First, a meta-analysis compared four erosion and flooding-related indicators: bulk density, hydraulic conductivity, runoff and soil loss between permanent grasslands, arable land and forests. The results show that permanent grassland soils had generally lower bulk density and higher hydraulic conductivity than arable soils, and generated less runoff and soil loss. Differences are less clear-cut in comparison with forests, although permanent grasslands had higher bulk density and runoff values. Secondly, a qualitative, in-depth review was performed to identify knowledge gaps related to the characteristics, importance and driving factors behind relevant soil erosion processes affecting grasslands in the EU. This identified six processes with appreciable knowledge gaps: trampling-induced erosion, gullying, piping, landsliding, snowmelt erosion, and avalanche erosion. Additionally, three processes were identified that promote runoff generation and soil erosion: compaction, hydrophobicity and wildfires.

1. Introduction

Climate change, land use change and management intensification all increase the vulnerability of European soils to increased runoff, flooding and soil erosion. Both flooding and soil erosion are projected to increase under future climate change in the EU. Alfieri et al. (2015) project a 220% increase in flood risk in Europe by 2080. Panagos et al. (2021) predicted an increase of 13–22.5% in soil loss for the EU and UK by 2050 due to water erosion. Both processes are closely linked, and mitigation measures require policy measures that promote soil conservation, and land use planning policies promoting land uses with high soil water holding capacity, low runoff generation potential, high vegetation cover and erosion resistance. Grasslands have an enormous potential to make our landscapes more resilient to floods and erosion (Bengtsson et al., 2019; Hussain et al., 2021; Yang et al., 2021), while contributing to the production of forage and other ecosystem services (Schils et al., 2022). Grasslands cover more than 30% of the earth's terrestrial surface, more than double the surface of cropland (Lemaire et al., 2011), and 35% of the European (EU-28) agricultural area (EUROSTAT, 2020). The European Union differentiates grassland type based on the age of the fodder and rotation. Permanent grassland is defined as land used to produce herbaceous forage, self-seeded or sown, not included in the crop rotation

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https://doi.org/10.1016/j.agee.2023.108443
Received 16 August 2022; Received in revised form 21 February 2023; Accepted 24 February 2023

for at least five years. Whereas, temporary grassland is land used to grow herbaceous forage included in the crop rotation (European Commission, 2007). In uplands, both permanent and temporary grassland reduce soil erosion, surface runoff and downstream flooding (Macleod et al., 2013). In lowlands, grasslands are capable of withstanding flooding better than other land uses and promote water infiltration (Strock et al., 2022). However, recent studies have shown that significant soil erosion can occur (Hancock et al., 2015) and that while erosion on well-conserved permanent grassland is generally low, these are increasingly under threat of intensification. Globally, 49% of grasslands has been degraded to some extent, and this process is accelerating in many parts of the world (Bardgett et al., 2021). Degraded grasslands are subject to severe erosion and runoff generation. In mountainous areas, such as the Swiss alpine uplands, water erosion can be severe and varies from 0.14 to 1.25 t $ha^{-1}month^{-1}$ depending on the phenological stage of grasses (Schmidt et al., 2019). Other processes, such as landslides or trail erosion contribute to sediment production (Zweifel et al., 2019) and have received little attention. In dryland regions, degradation and abandonment leads to increased woody plant encroachment and fire risk, which in turn exposes bare soil, increasing soil loss by 60% (Johansen et al., 2001) and creating feedback loops that accelerate degradation.

Panagos et al. (2020) reported that 25% of European soils have erosion rates higher than the sustainable threshold (2 t ha^{-1} yr^{-1}) and 6% of agricultural land exceeds 11 t ha^{-1} yr^{-1}. These areas are mostly under cropland and permanent crops, while grassland and forests have a lower impact on erosion generation (Cerdan et al., 2010; Panagos et al., 2015, 2021). However, widespread agricultural intensification, either by grassland conversion or management intensification, inevitably leads to increases in soil erosion. Therefore, it is important to quantify the erosion and flooding mitigation potential of permanent grassland compared to other land uses. This will aid evaluation of the impact of policies designed to influence land use and maintenance of permanent grassland, such as the Eco-schemes proposed under the new Common Agricultural Policy (CAP) 2023–2027 (European Commission, 2021a). It is also necessary to better understand the main soil erosion and runoff processes under intensified permanent grassland. Much of our knowledge is limited to sheet and rill erosion, but it is necessary to look beyond the processes that can be modelled using RUSLE (Quine and Van Oost, 2020), such as gullies, landslides or, in the case of grasslands, trampling or trail erosion due to overgrazing. In this study we aim to present a comprehensive overview of soil erosion and flooding issues that affect European permanent grassland by performing: (i) a quantitative meta-analysis of the soil erosion and flooding mitigation role of permanent grassland (ii) and a qualitative evaluation of additional erosion and flooding-related processes that threat permanent grassland in Europe.

2. Materials and methods

We quantified the role of permanent grassland in erosion and flood mitigation in contrast with arable land and forest land by performing a meta-analysis. that focusses on four indicators: bulk density, hydraulic conductivity, runoff and soil loss. These four indicators were selected for two reasons: (i) because they are widely acknowledged to be well related to runoff and erosion generating processes, and (ii) because they are widely used in literature and enough studies are available that report on the land use contrasts studied here. Bulk density is widely considered an important soil quality indicator that reflects the soil structure and soil compaction, and is directly related to other soil quality parameters such as soil porosity (Hernanz et al., 2000; Topa et al., 2021). Hydraulic conductivity is an important property in natural flood management for the understanding of the surface permeability of soil with the view of increasing rainfall infiltration and runoff reduction (Bens et al., 2007; Marshall et al., 2009; Talsma, 1987). Runoff and soil loss considered in this study are direct measures of the amount of water and soil loss, and are assessed at field scale by using runoff plots. Although the relation between plot and catchment scale is complex, both indicators are well suited for comparing the response of land use or management types (Maetens et al., 2012). To evaluate the additional erosion and flooding risk in permanent grassland, we review the main soil degradation processes and the related promoting processes that foster erosion and flooding.

2.1. Search strategy

In the end of 2019, a systematic literature search was performed to identify studies reporting on the effect of grasslands on soil erosion and flooding. The literature was screened based on the criterion that a selected set of indicators were reported in a land use contrast: either permanent grassland-arable land, or permanent grassland-forest. The selected indicators are: (1) hydraulic conductivity (mm h^{-1}); (2) bulk density (g cm^{-3}), (3) runoff (mm); and (4) soil loss (t ha^{-1}), (Tables S1, Appendix 1).

The search was limited to articles published from 1980 to 2018, and within the Europe-27, including also the EU-27 neighbourhood countries such as United Kingdom, Albania, Belarus, Bosnia Herzegovina, Kosovo, Macedonia, Moldova, Montenegro, Norway, Serbia, Switzerland and Ukraine. The research was conducted in Scopus and CAB abstract, using a keyword string aiming to collect the wider radius of scientific papers regarding soil degradation issues in permanent grassland land, as described in Schils et al. (2022) (Table S2, Appendix 1).

2.2. Data extraction and inclusion criteria

The screening process was implemented using "EPPI reviewer 4 tool" (http://eppi.ioe.ac.uk/cms/). Valid data sampled by the full text screening were extracted and transcribed in MS Excel form, creating a database of the number of field assessments, mean value, and standard deviation. In this first step of the systematic search, 14203 articles were collected, of which 3150 articles were removed due to duplicates, leaving a net total of 11053. A second screening process was then carried out: by title, by abstract and by full text. Exclusion criteria were set retaining only papers in English language that report on results of field experiments or measurements, rejecting model studies and reviews. At the end of the screening process, only 24 scientific papers were included in the meta-analysis. The full selection process is shown in Table1.

2.3. Reviewer bias

The processes of screening and data extraction were carried out by experts, consisting of a head-reviewer and two co-reviewers. The assessment of the head-reviewer was used as a benchmark against which the co-reviewers' decisions were compared. At least 5% of papers were double-screened to assess the rate of discrepancy between the head-reviewer and the co-reviewer's decision, identifying the "false exclusion rate". If the false exclusion rate was higher than 10%, the processes were discussed, and the issue was adjusted.

2.4. Weighted meta-analysis

The extracted data were analysed using the logarithm response ratio weighted meta-analysis approach (Hedges et al., 1999). For every single entry, the effect of land use on the selected contrast was assessed as the natural logarithm response ratio (*LnRR*) of the mean of the contrasting land uses.

$$LnRR = \ln\frac{\overline{X_x}}{\overline{X_{PG}}}$$

Where the *LnRR* is the natural log of the mean of forest or arable groups ($\overline{X_x}$) against the mean of the permanent grassland group ($\overline{X_{PG}}$).

The variance for each group was calculated as:

$$Var = \frac{SD_x^2}{N_x \overline{X}_x} + \frac{SD_{PG}^2}{N_{PG} \overline{X}_{PG}}$$

Where SD_x is the standard deviation of forest or arable groups, SD_{PG} is the standard deviation of permanent grassland group; N_x is the sample size of forest or arable group, and N_{PG} is the sample size of permanent grassland groups.

A random-effects model (RE) was fitted to the data. The amount of heterogeneity was estimated using the restricted maximum-likelihood estimator (Viechtbauer, 2005). The studentized residuals and Cook's distances are used to examine whether studies may be outliers and/or influential in the context of the model (Viechtbauer and Cheung, 2010). The analysis was carried out using R (version 4.1.2) (R Core Team, 2020) and the metafor package (version 3.0.2) (Viechtbauer, 2022).

3. Results and discussion

3.1. Weighted meta-analysis

Meta-analysis results are shown in Figs. 1 and 2 for the comparison of permanent grassland with arable land and forestry land respectively. In contrast to arable land, there were no significant differences in bulk density (RE [95%CI] = 1.17[−0.07; 0.40], n = 9 studies yielding). An examination of the studentized residuals revealed that the study of Pardini et al. (2017) had a value larger than 2.77 and may be an outlier in the context of this model. Therefore, 44% of the entries reported positive response rates that were significantly above 0, while 33% of entries reported a ratio of mean higher than 0but do not show significant differences. According to the Cook's distances, two studies (Nunes et al., 2011; Pardini et al., 2017) could be considered overly influential. This surprising result is probably related to the evolution of bulk density after tillage in relation to when the measurements were taken. Soil bulk density decreases with every tillage operation, but then changes very fast. Osunbitan et al. (2005) reported an increase in bulk density of up to 61% in only 8 weeks after tillage. Alletto and Coquet (2009) reported a similar increase in bulk density in a study in France. Since none of the included studies evaluated the temporal evolution of soil properties, nor details of the time of sampling and the time passed since the last tillage operation, this could easily explain some of the non-significant and negative entries.

Also, no significant differences have been reported in hydraulic conductivity (RE [95%CI=−0.01[−0.61;0.59] n = 5 studies yielding), although the majority of estimates are negative (60%). An examination of the studentized residuals revealed that the study of Brejea (2010) has a value larger than 2.57 and may be a potential outlier in the context of this model, influencing indeed the RE outcome. Again, tillage operations temporarily modify the physical status of topsoil increasing the hydraulic conductivity, although this effect quickly disappears after a couple of weeks (Kool et al., 2019).

The estimated average response rate based on RE of runoff is positive, although it is not significantly different from zero (RE [95% CI=0.30 [−0.43; 1.02] n = 6 studies yielding). Most of the studies display a higher runoff generation in arable land (67%). Pardini et al. (2017) have a large sample size (n = 20) influencing negatively the weight of RE. According to our assessment, soil loss generation is higher in arable land than in permanent grassland, although it is also not significant (RE [95%CI=1.73 [−0.09; 3.56] n = 7 studies yielding). In fact, the estimated RE outcome is significantly higher in arable land in 86% of the analysed studies. Pardini et al. (2017) have a studentized residual value larger than 2.69 and it is considered an outlier in the context of the model. Local environmental conditions can overturn the erosion and runoff mitigation effect of permanent grassland. For example, Pardini et al. (2017) observed a higher runoff and soil loss under permanent grassland. Nonetheless, this can be understood because this study measured the erosion generated in a permanent grassland area regrown

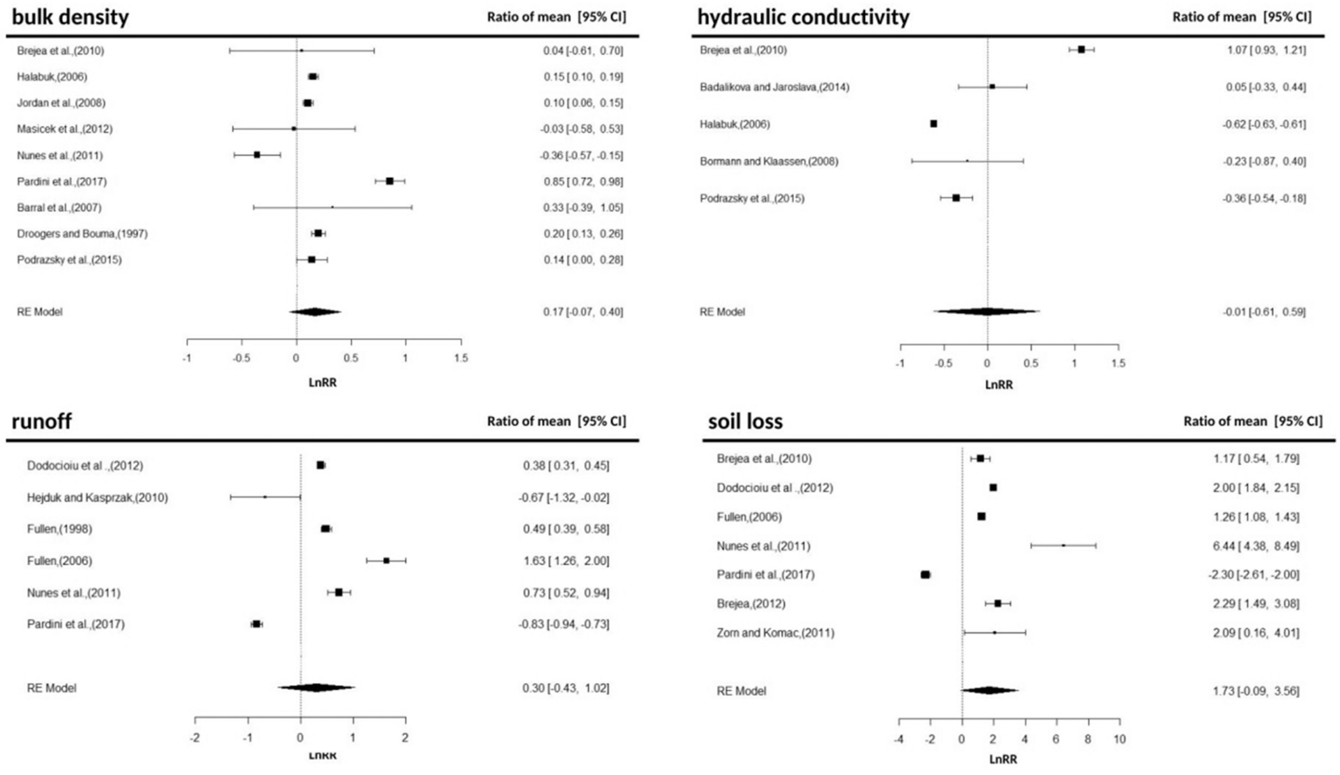

Fig. 1. Weighted mean effect (log response ratio, LnRR) and 95% confidence interval of permanent grassland vs. arable land on bulk density, hydraulic conductivity, runoff, and soil loss. A LnRR>0 indicates a higher value of the indicator under arable land, while LnRR<0 indicates a lower value under arable land, compared to permanent grassland. Effects are significant ($P \leq 0.05$) where confidence intervals do not intercept 0.

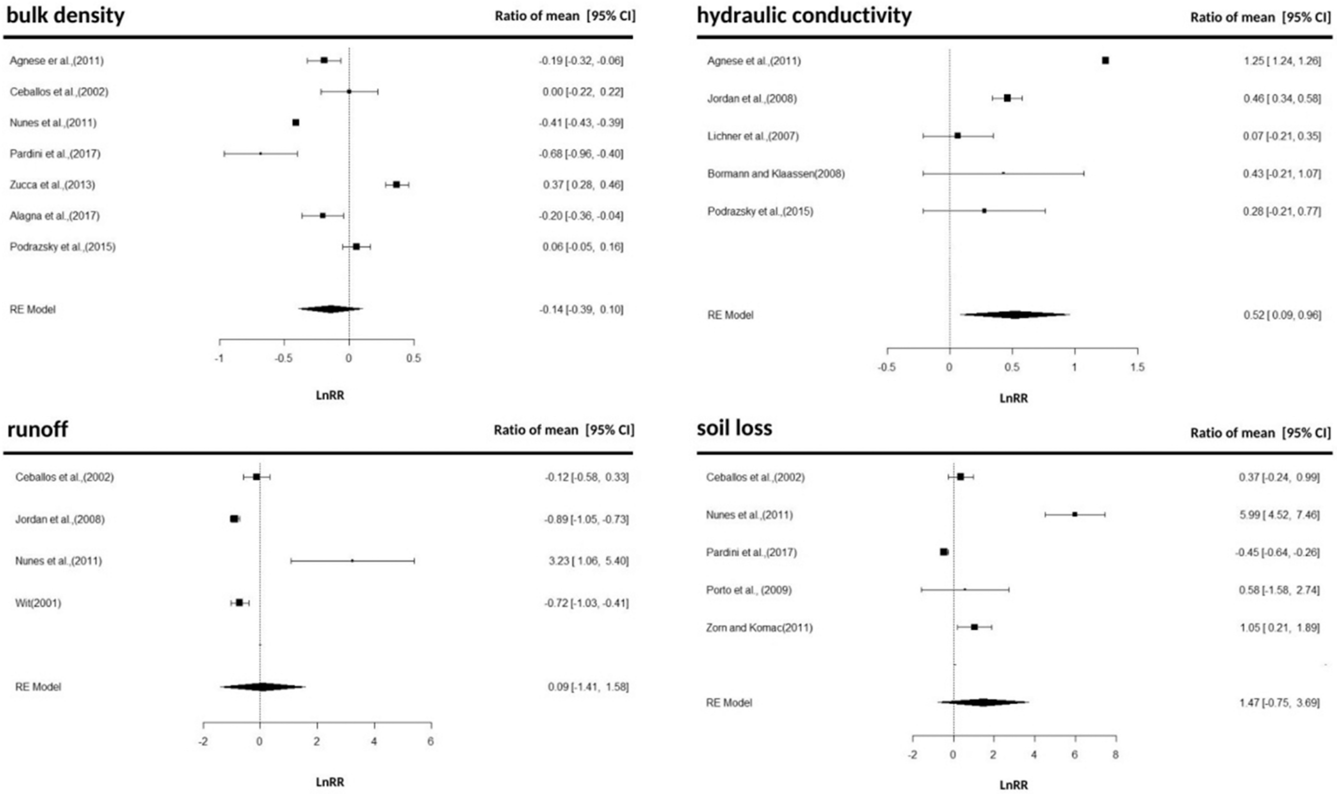

Fig. 2. Weighted mean effect (log response ratio, LnRR) and 95% confidence interval of permanent grassland vs. forest land on bulk density, hydraulic conductivity, runoff and soil loss response. A LnRR>0 indicates a higher value of the indicator under forest land, while LnRR<0 indicates a lower value under forest land, compared to permanent grassland. Effects are significant ($P \leq 0.05$) where confidence intervals do not intercept 0.

after a fire event in Catalonia. Fire severely compromises some soil properties, increasing the bulk density, as organic matter is lost, and the soil structure can collapse completely. This enhances soil loss and runoff. The role of fire on soil degradation and the effect of permanent grassland will be discussed in more detail in the next section. Also, Hejduk and Kasprzak (2010) observed a higher runoff in permanent grassland compared to arable land in the Czech Republic, and attributed this to quicker snow melting process in permanent grassland.

In terms of the contrast between permanent grassland and forest, the differences are not as clear-cut as compared to arable land. In contrast to forest land, there were no significant differences in bulk density (RE [95%CI] $= -0.14[-0.39; 0.10]$, $n = 7$ studies yielding). Overall, 57% of entries were significantly negative, while only the study of Zucca et al. (2010) was significantly positive [LnRR [95% CI] $= 0.37[0.28;0.46]$. Hence, the average outcome is estimated to be negative. Bulk density is the only indicator that is generally lower in forestry land, except for the study by Zucca et al. (2010), which underlines the role of permanent grassland management on this indicator. In terms of hydraulic conductivity, similar results have been assessed, the observed response ration ranged from -0.21 and 1.26, with the totality of estimates being positive. The estimated average response ratio differed significantly from zero (RE [95%CI] $=0.52$ [0.09; 0.96]. An examination of the studentized residuals revealed that one study (Agnese et al., 2011) had a value larger than 2.57 and may be a potential outlier in the context of this model. The observed response ratios of runoff ranged from $-$ 0.89–3.23, with the majority of estimates being negative (75%). The estimated average response ratio did not vary significantly from zero, (RE [95%CI] $=0.09$ [-1.41; 1.58]. Only one study exceeded the studentized residuals values of 2.49 (Nunes et al., 2011) and may be a potential outlier in the context of this model. Also for the soil loss indicator, the estimated average response ratio based on the RE did not differ significantly from zero (RE [95%CI] $=1.47$ [-0.75; 3.69]. Moreover, the observed response ratios ranged from -0.45 to 5.99. Also, in this case, the study of Nunes et al. (2011) is considered a potential outlier within the RE.

In conclusion, while it is generally assumed that converting permanent grassland to arable land leads to more runoff, soil loss and flooding, and, overall, the results of our systematic analysis do indeed confirm this, the results are not always clear and significant. Numerous exceptions were found where the effect was found to be negative or non-significant. A deeper analysis of local conditions helps explain some of these differences, for example the effect of fire or snow-melt erosion led to a negative effect under permanent grassland. The effect of tillage on arable land is also important. Vegetation conditions, bulk density and hydraulic conductivity are highly dynamic and the time of the measurement with respect to tillage operations was not always well detailed in the analyzed studies. The comparison between permanent grassland and forest showed that the difference was even less clear, with no significant differences, except for hydraulic conductivity. This study indicates that permanent grassland is similar to forest in terms of erosion and flooding mitigation.

3.2. *Additional erosion and degradation processes*

The four simple indicators analysed in the meta-analysis give a first diagnosis of erosion and flooding problems and are well related to runoff generation and sheet and rill erosion. However, grasslands are threatened by additional important erosion processes. We identified six additional erosion processes: trampling-induced erosion, gullying, piping, landsliding, snowmelt erosion, and avalanche (Fig. 3), that are poorly studied and will be discussed in detail below. Also, we identified three erosion promoting processes, hydrophobicity, fires and compaction, that are related to grassland soil management, which exacerbated these erosion processes.

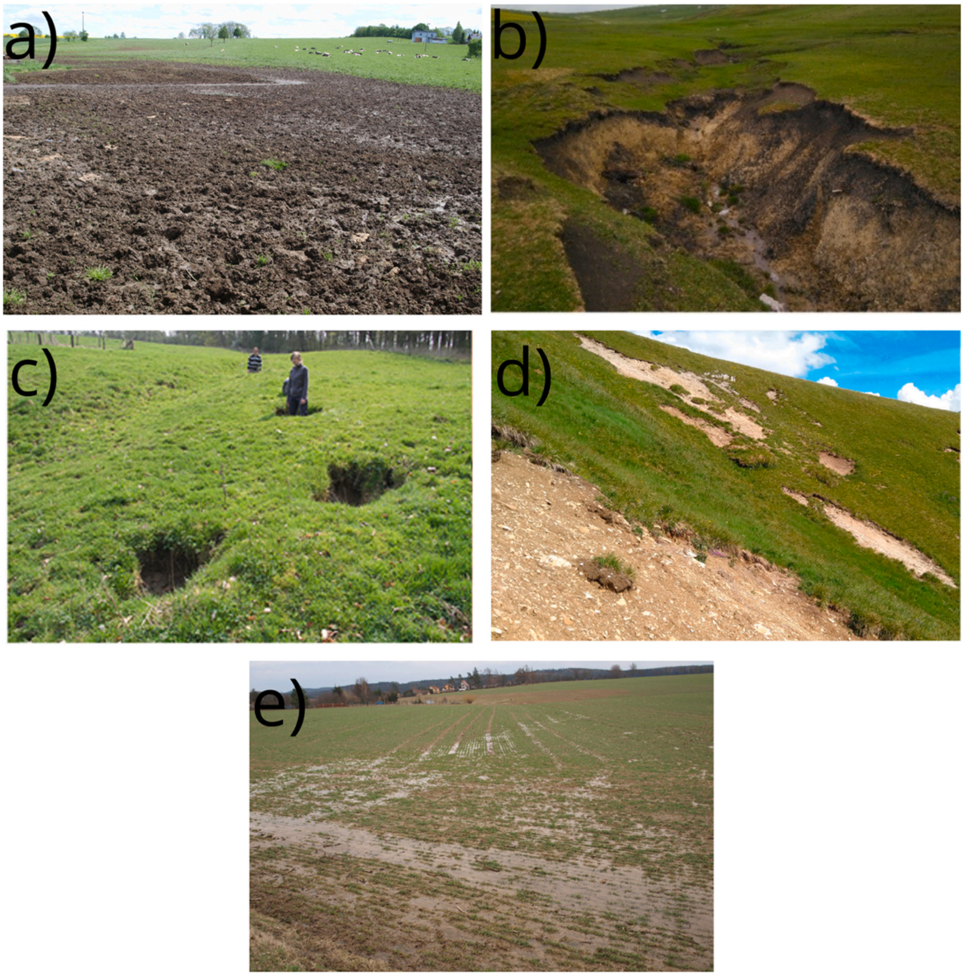

Fig. 3. Main soil erosion processes: a) trampling-induced erosion in the Czech Republic; b) Gully erosion in Romania (Nicu, 2018); c) Pipe erosion in Belgium (Verachtert et al., 2011); d) Landsliding in UK (DEFRA, 2010); e) Snowmelt erosion and flooding in Czech Republic.

3.2.1. *Trampling-induced erosion*

Animal trampling increases soil erosion by degrading local vegetation cover, disturbing soil and unconsolidated materials (Apollo et al., 2018; Torresani et al., 2019; Marzen et al., 2019). Trampling also decreases water infiltration, which in combination with high runoff, reduces both soil health and permanent grassland productivity (Dubeux et al., 2009; Yang et al., 2013). The vegetation plays an important role in restricting the damage due to trampling by reducing soil moisture during the warm weather and increasing the potential of soils to absorb water during periods of rain (Pande and Yamamoto, 2006; Liu et al., 2016). Permanent grassland degradation by livestock trampling depends on different local factors, such as soil structures, soil wetness, grass and livestock types, and the period when livestock roam (Bilotta et al., 2007). Cole (1995) observed the trampling effect on 18 grassland sites that were trampled between 0 and 500 times, concluding that there is no linearity between trampling intensity and vegetation cover disturbance. Indeed, the degradation was better described by a second-order polynomial function underlining a multi-fold relationship. Manthey and Peper (2010) studied the trampling effect in semi-arid rangeland, finding no linear relationship between grassland degradation and livestock intensity, but with a better relationship with the temporal distribution of the animal roaming. Trampling processes are particularly important in areas of high livestock concentration, such as livestock trails or around drinking or feeding areas, although specific studies on the extension and associated erosion rates are rare. Samarin et al. (2020) mapped a threefold increase of livestock trail erosion in a 26 km^2 alpine valley in Switzerland over the last 20 years, from 1 to 3 ha.

3.2.2. *Gully erosion*

Gully erosion is the formation and subsequent expansion of channels in the soil as a result of concentrated overland flow. In grazing areas in Australia, it has been documented that gully erosion is one the largest sediment contributors (Wilkinson et al., 2018). This study found that gully sediment yields were reduced by 77% if cattle was excluded from grazing within and around the gullies, therefore concluding that reducing livestock grazing pressure is crucial for gully erosion control. In Europe there has been less research on gullies in grazing areas, especially in permanent grassland. Torri and Poesen (2014) reviewed 39 publications on topographic thresholds for gullying. They identified 19 out of 49 sites where gullies had formed under permanent grassland and concluded that soils under permanent vegetation were almost four times more resistant to gully erosion than cropland. Only four of these studies were done in Europe, most of them in the Mediterranean region. Vandekerkhove et al. (2000) measured and compared gullies under rangeland in SE Spain and Lesvos Island, Greece, but noted that in the first case gullies actually formed when the area was still cultivated, and in the latter case that the vegetation cover was highly degraded due to overgrazing and frequent fires. Zucca et al. (2006) pointed to overgrazing as the main cause for the formation of gullies in their study area in Sardinia, Italy. Gutiérrez et al. (2009) studied gullies in the dehesa landscape of Southern Spain, a type of permanent grassland consisting of grass layer with dispersed tree cover. They found that gullying was significantly related to grazing intensity. Strunk (2003) reported gullying in mountain pastures of N Italy, and also linked this to overgrazing. Menéndez-Duarte et al. (2007) studied severe gully erosion in the north of Spain, an area with agroclimatic conditions comparable to UK, Ireland and Northern Europe (Ceglar et al., 2019). In a recent study, Nicu (2018) explored the relation between overgrazing and gullying in Romania, and mapped 677 gullies in a 550 km^2 area, using a combination of aerial photos and field mappings. The lack of more detailed studies indicates that there is an important research gap here.

3.2.3. Piping erosion

Piping erosion is an underground process, which consists of the displacement of soil through empty spaces (macropores, roots or biological channels) by concentrated water flows, that can collapse and become a discontinuous gully (Hagerty, 1991). This phenomenon is more widespread than often assumed, and it occurs in almost all the bioregions and it is prompted by different factors such as climate, soil properties, topography, land use and management (Carey and Woo, 2000; Zhu, 2012; Faulkner, 2013). Pipe erosion is often followed by other soil erosion process such as landslides (Jones, 2004; Hencher, 2010; Verachtert et al., 2013) and gullies (Jones, 1981; Gutiérrez et al., 1997; Faulkner, 2013). Due to the underground nature of the process, it is challenging to detect, control and measure, and is usually only discovered when the roof of the pipe collapses (Verachtert et al., 2013; Bernatek-Jakiel et al., 2016). Relatively few studies have specifically assessed pipe erosion rates, the majority focussing on cropland by measuring sediment yield (Farres et al., 1990; Øygarden et al., 1997; Sogon et al., 1999) or tracers as Pb^{210} and Cs^{137}. Verachtert et al. (2011) found the pipe soil loss rate of a Belgium permanent grassland to be between 2.3 and 4.6 t ha^{-1} y^{-1}, which is considerably above the superficial European mean soil loss rate in permanent grassland, excluding the Mediterranean region (Cerdan et al., 2010).

3.2.4. Landslides

Landslides are defined as the movement of a mass of rock, debris, or earth down a slope by the force of gravity and thereby, the loss of one or more soil functions. It is one of the major local soil threats in Europe's mountainous regions and slopes (European Commission, 2008). This phenomenon is widespread in the European Alps and has enduring degradation effects on permanent grassland (Wiegand and Geitner, 2013). In the Austrian Alps, a landslide is locally called "Blaike" which is a German word that refers to an extremely eroded spot surrounded by undisturbed grassland (Stiny, 1910). Indeed, Landslide is promoted by intense rainfall events, snowmelt abrasion (i.e avalanche and snow gliding) or a combination of both (Geitner et al., 2021; Wiegand and Geitner, 2013). However, many other factors such as topography, soil and bedrock, vegetation and human activities are interacting with slope stability (Bíl and Müller, 2008; Stolte et al., 2015). An increase in animal stocking rates also has significant impacts on landslide incidence (Meusburger and Alewell, 2008). In the European Alps and other mountains regions, for example the Spanish Pyrenees, shallow landslides, where superficial erosion removes a layer of soil in a small area, between 2 and 200 m^2, exposing the mother rock (Geitner et al., 2021; Wiegand and Geitner, 2013), are a widely spread phenomena in grasslands and happen when prolonged precipitation or snowmelt displaces the topsoil layer (García-Ruiz et al., 2010; Zweifel et al., 2019). Recently, landslide events in Europe have increased regionally with different intensities (Kundzewicz, 2019; Van Beek and Van Asch, 2004). Crozier (2010) expected more future landslides due to global warming and extreme precipitation events.

3.2.5. Snowmelt erosion and flooding

Snowmelt runoff is an important factor in flooding and soil erosion in higher and cold regions of the world. In Nordic countries of Europe, snowmelt processes significantly affect water resource recharge but also the occurrence of natural hazards (overland flow, flooding and shallow erosion) (Øygarden, 2003; Kremsa et al., 2015). The mechanism of surface runoff formation from frozen soil is completely different compared to surface runoff caused by torrential rains on unfrozen soil (Hejduk and Kasprzak, 2004), which means that permanent grasslands are more prone to generate snowmelt erosion and runoff compared to other land uses. When snow melts, the magnitude of the runoff event depends on the soil frozen layer structure, which is increased from the discontinuity and the heterogeneity of the icy layer. Tillage and fertilization practices increase the volume, the surface roughness and the formation of a heterogeneous soil frozen layer that increases the runoff formation, which explains its importance for permanent grassland (Nyberg et al., 2001; Miller et al., 2017). Kremsa et al. (2015) studied the snow layer in forest and in grasslands, observing that in forest areas, the snow-depth was 26% higher. This was explained particularly by wind effects and higher snow erosion in the open landscape. The final snowpack depletion in the forest occurred over 44 days, compared to 25 days in grassland areas, with a mean melt intensity 7 versus 10 mm day^{1}. Chanasyk et al. (2003) found that surface runoff from grasslands in Alberta (Canada, c. 1300 m a.s.l.) were much higher during snow melt in early spring compared to summer runoff after heavy storm rains. The early spring runoff accounted for 78% and 96% of total annual runoff from mown and grazed grasslands, respectively. Snow thaw was much faster on ungrazed grassland (2 days) compared to grazed (10 days), probably due to residual biomass on ungrazed stand and deeper frost penetration on the grazed stand due to soil compaction (higher heat conductivity). Hejduk and Kasprzak (2004) compared surface runoff from arable land and grasslands in winter seasons. They reported that mown grasslands had a higher susceptibility to formation of surface runoff than winter wheat (sown into tilled soil). In grasslands, a higher surface runoff was caused by quicker thawing of snow cover 'hanging' of the grass stubble and slower melting of soil (icy layer insulated by grass biomass). Soil erosion in winter and early spring can be particularly severe in connection with rain on partially thawed soil (Øygarden, 2003), when infiltration is restricted and fast water flow can detach particles from the thawed soil surface. However, Ulén et al. (2012) stated, that in contrast to rain, snowmelt is a gentler process.

3.2.6. Avalanche erosion

The problem of soil erosion by snow is becoming increasingly relevant. Besides that occurring in spring by snowmelt discussed in the previous paragraph, winter avalanches might contribute strongly to soil erosion in alpine grasslands (Ceaglio et al., 2011; Jomelli and Bertran, 2001). Identifying and classifying avalanche formation is complex; its multifactorial nature means that local conditions influence its pathway and dynamics (Schweizer et al., 2003). Snow avalanches are both an erosional and flooding process, and may modify or produce other erosion processes, such as gullies and landslides (Luckman, 1977). Meusburger et al. (2014) assessed the importance of snow gliding or avalanches for soil erosion in grasslands of the Swiss alps. They compared modelled erosion rates using the RUSLE model with measured erosion rates, using Cesium-137 radioisotopes, and found a large difference that could be attributed to the effect of avalanche erosion. They also measured soil deposition by avalanches directly during one year, obtaining soil erosion rates between 0.03 and 22.9 t ha^{-1} yr^{-1}. Stanchi et al. (2014), developed the winter factor (W-factor) to adapt the RUSLE model. W-factor is the ratio between the ^{137}Cs derived erosion rates, including all erosion processes, and erosion rates modelled by RUSLE, that only include sheet and rill erosion. However, avalanche parameterization and the soil erosion assessment derived from it, are still relatively new and much more research is needed.

3.3. Processes promoting erosion and flooding

3.3.1. Compaction due to trampling and wheeling, poaching and pugging

Soil compaction is the process of densification and distortion of soil leading to lower soil pore volume, resulting in loss of one or more of the soil's functions (Akker et al., 2004). Soil compaction is a major soil threat in Europe where about 32% of soils are highly susceptible and 18% are moderately susceptible to it (European Commission, 2021b). In permanent grasslands, soil compaction occurs due to animal trampling, machinery wheeling and poaching or pugging (i.e. penetration of soil surface by the animal hooves). It represents one of the main factors that leads to degradation of soil physical quality (Imhoff et al., 2000). It negatively affects soil structure, water retention, water uptake, soil porosity, soil nutrients and grass production (Freddi et al., 2009; Hargreaves et al., 2019; Silva et al., 2015). Heavy animal grazing and introduction of larger machinery in European grasslands has led to compaction becoming a more common phenomenon. In addition, poaching or pugging can stimulate water runoff, expose soil surface to water erosion and cause damage to swards (Evans et al., 1999). Johnson et al. (1993) found that pasture with a reduction in growth due to pugging/poaching can be effectively renovated by undersowing. The structural damage of soil due to compaction in Europe can be very serious, especially when the soil conditions become wet. In Ireland, Bondi et al. (2021) noticed that poorly drained fields were highly vulnerable to wheeling intensity. One of the effective indicators for soil compaction in grazed pastures is penetration resistance (resistance of soil matrix to penetration by growing roots) (Benevenute et al., 2020), which is very sensitive to compaction by animal trampling (Scholz and Hennings, 1995). Mapfumo et al. (1999) and Ludvíková et al. (2014) reported that heavy grazing, even for a short period, significantly increased the penetration resistance, and reduced vascular plant richness, overall plant species composition, plant cover and sward height.

3.3.2. *Hydrophobicity and water repellence*

A specific phenomenon that occurs especially on grasslands with sandy and organic soils is called hydrophobicity or soil water repellence (SWR). It can decrease the infiltration rate of soil and increase the potential for surface runoff in response to rainfall (Bauters et al., 2000; Dekker et al., 2001). The likelihood of SWR increases as the soil surface dries out in warmer months (McDowell et al., 2020). One of the factors that creates SWR can be manure applications, or the presence of certain plant waxes on soil particles (Miller et al., 2017). Infiltration in hydrophobic soils is limited to preferential pathways that increase leaching of pesticides and nitrates from the soil (Aamlid et al., 2009). The cause is usually the coating of soil particles with hydrophobic compounds, which are produced by the plants themselves (leaf waxes, root exudates) or microorganisms (especially fungi). Hydrophobicity is also often caused by irreversible changes in organic colloids as the soil dries out. To reduce the negative phenomena caused by the hydrophobicity of soils, it is possible to use soil wetting agents, the application of which, however, is justified in view of the high price only in intensively treated turfgrasses and in fruit orchards (Moore et al., 2010). Lichner et al. (2011) measured the differences between topsoil (sand with roots and organic matter) and subsoil (pure sand) of grassland on sandy soil in SW Slovakia. They found that grassland soil had an index of water repellence about 10 times that of pure sand and the persistence of water repellence almost 350 times that of pure sand. Hydraulic conductivity and saturated hydraulic conductivities in the grassland soil were 5% and 16% of those of the pure sand. The grassland soil was substantially more water repellent and had three times the degree of preferential flow compared to pure sand. Runoff is likely to be exacerbated by water repellence, as it decreases infiltration rates, enhances overland flow and increases the risk of soil erosion (Doerr et al., 2000). Water repellence is a transient soil property, which tends to be both spatially and temporally highly variable. It often disappears after periods of prolonged soil wetting, but will usually re-emerge during drier periods when soil moisture falls below a critical threshold (Dekker et al., 2001). Water flow paths, once created, persist over time during summer, but over annual cycles their spatial arrangements can change completely (Wessolek et al., 2009). Grass cover can induce water repellence in all soil types ranging from sands (Dekker et al., 2001) to clays (Dekker and Ritsema, 1996) by both root exudates and thatch (the layer of organic matter between the mineral soil and the green grass).

3.3.3. *Fires in Mediterranean pastures*

Fire is an important natural landscape shaping agent, and the Mediterranean area is the most fire-prone zone of Europe due to land use and climate (Pausas, 2004). Depending on the fire characteristics, as the intensity or the severity, it can cause shorter or longer-term impacts (Vieira et al., 2015). The most important short-term impact, in terms of soil erosion risk, is the reduction of the vegetation cover which increases runoff and erosion (Soler and Sala, 1992; Zavala et al., 2014). Moreover, fire events can cause deterioration, partially or completely, the soil structure, the porosity and increase the bulk density (Mataix-Solera et al., 2011). Consequently, fire produces negative impact on the soil hydraulic properties (Imeson et al., 1992). Studies reported that it can also reduce soil aggregate stability that can contribute to an intensification of soil detachment (Llovet et al., 2009; Ubeda and Bernia, 2005), and, raise soil repellence (Doerr et al., 2000). Pardini et al. (2017) assessed the effect of fire on runoff and soil loss in grassland and olive orchard, observing a remarkable runoff and soil loss mitigation of permanent grassland. Despite these negative effects summarized above, prescribed fire is a common management practice in the Mediterranean, aimed at burning bushland in favour of pasture. It is considered an efficient and cost-effective land management practice for livestock feed production. In arid and semi-arid climates, prescribed fire executed in late spring exposes erosion-prone sites to elevated summer runoff and soil loss events (O'Dea and Guertin, 2003). The effect of fire on erosion is widely studied. Shakesby (2011), reviewed the post-wildfire soil erosion in the Mediterranean basin and found only 6% of the reviewed studies focussed on the permanent grassland land use. Vieira et al. (2015) reviewed 109 studies globally about the effect of post-fire on erosion and runoff generation, claiming that 63% of studies are located in the USA, 25% in Spain, and only 10% of those are focussed on permanent grassland land uses. According to these global studies, it is clear that fire risk affects mainly forest land, and fire risk in permanent grassland is lower, but if it occurs, it causes significant damage.

4. Conclusions

Our study provides a deeper overview of the importance of permanent grassland for erosion and flood mitigation in Europe and the UK. Firstly, a quantitative meta-analysis evaluated four erosion and flooding-related indicators, bulk density, hydraulic conductivity, runoff and soil loss, between three land uses: permanent grassland, arable land and forests. In total 24 articles were analysed, after screening over 14,203 articles. The results showed that on the one hand, in comparison with arable land, results are often in contrast to the widespread opinion of topsoil structural amelioration of grassland. In fact, no significant differences have been reported comparing bulk density and hydraulic conductivity and soil loss, highlighting the temporary effect of tillage and of the local environmental conditions that can promote soil degradation (i.e. fire). On the other hand, permanent grassland mitigates better runoff than arable land. In contrast with forest land, differences are not clear cut, suggesting that soil erosion and runoff mitigation condition are similar between the two land uses, except for the hydraulic conductivity which is higher in forest land.

However, these general indicators are limited in scope. A second, broader review showed how European permanent grasslands suffer from additional land degradation hazards. This additional review identified six processes important for soil erosion in European grasslands: trampling-induced erosion, gullying, piping, landsliding, snowmelt erosion and avalanche erosion. All these processes were documented in European grassland to have cause significant erosion problems locally. At present, their extent and regional impact is mostly unknown. These are boosted by several promoting processes related to soil management and environmental conditions: compaction, hydrophobicity and wildfires. In summary, although permanent grasslands are considered crucial for the reduction of soil loss and flood, they are under degradation risk. Due to the complex nature and the interconnection between erosion and flooding processes, and the lack of knowledge on many of the processes involved, their assessment, understanding and modelling are still often challenging. Therefore, these processes must be studied more in detail in order to get a good view of the status of European permanent grasslands. This will help with designing a site-specific soil management strategy for European grasslands, aiming at the zero net land degradation goals promoted by the Green Deal.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Filippo Milazzo reports financial support, administrative support, equipment, drugs, or supplies, statistical analysis, travel, and writing assistance were provided by University of Cordoba. Filippo Milazzo reports a relationship with University of Cordoba that includes: employment.

Data availability

Data will be made available on request.

Acknowledgements

This research is funded by the European Union, under the Horizon 2020 project “Developing SUstainable PERmanent Grassland systems and policies (Super-G)”, grant no. 774124. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European UnionEU or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. Vanwalleghem and Milazzo also acknowledge additional financial support from the Spanish Ministry of Science and Innovation, the Spanish State Research Agency, and through the Severo Ochoa and María de Maeztu Program for Centers and Units of Excellence in R&D (Ref. CEX2019–000968-M).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108443.

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