Irish Geography
Vol. 58, No. 2 November 2025
DOI: 10.55650/igj.2025.1524

The potential impact of climatic change on landslides in Ireland

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First received: October 2025 *Accepted for publication: April 2026*

Abstract: This paper presents a position-based review of how climate change may influence landslide hazards in Ireland, drawing on existing datasets and published examples. We focus on the climate parameters commonly associated with slope instability, including rainfall intensity and duration, prolonged dry and rewetting cycles, storm tracks, wind, and wave action. To illustrate how projected climate changes may affect landslide activity in Ireland, we draw on data from a new all-Ireland landslide inventory employ and draw upon three selected case studies to show how meteorological conditions affect slope failure. Our analysis of hourly rainfall preceding these selected landslides shows that failures, particularly in peatlands, may occur under varying hydrometeorological conditions. In two cases, landslides followed intense rainfall after prolonged dry periods, while in another, failure occurred during an extended period of persistent wetness. Based on this and broader evidence, we suggest that landslide frequency in Ireland is likely to increase under future climate conditions characterised by more intense rainfall and greater variability in wet and dry spells. While most well documented events to date involve peat failures, we note a significant data gap regarding coastal slope failures, where climate-driven changes in sea level and storm dynamics may have compounding effects. Addressing these gaps is essential for improving future landslide risk assessment and mitigation strategies.

We propose that future landslide research in Ireland prioritise several key areas. First, there is a need for detailed investigation into the role of rainfall intensity, duration, and temporal variability in triggering mass movements, particularly under changing climatic conditions. Second, long-term (multi-decadal) studies should be undertaken to capture the full range of slope responses to individual events and to sequences of storms, helping to distinguish between immediate triggers and cumulative preconditioning factors. Third, more frequent and systematic monitoring is needed, including annual topographic surveys and rapid post-event assessments, to document geomorphic change and improve hazard forecasting. Finally, dedicated research is required to understand the interaction between sea-level rise, storm surges, and wave impacts on coastal landslides, where both marine and terrestrial processes are important.

Keywords: *Landslides, climate change, Ireland.*

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1. Introduction

This paper presents a position-based review of how climate change may influence slope-failure (landslide) hazards in Ireland, drawing on a recently published all-Ireland inventory and selected case studies. Globally, landslides can be triggered by a number of singular and complex causes, such as seismic activity, subsidence and human activities (Donnelly *et al.,* 2001; Rodrıguez *et al.,* 1999). Ireland's landslide inventory includes more than 3000 entries, with peat failures, translational slides, and debris flows being most common (Creighton and Group, 2006; Cullen and Bourke, In press). Historical under-recording further obscures long-term trends (Creighton and Group, 2006) but landslide occurrence is expected to increase further in the next century. Dykes (2022) suggests that a rise in slope instability in Ireland may be linked to increased rainfall. Moreover, several studies have predicted that there will be an increase in the exposure of people and infrastructure to landslides (Davies, 2015). This paper focuses on slope instability processes, primarily landslides, including peat failures, debris flows, rock falls and shallow translational slides. We examine the historic, current and projected climate parameters commonly associated with slope instability, including rainfall intensity and duration, prolonged dry and rewetting cycles, storm tracks, wind, and wave action.

The most cited cause of landslides in Ireland (which has been reported for over 200 years (see Leonard, 1821, cited in Sollas *et al.,* 1897 p.499) is an excess of precipitation. The most common type of landslide reported occurs in organic soils (peats) that developed during the mid to late Holocene and cover 20.6 % of the landscape (Connolly, 2018). The blanket bogs which cover upland hillslopes are a unique wetland system and are subject to specific types of failure (e.g., bog slides, peaty-debris slides, bog flows, flows and bursts), although bog flows and bog slides are less common and relatively unreported outside Ireland (Dykes, 2022). Indeed, so important are landslides in peat that they warranted the generation of an addendum to existing landslide classifications (See Dykes and Warburton, 2007). Global Climate Models (GSMs) models suggest that global precipitation extremes will occur more frequently under medium and high emission pathways (Thackeray *et al.,* 2022), which could increase the frequency and magnitude of these types of slope failure.

Another land system subject to landslides is the extensive coastline of Ireland. It is estimated to be about 7000 km in length and composed of a mix of rocky cliffs, Quaternary sediment cliffs, sand deposits and anthropogenic structures (Devoy, 2008). The coastline is subject to ongoing wave and subaerial erosion (Cooper, 2013). However, the rates and dynamics of landslide processes are understudied, particularly as individual cliff-top assets will be lost due to coastal slope failure. Projected changes to sea-level, wind and wave action and storm frequency will impact on these landslide types.

A record of the past and current response of slopes to weather is an important step in providing a record of the past and current response of slopes to weather is an important step in providing a reliable baseline in order to predict future response to changes in climate. For a better understanding of past landslides, numerous studies have investigated paleo-landslide records to link their activity to past climate changes;

others have examined whether modern landslide reactivations are related to specific recent weather trends (Borgatti and Soldati, 2010; e.g. Bovis and Jones, 1992; González Díez *et al.,* 1996; Schmidt and Dikau, 2004). Studies of more recent landslides have benefited from detailed weather data and climate models. These analyses suggest an overall increase in the frequency of all types of landslides, particularly in locations of cryosphere changes (Ballantyne, 2002; Huggel *et al.,* 2010; Jacquemart *et al.,* 2024; Paranunzio *et al.,* 2016; e.g. Stoffel *et al.,* 2014). Studies examining the future response of slopes to climate change highlight the requirement for a bespoke approach that integrates local slope properties, drainage and hydrology, projected weather forcing, and land-use conditions (e.g. Ciabatta *et al.,* 2016; Dijkstra *et al.,* 2017; Gariano and Guzzetti, 2016; Pacheco Quevedo *et al.,* 2023).

National Landslide Inventories Approaches are commonly used to investigate and understand climate-related landslides but such studies are limited in Ireland (e.g. Martinović *et al.,* 2018). Moreover, regional syntheses linking landslides and climate change have been developed for several other temperate regions (e.g. Coe, 2016; Dijkstra *et al.,* 2017; Gariano and Guzzetti, 2016), but Ireland currently lacks a comparable national evaluation. Here, we start the process of developing a comprehensive landslide assessment for Ireland that can be used to manage these hazards in a changing climate. The structure of this work is as follows:

1. First, we use published sources to summarise the climate of Ireland from Holocene to future modelled projections.
2. Second, we use a landslide database (Bourke and Cullen, 2024) to review the weather conditions, where known, prior to and at the time of landslides.
3. Third, we undertake a qualitative assessment of the role that climate change may have on landslides, including coastal events, using the approach developed by Crozier (2010).

Finally, we highlight areas of future landslide research for Ireland. The location of all places mentioned in the text are shown in Figure 1.

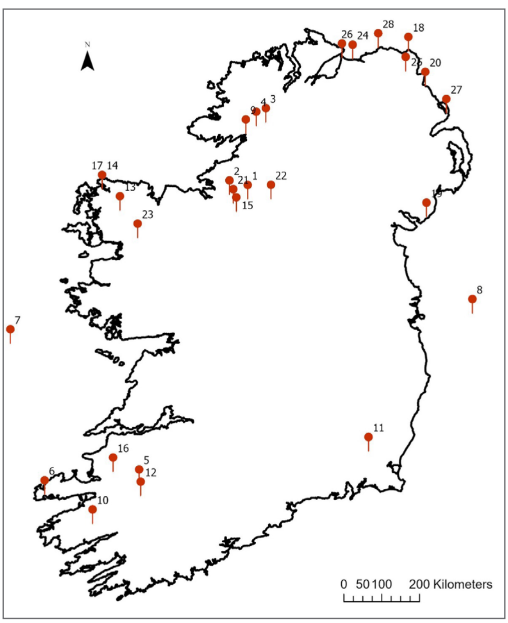

Figure 1. Map of Ireland showing the locations discussed in the text.
1 Shass Mountain, **2** Dromahair, **3** Meenbog, **4** Ardnawark, **5** Mount Eagle, **6** Ventry, **7** Atlantic Ocean, **8** Irish Sea, **9** Donegal, **10** Ballaghbeama Gap, **11** Clonroche, **12** Knocknageeha, **13** Belcorrick forest, **15** Straduff, **16** Ballincollig Hill, **17** Pollatomish, **18** Fairhead, **19** Kilteel, **20** Minnis North, **21** Garvagh Glebe, **22** Cuilcagh Mountain, **23** Croaghmoyle, **24** Downhill, **25** Trostan, **26** Macgilligan, **27** The Gobbins and **28** Giants Causeway.

2. Ireland's climate

A robust assessment of landslides under changing climate scenarios requires knowledge of past, present and future climate conditions. Here we briefly review what is currently understood of the past, present and future climate in Ireland.

Ireland has a rich paleoenvironmental record of climate change that identifies key trends throughout the Holocene. These proxy records, derived from speleothem, lacustrine, isotope and peatland studies provide a spatial and temporal chronology of changes in precipitation and temperature during the Holocene (Casparie, 2005; Chambers *et al.,* 2004; Holmes *et al.,* 2010; McDermott *et al.,* 1999; Swindles *et al.,* 2010). These data suggest a shift to wetter conditions at c. 2700 cal. BP and again at 1400 cal. BP and a wet phase from c. 500 to 100 BP. Less humid phases are reported for the periods 3200 to 2750 cal. BP and 2250 to 1550 cal. BP (Swindles *et al.,* 2013).

Ireland's current climate can be described as temperate oceanic, marked by mild summers, cool wet winters, and relatively stable temperatures year-round (Met Éireann, 2023a; Peel *et al.,* 2007). Temperatures are moderate by European standards, averaging 14.6°C in summer and 5.4°C in winter (Met Éireann, 2023a). Rainfall occurs throughout the year but is heaviest in winter, particularly in the west due to prevailing Atlantic airflows. Based on 1991–2020 climate normals, the annual average number of rain days (≥ 0.2 mm) ranges from approximately 199 days in eastern and low-lying regions to upwards of 273 days in elevated western areas (Met Éireann, 2023). Interannual climate variability is strongly influenced by the North Atlantic Oscillation (NAO). Positive NAO phases are associated with wetter, windier winters, while negative phases can also produce intense storms (Hurrell, 1995; Hurrell *et al.,* 2002; Pinto *et al.,* 2009). The mixing of tropical and mid-latitude depressions in late summer and autumn occasionally leads to severe weather events (Met Éireann, 2023a).

Mean wind speeds vary regionally, from 3 m/s in sheltered areas to over 8 m/s along exposed western coasts (Met Eireann, 2026). Gale-force winds (>17.2 m/s) are common in the northwest, with up to 66 such days annually recorded at Malin Head (Met Éireann, 2023b). Wind patterns are further modulated by the NAO, Eastern Atlantic (EA), and Scandinavian (SCA) climate modes (Zubiate *et al.,* 2017). Extratropical cyclones affect Ireland year-round, with evidence suggesting increasing intensity in recent decades, though trends remain uncertain (Matthews *et al.,* 2016). Storm surges are most frequent in winter and linked to NAO variability (Marcos *et al.,* 2015; Menéndez and Woodworth, 2010). Surge-related erosion is particularly significant along Ireland's meso- and macrotidal coasts (O'Brien *et al.,* 2018). Ireland's Atlantic coastline experiences one of the most energetic wave climates globally. Winter significant wave heights (the average height of the highest one-third of waves) average 5 m in the west and 1 m in the east (Gallagher *et al.,* 2013). Rogue waves exceeding 20 m have been recorded (O'Brien *et al.,* 2018) and while rare, can cause substantial geomorphic change.

Analysis of long-term Irish meteorological records by Murphy *et al* (2023) reveals an emerging anthropogenic climate change signal in precipitation. At many stations, annual totals have increased relative to early industrial baselines (circa 1750). Analyses of long-term precipitation extremes show a growing contribution of extreme events to annual totals, with the strongest trends observed in the east and southeast of the country (Ryan *et al.,* 2022). Long-term Irish meteorological records show a detectable warming signal in both average and extreme temperature behaviour, with observed changes at a number of stations exceeding the range of early industrial natural variability (Murphy *et al.,* 2023).

Climate projections are derived from high-resolution regional climate models and ensemble approaches. Recent work from the Environmental Protection Agency (2023) and Nolan (2024) provide the most robust and up-to-date assessments of likely climate futures. These projections are based primarily on Shared Socioeconomic Pathways (SSPs), which consider a range of greenhouse gas emissions and global development trajectories (O'Neill *et al.,* 2017). The most commonly used scenarios include SSP2-4.5 (a stabilisation pathway) and SSP5-8.5 (a high-emissions pathway). Projected changes are considered for the mid-century (2041–2060) relative to a 1981–2000 baseline.

Precipitation

Future precipitation in Ireland is projected to change in complex and seasonally variable ways. Ensemble model results show a general increase in winter precipitation with uncertainty in magnitude and spatial distribution (EPA, 2023). Global ensemble projections suggest a tendency towards wetter autumns and winters and drier summers, although this signal is not consistent across all models (EPA, 2023). Complementary high-resolution national simulations by Nolan (2024) show a broadly similar pattern, with increasing autumn and winter precipitation and more frequent heavy rainfall extremes, but with considerable spread and regional variability. These seasonal shifts are expected to alter the hydrological regime, with potentially important implications for slope stability (Gariano and Guzzetti, 2016).

Temperature

Global ensemble projections indicate warming across all seasons under all emissions scenarios (EPA, (2023). Projected mid-century temperature increases show variability across emissions pathways and considerable ensemble spread in seasonal and regional patterns (Nolan, 2024). Warming will reduce the frequency of frost days and may substantially reduce the occurrence of freeze–thaw cycles, particularly in upland regions. This could potentially increase geomorphological hazards, e.g. rockfalls, affected by freeze thaw processes (D'Amato *et al.,* 2016), but knowledge of it is still not sufficient due to the lack of exhaustive and precise rockfall databases. Additionally, dry spells are projected to increase in summer, amplifying drought risks, which could in turn impact antecedent conditions leading to slope failures on rewetting (EPA, 2023).

Drought termination events, intense rainfall following prolonged dry spells, have been highlighted in hydrological studies of the British–Irish Isles as abrupt climatic shifts (Parry *et al.,* 2023).

Storminess, wind and waves

Atmospheric modes of variability, particularly the NAO, are projected to remain key drivers of interannual and decadal variability in storminess and precipitation over Ireland. Projections for storm frequency and intensity remain highly uncertain (EPA, 2023). A collapse in the Atlantic Overturing Meridional Circulation (AMOC) would likely result in an increase in storminess (EPA, 2023). Wind speed projections suggest minor to moderate reductions in 10 m mean wind speed across Ireland but with high uncertainty (Nolan, 2024). In the marine environment, significant wave height is projected to decrease slightly but changes in extreme wave heights, related to storminess in the Atlantic, are highly uncertain (Dabrowski *et al.,* 2023).

3. Climate change and landslides

Aligning the specific effects of climate change with landslide activity is limited by uncertainties. Conditioning and triggering factors for slope stability vary spatially and temporally and this complicates any attempt to extract a simple relationship between climate change and an increase in magnitude or frequency of landslides. Dykes *et al.,* (2008) emphasised the dominant role of geomorphological and hydrological controls on landslide occurrence, with rainfall acting as a trigger on predisposed terrain. This highlights that long-term slope processes can strongly condition failure thresholds alongside climatic forcing. Others have tentatively suggested an increase in landslides clustered around high magnitude rainfall events (Long *et al.,* 2011). Martinović *et al.* (2018) concluded that antecedent rainfall and intense falls lead to failure of natural and anthropogenic slopes. While 'slope stability' refers broadly to the physical condition of sloping terrain, the term 'landslide' is used throughout this paper to refer to specific types of mass movement events.

Climate projections summarised above suggest the following trends for Ireland: 1. Wetter antecedent conditions, 2. Higher rainfall intensities 3. Dry antecedent conditions (followed by intense precipitation). In the following sections, we address these trends and use examples of previous landslides sourced from the all-Ireland inventory (Bourke and Cullen, 2024) where environmental conditions were recorded to identify the weather conditions associated with landslides in Ireland. This paper draws from that inventory but focuses on three recent failures as illustrative examples; these were selected due contrasting settings and data availability, particularly around the antecedent conditions and timing of failure. We use these observations to suggest the likely future response to projected climate changes. Table 1 provides a summary of projected climate changes for Ireland and their potential impacts for landslide occurrence.

Table 1. Projected Mid-Century Climate Changes in Ireland and Potential Implications for Landslides
Climate projections adapted from EPA (2023), Nolan (2024) and Dabrowski et al (2023).

Climate Variable	Projected Change	Implications for Landslides
Winter precipitation	Tendency towards wetter winters (EPA, 2023 and Nolan, 2024)	Greater soil saturation; potentially higher risk of rainfall-triggered failures
Summer precipitation	Tendency towards drier conditions overall (EPA, 2023)	Drier antecedent conditions; vegetation stress
Extreme precipitation events	Increased frequency and intensity with further warming	More short-duration, high-intensity triggers
Mean annual temperature	Warming under all scenarios; magnitude scenario-dependent	Reduced soil cohesion; vegetation stress; fewer freeze–thaw cycles
Frost days	Decline in frequency of 29% under SSP1-2.6)	Potentially fewer rockfalls driven by freeze–thaw processes
Dry spells (summer)	Tendency towards drier summers; magnitude uncertain	Enhanced risk of drought–rewetting slope failures
Storminess and winds	Uncertain	May alter spatial patterns of heavy rainfall and wind
Significant wave height	Overall decrease (by 2100)	Erosion potential on coastal cliffs and slopes
Extreme waves	Highly uncertain	Erosion potential on coastal cliffs and slopes

3.1 Wet antecedent conditions

Periods of wetter-than-normal conditions are known to reduce the rainfall threshold required to trigger slope failure. This is due to an increase in the bulk density of the material followed by a reduction in the ratio of shear strength to shear stress promoting instability (Crozier, 2010; Crozier, 1986). There are several reports of antecedent wet conditions prior to slope failure in the literature. Cullen and Bourke (In press) found that of the 163 landslides that reported weather in the all-Ireland inventory, 13% noted wet antecedent conditions. The 1993 failure in the Sperrin Mountains of Northern Ireland followed a period of above average monthly rainfall and a high magnitude rainfall event on the preceding day. In Straduff townland Co. Sligo (Fig. 2) in 1984, 25% of the October average rainfall fell in the 3 days prior to the failure of a peat bog (Alexander *et al.,* 1986). Moreover, Martinović *et al.,* (2018) found that 63% of landslides occurred during the annual wet period (November to January).

Theoretically, higher and perched water tables would facilitate the attainment of the critical thresholds more frequently as a result of the reduction in shear strength caused by increased pore water pressure (Brooks *et al.,* 2004; M. Crozier, 2010). This is particularly important for water tables in peat, which are generally higher (Feehan and O'Donovan, 1996). A geotechnical analysis by Long *et al.* (2011) of a peat slide at Ballincollig Hill in Co. Kerry, which occurred after heavy rainfall, indicated that the factor of safety was sensitive to the location of the water table. The factor of safety refers to the ratio of resisting forces to driving forces acting on a slope. Slope instability occurs when the factor of safety, the ratio of resisting to driving forces, falls below 1. Long *et al.* (2011) reported the margin of safety to be reduced by > 50% where the water table is close to or at ground level compared to a water table which was 1 meter below the failure plane.

High and perched water tables are also important in other failure types in Ireland. Several rock falls, mudslides and landslips south of Fair Head, Co. Antrim (Fig. 2) were attributed to a perched water table above impermeable Liassic clay (Stephens, 1970). McGreal and Craig (1977) examined the differing responses of a slope composed of glacial till to groundwater conditions at Kilkeel, Co. Down and Minnis North, Co. Antrim (Fig. 2). They found that patterns of shallow slope failure coincided with groundwater fluctuations and corresponded to periods a) where groundwater levels were at a maximum and b) periods of rapidly rising groundwater.

We note that antecedent rainfall conditions may be decoupled from the timing of the failure event. Some hillslopes exhibit a delay between the receipt of rainfall and the moment where the stability threshold was exceeded. For example, a failure which occurred in August of 2008 at Ballincollig, Co. Kerry (Fig. 2) was preceded by several weeks of wet weather with daily average precipitation of up to 49mm. Yet low rainfall was recorded in the days leading up to the event (Long *et al.,* 2011). It was similar to the failure at Garvagh Glebe North in Co. Leitrim (Fig. 2) in September 2009 where a period of intense rainfall occurred 1-2 weeks before the event was followed by dry weather (Long *et al.,* 2011). This aspect is not well understood and requires further study.

These and other studies support the proposition that wetter antecedent conditions arising from increased precipitation as a consequence of climate change, will likely see an increase in slope failure in Ireland, particularly where other contributing factors to slope instability are present.

3.2 Increased rainfall intensity

Landslides triggered by intense rainfalls have been reported for Ireland (e.g. Long and Jennings, 2006). Climate model outputs suggest an increase in the frequency of intense rainfall especially during autumn and winter (EPA, 2023; Nolan, 2024). As the rainfall intensity increases it becomes more likely that the infiltration capacity of the soil will be exceeded (Crozier, 1986). Where this occurs, a perched water table may form, and the likelihood of failure may increase (see above).

Intense precipitation may also facilitate greater throughflow (Long *et al.,* 2011), increasing shear (drag) stress, removal of underlying material and soil piping. The presence of soil pipes can enhance sub surface drainage or, where they collapse, can lead to an increase in pore water pressure. Dykes *et al.* (2000) analysed the triggering factors for failure for multiple peat slides on the slopes on Cuilcagh Mountain in Northern

Ireland (Fig. 2) and found that the factor of safety was reduced to less than 1 when the contribution of a collapsed drainage ditch and soil pipes were considered.

Similar sub-aerial processes that contribute to slope instability described for inland mass movements, are also contributory factors to coastal cliff instability. Some have highlighted the role of heavy rainfall in contributing to rock falls (McKenna *et al.,* 1992) often working in combination with freeze-thaw conditions. Wilson and Cunningham (2014) carried out a study on rock falls on the Antrim coast. They determined that it was a combination of frost related process and high cleft water pressures in the basalt from heavy rainfall that triggered the 2002 failure in the Downhill area of Co. Derry.

3.3 High antecedent rainfall followed by intense rainfall.

Rainfall characteristics such as the duration, spatial and temporal heterogeneity or homogeneity of precipitation are important in controlling landslide activity (Von Ruette *et al.,* 2014). There are several case studies that support the importance of high antecedent rainfall followed by an intense precipitation for landslides. For example, the 1896 bog flow at Knocknageeha, Co. Kerry (Fig. 2) was reported to occur after a wet autumn was followed by heavy rainfall (Cole, 1897; Praeger, 1897). A number of bog flows and debris flows in the north of Ireland in 1965 were preceded by excess rainfall receipts (175-200% of average annual receipts) with high intensities (38-63mm in 24 hours) (Colhoun *et al.,* 1965). A study of anthropogenically steepened and natural glaciogenic slope sediments suggest that 30 mm/hour is the critical rainfall threshold for peaty debris slides in Ireland, particularly following high antecedent rainfall (Martinović *et al.,* 2018).

We suggest that the sequence of wet antecedent conditional followed by intense rainfall events may be a more important conditioning factor for landslides in Ireland than either high antecedent rainfall or intense rainfall events alone. These observations align with other regions that have similar soil/climate/topography (e.g. Scotland, Winter *et al.,* 2010; Winter and Shearer, 2015).

3.4 Dry and or warm antecedent conditions

Climate projections indicate that Ireland can expect drier summers in the future but more frequent intense rainfall events. More frequent wetting and drying cycles will increase fissuring in soils and promote widening of joint fissures in rock thus reducing cohesion and joint friction (Crozier, 2010). There are global theoretical predictions of increased landslide activity due to increases in wetting and drying cycles associated with increased variability in temperature and precipitation regimes (Crozier, 2010). These have applications in Ireland as peatlands are affected by summer drying. Cracking of the peat surface may result in a greater susceptibility to decomposition and erosion in wetter conditions. Several landslides in peat are notable for the role that preceding periods of dry weather followed by heavy rainfall may have played e.g., Pollatomish, Dooncarton Mountain in 2003 (Creighton and Verbruggen, 2003). At Belcorrick Forest in Co. Mayo 1988 (Fig. 2), a bog flow occurred during a particularly heavy rainfall event preceded by 2 months of drought and then the wettest July in 30 years (Hendrick, 1990). Cullen and Bourke (In press) found that of the 163 landslides that reported weather in the all-Ireland inventory, 4% noted dry antecedent conditions.

Temperature increases would enhance evapotranspiration and lower antecedent soil water content, thus requiring greater event rainfall to trigger failure (Crozier, 2010). Potential evapotranspiration (PET) is cited as important when considering the effects of climate change on slope stability (Van Asch *et al.,* 1999). However others have suggested that any increase in winter precipitation would likely be compensated by the soil deficit produced in summer due to a projected increase in evapotranspiration (Collison *et al.,* 2000) although the evidence to date does not support this and the potential impact on landslide occurrence is still unclear.

In addition to the frequent failure of the blanket peat on Ireland's steeper slopes Long *et al.* (2014) conducted an investigation between slopes and an investigation into the failure of 'raised' bogs situated on 1° slopes. They suggest that factors leading to instability are linked to moisture content but also the build-up of gas leading to the explosion of the peat mass (Long *et al.,* 2014). Projected increases in global temperatures indicate an accelerated build-up of methane in peat (Mastepanov and Christensen, 2009; Svensson, 1984). This suggested the potential for an increase in the frequency of this form of peat failure in Ireland.

Many have highlighted the role of freezing conditions in contributing to rock falls (Douglas, 1980; Prior *et al.,* 1971). Climate warming may decrease the frequency of freeze–thaw cycles that contribute to rockfall activity, particularly in upland or exposed settings (D'Amato *et al.,* 2016). Rockfalls are considered within the broad spectrum of landslides discussed in this paper.

3.5 Increased wind speed

Climate projections indicate an overall reduction in wind speed (Nolan, 2024) although there is high uncertainty. Increases in the speed and duration of wind may enhance evapotranspiration (Crozier, 2010), reduce soil moisture and produce a similar effect to that of increased temperature described above. Prolonged, high speed winds may also enhance wind throw and tree root levering thus reducing slope stability through loosening or dislodging of slope material (Crozier, 2010; Dhubhain *et al.,* 2001).

For coastal landslides, marine processes are also important. While the projections of increased storm frequency and intensity are subject to significant uncertainty (EPA, 2023; Nolan, 2024), projected increases in sea level rise (SLR) alongside any potential increase in storm frequency and/or intensity has the potential to increase coastal landslides frequency. McKenna *et al.* (1992) identified a variety of marine conditions associated with rock falls in basalt cliffs along the northeast coast of Ireland in the face of projected climate change, these included storm surges, abnormal wave conditions and undercutting by marine erosion. For rock coasts, wave-induced micro-seisisms have been suggested to have a role in promoting rock fatigue (Adams, 2005; Lim *et al.,* 2010; Norman, 2012).

4. Landslide case studies

The following describes the response of three blanket bog locations to the antecedent moisture conditions. We include this to provide an illustration of the potential response of soils on slopes to the projected climate changes described above. Weather conditions during the 2020 summer and autumn were unusually dry and warm, followed by intense summer and winter storms and long-duration rainfalls. As antecedent conditions are known to increase susceptibility to landslides, especially in organic (peat) soils, we examined the rainfall conditions that preceded three separate failures in blanket bog in Ireland in 2020. Rainfall data are taken from the Met Eireann historical data (Met Éireann, n.d.).

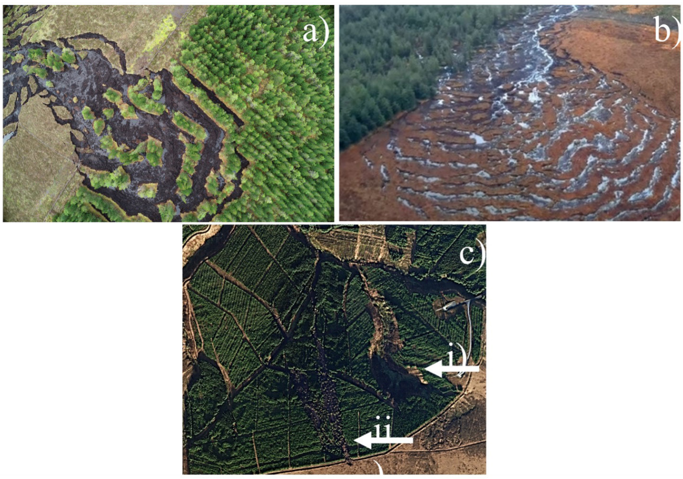

Figure 2. Images of the three 2020 blanket bog failures, Ireland. a) Shass mountain, Co. Leitrim (Source: drone Image, M. Bourke) b) Meen Bog, Co. Donegal c) Eagle Mountain, Co. Kerry. Additional un-reported landslide that occurred sometime between 2012 and 2020)

The Shass Mountain peat failure (54°12’31.33”N, 8° 4’38.31”W) occurred in June 2020 in Co. Leitrim. The site is located on peat-covered slopes that are used for commonage grazing. The peat upslope to the failure has been drained for extensive Sika Spruce plantations (Fig. 2a). The Meenbog failure in Co. Donegal (54°43’6.31”N, 7°52’32.66”W) occurred in November. The peat adjacent to the failure has been drained for extensive Sika Spruce plantations (Fig. 2b) and the area is also the site of wind farm construction. The Mount Eagle failure Co. Kerry (52°13’35.11”N, 9°18’18.45”W) (Fig. 2c) occurred two days later in November. It is located within peatland drained for extensive Sika Spruce plantations (Fig., 4ci). The area is also the site of wind farm construction. Interestingly, it is located adjacent to another landslide which image data indicate occurred between 2012 and 2020 (Fig. 2cii). Landslide susceptibility ratings for all three sites were in the lower range (Bourke *et al.,* 2021). General data on the landslides is listed in Table 3.

Table 2: Landslide data for 2020 events.

	Shass Mountain, Co. Leitrim	Meen Bog, Co. Donegal	Mt Eagle, Co. Kerry
Date of landslide	28/06/2020	13/11/2020	15/11/2020
Distance to rainfall station (km)	17	10	70
Average annual rainfall (mm)	1270.25	1892	1166.1
Average (event month) rainfall (1961/1983-2020)	88.1	194	139
Length of storm (days)	4	4	6
Storm total (mm)	84.9		68.6
Event month rainfall total (mm)	179	264	121
Cumulative 10-day antecedent (mm)	101.3	46.1	67.3
Cumulative 27-day antecedent rainfall (mm)	118.3	273	200.7
27 days rainfall prior as percentage of annual average (%)	13	14	17.2
Deviation of event month from monthly average (%)	103	36	-13
Very wet days (>10 mm)	5	22	7
Wet Days (>1 mm)	16	10	19

The antecedent rainfall for the landslides is shown as the deviation from the monthly average for the months (6 months max) preceding the event in that calendar year and the cumulative rainfall totals in the preceding 28 days for each failure. It is plotted with the long-term average for that month (dashed line). For Shass Mountain, the dry spring conditions are evidenced by the lower-than-average rainfall receipts in March – May (-72% deviation from the long-term average, Fig. 3). June was also dry at the beginning of the month (Fig. 3), however, the rapid increase in cumulative rainfall conditions in the last week of June (Fig. 4) resulted in the total June rainfall being double the average (+103% in excess of the long-term monthly average) (Table 3).

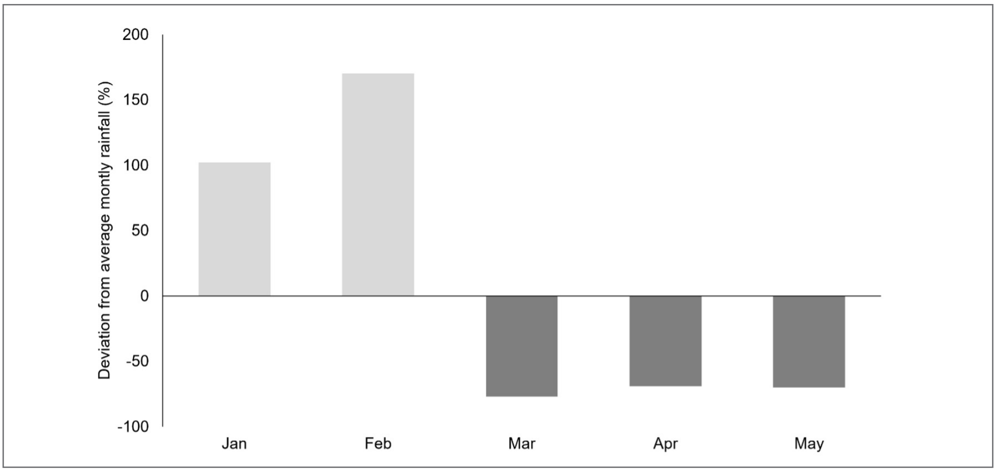

Figure 3. Deviation (%) from average monthly rainfall (1961-2019) in the 5 months preceding the Shass Mountain landslide, Co. Leitrim on the 28th of June 2020. Positive values represent above average rainfall; negative values represent below average rainfall.

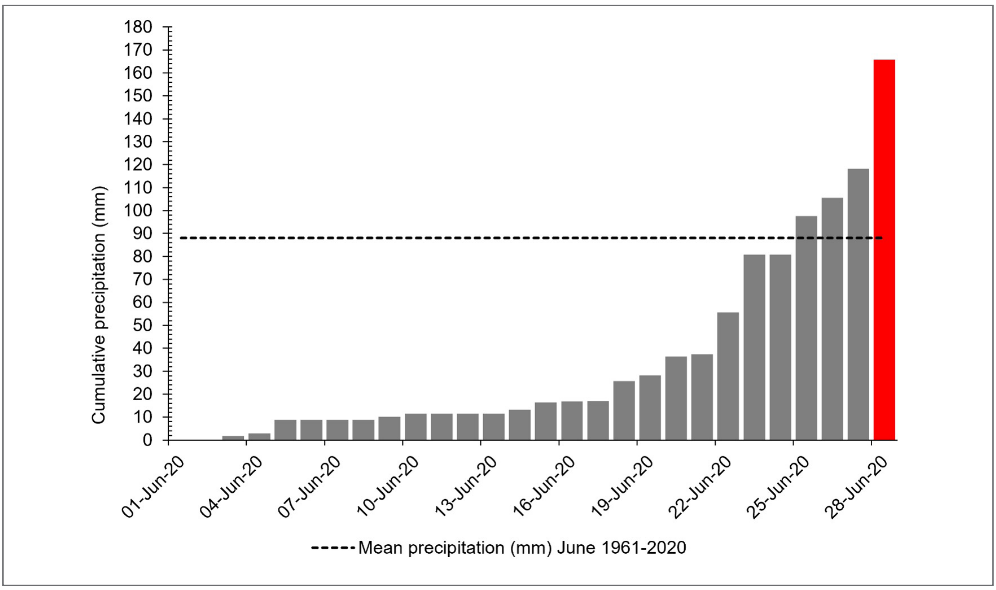

Figure 4. Cumulative precipitation for the 28 days leading up to and including event date for Shass Mountain landslide, Leitrim on the 28th of June 2020. Mean June precipitation for June (dashed line) is derived from Met Eireann records (1961-2020) from the Dromahair (Market Street) weather station located approximately 17 km from the failure site.

For Meenbog, May and July rainfalls were also significantly lower than average (-56% of long-term monthly average) and June was significantly wetter, (+124%) (Fig. 5). However, there are no reports of failure at this site in June. Autumn and winter rainfalls were higher than average (Fig. 5). Although not as high as June, rainfalls from August through November were 33% above average and the 28-day cumulative rainfall exceeded the November average two weeks before the failure (Fig. 6) (Table 3). November in Donegal is a wet month in the annual calendar with an average of 194 mm of rain (Met Éireann, n.d.). In 2020, 12 of the 28 days prior to the failure are noted to be very wet days (>10mm) with several days recording > 25 mm rain (Fig.8) (Met Éireann, n.d.). The 10 and 11th of November recorded 30 mm. The days immediately preceding the reported failure had relatively low rainfall amounts (5 and 6mm) (Table 3).

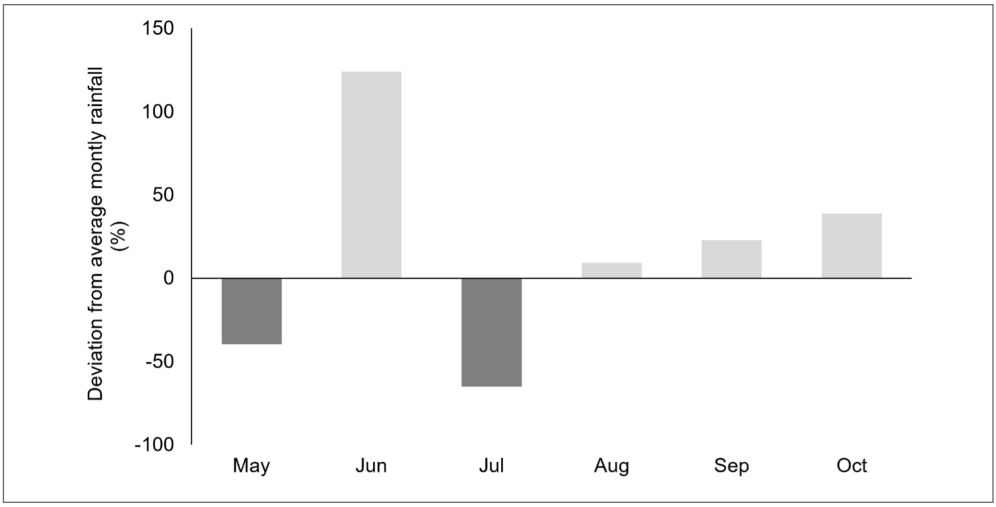

Figure 5. Deviation (%) from the long-term average monthly rainfall (1982-2020) for the six months preceding the event month for the Meenbog landslide, Co. Donegal on 13th November 2020. Positive values represent above average rainfall while negative values represent below average rainfall.

Mount Eagle did not receive the very high June rainfalls recorded at the other two sites (Fig. 7). The May-June rainfalls were about half the long-term average (-45%). July and August were wet months, approximately 67% above the long-term average. Similar to Site 2, July was below average. October had 192 mm rain about 35% above average. The cumulative rainfall receipt in the 28 days prior to the failure passed the long-term average at the beginning of November (Fig. 8).

The 5 days before the Shass Mountain failure were wet with approximately 130 mm of rainfall. On the day of the failure 47.5 mm of rain fell. For Mount Eagle, 70 mm fell in the previous 7 days but the highest fall of 32.1 mm was on November 10th with 9.5 mm falling on the day of the failure. For Meenbog, 34.6 mm fell in the 3 days prior to failure and 4 mm on the day of failure (Met Éireann, n.d.).

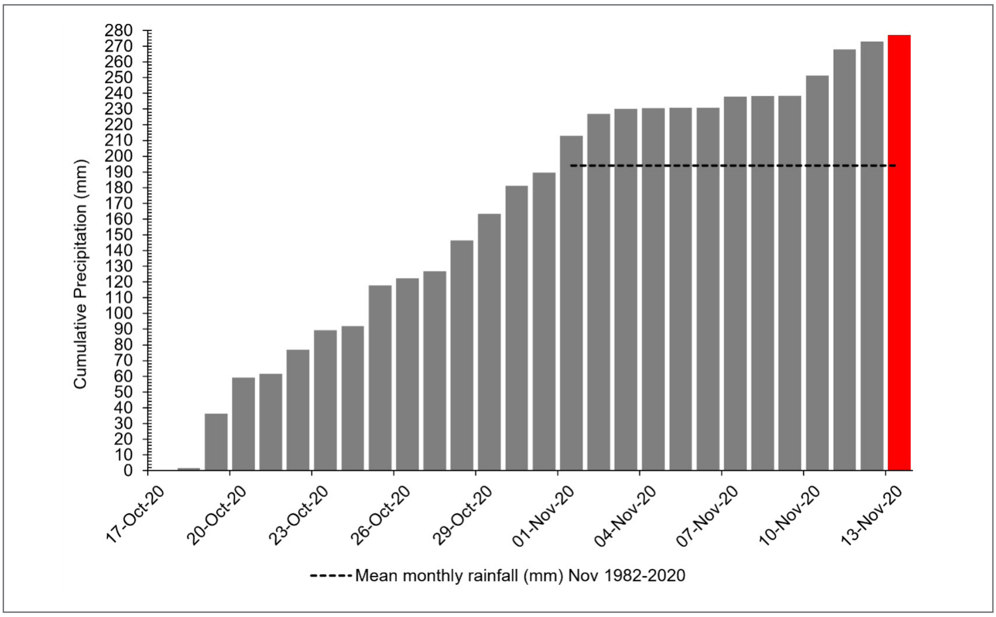

Figure 6. Cumulative precipitation for the 28 days leading up to and including event date for Meenbog landslide, Donegal on the 15th of November 2020. Mean November precipitation (dashed line) is derived from Met Eireann (Year) records (1982-2020) from the Ardinawark (Barnsemore) weather station located approximately 10 km from the failure site.

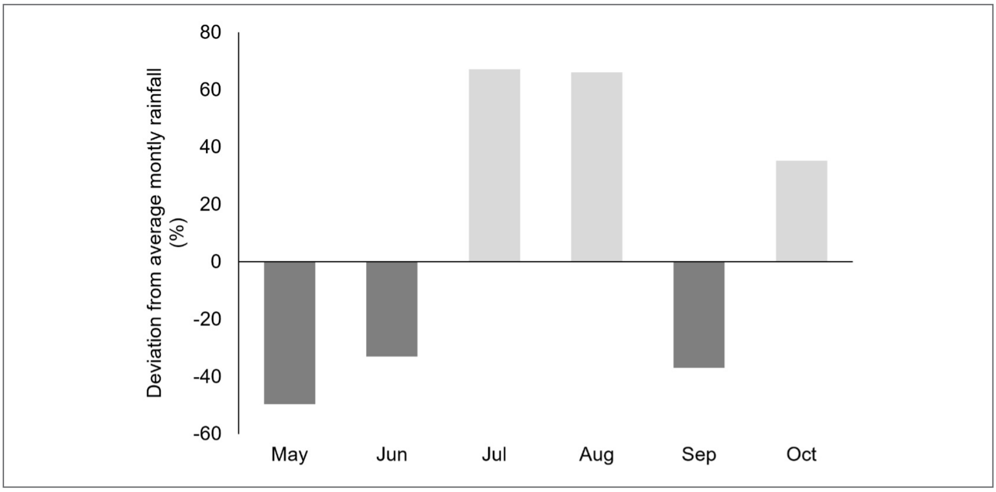

Figure 7. Deviation (%) from the long-term average monthly rainfall (1982-2020) for the six months preceding the event month for the Mount Eagle landslides, Co. Kerry which occurred around the 13th of November 2020*. Positive values represent above average rainfall while negative values represent below average rainfall. *Exact event date is unknown but thought to have occurred within 1-3 days prior to discovery.

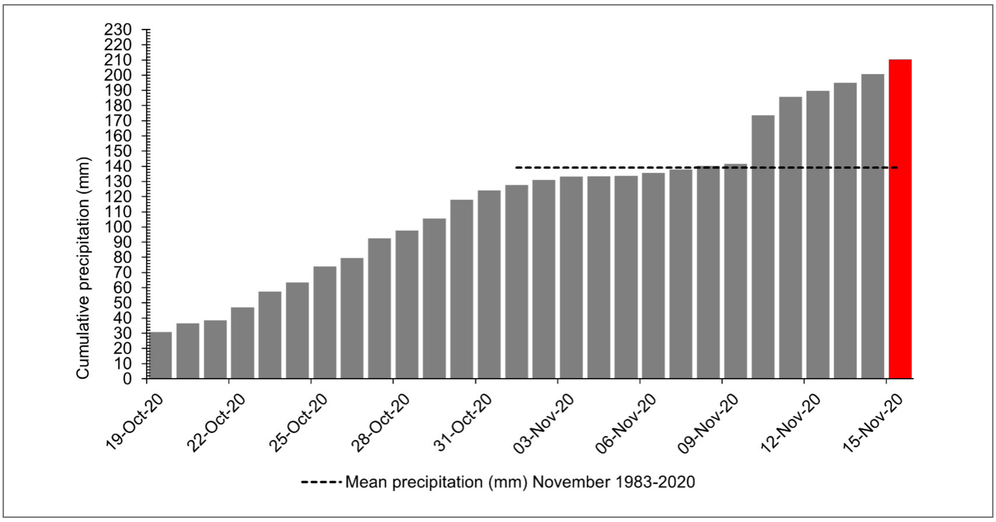

Figure 8. Cumulative precipitation (mm) for the 28 days leading up to and including event discovery date* for the Mount Eagle landslide, Co. Kerry which occurred on or around the 13th of November 2020. Mean November precipitation (dashed line) is derived from Met Eireann (REF) records (1982-2020) from the Ventry (The Boat Slip) weather station located approximately 70 km from the failure site. *Exact event date is unknown but thought to have occurred within 1-3 days prior to discovery

The rainfall at Shass Mountain would fall into the category of antecedent dry conditions followed by intense 24-hour rainfall receipts. It is likely that the dry summer conditions caused peat contraction and the opening of tensional fissures. These fissures provide accelerated flow pathways for surface waters to access the subsurface, often enhancing a lubricated plane along which peat movement occurs, particularly at the underlying rock interface. Meenbog rainfall suggests that longer-term wet conditions were important in leading to failure. There is also a possibility that the extreme rainfall in June may have initiated the failure, but we do not have data to confirm this. The Mount Eagle landslide was also not triggered by an intense rainfall storm, but a cumulative antecedent of high rainfall amounts in the 28 days leading up to failure. From these data we can assume that soils were close to saturated conditions.

These case studies suggest that the modelled increase in rainfall will likely increase landslides in Ireland, particularly as a majority of failures in the all-Ireland landslide inventory occur in peat (Cullen and Bourke, In press). We acknowledge that there are other factors which influence slope stability. Of notable importance is the role that human activity plays in destabilising slopes as is discussed in Dykes (2022) for the case studies considered here. Landslides are often the result of complex interactions between natural triggers (e.g., rainfall) and anthropogenic modifications (e.g., drainage, deforestation. Nevertheless, there is strong evidence that rainfall plays an important role in triggering slope failures in Ireland (and elsewhere). Noting this, we suggest some future research foci below.

Research gaps and priorities for future landslide research

The analysis presented here highlights a number of critical gaps in understanding landslide processes in Ireland under changing climatic conditions. These gaps limit the ability to robustly assess future landslide hazard, particularly in relation to projected increases in rainfall intensity, variability, and hydrodynamic forcing. Building on these broad gaps, we identify six priority areas for future research.

- Develop a bespoke coastal landslide inventory
- Undertake annual topographic surveys and rapid response observations following events
- Investigate the role of rainfall intensity, duration, and variability on triggering landslides
- Study the combined effects of sea-level rise and storm wave impacts on coasts
- Investigate the contribution of rainfall-triggered landslides to coastal erosion
- Undertake long-term studies to assess slope and coastal responses to individual storms, storm clusters, and sea-level rise

In the following sections, we outline each of these areas and identify the key research actions required.

5.1 A coastal landslide inventory

A major finding of this study is the underrepresentation of coastal landslides. Despite Ireland's extensive coastline, coastal landslides account for <1% of the National Landslides Database (NLD), with most reported on rock slopes (Cullen and Bourke, In press). In addition to subaerial processes affected by climate change and described in this study, marine processes such as wave climate, exposure and sediment fronting act as key controls on coastal landslide occurrence.

Several studies have found an increase in coastal cliff erosion, including landslides, related to an increase in wave erosion and lower sand elevations (Carter and E. Guy, 1988; Collins and Sitar, 2008; Komar and Shyuer-Ming Shih, 1993; Sallenger *et al.,* 2002). For rock coasts, lithology (rock type and rock mass properties), exposure to wave energy, shoreline orientations, and sediments fronting sea cliffs will determine the erosion rates (Budetta *et al.,* 2000; Edil and Vallejo, 1980). Hard rock coasts had received relatively little attention prior to the 21st century (Naylor *et al.,* 2010) and mass movement processes are less often studied owing to the longer time scales involved (McKenna *et al.,* 1992). Recent estimates of European rock coast erosion rates (Regard *et al.,* 2022) found that millennial-scale coastal retreat rates are similar or lower than current rates (Regard *et al.,* 2012; Swirad *et al.,* 2020). Any acceleration is suggested to be due to anthropogenic activities (Duguet *et al.,* 2021; Hurst *et al.,* 2016).

Studies on Irish coastal landslides are limited. McKenna *et al.* (1992) analysed the rates and controls of cliff retreat along the Irish coast from Macgilligan, Co. Derry to The Gobbins, Co. Antrim in Northern Ireland (Fig. 1). They identified numerous slope instabilities in dolerite and basalt cliffs which they attributed to a combination of marine erosion and sub aerial processes (heavy rainfall). Specifically, for Ireland, erosion estimates for 'soft' coasts are estimated at 0.2-0.5m/yr and for rocky coasts are 0.01m per century (Carter and Bartlett, 2016; Devoy, 2008; NCES, 1992). More recent monitoring in Co. Clare, suggest that rock coast erosion can be as much as 0.37 cm yr-1 (Cullen, 2019). This value is comparable to global estimates for the similar lithologies (see Prémaillon *et al.,* 2018 and references therein). Coastal landslides are not adequately reported in the all-Ireland inventory (Cullen and Bourke, In press).

Importantly, coastal landslide data are often incorporated with broader studies of coastal erosion rather than being systematically recorded as discrete events. Initiatives such as EUrosion (Lenôtre *et al.,* 2004) and the Irish Coastal Protection Strategy Study (OPW, 2019) provide estimates of overall coastline retreat but do not specifically resolve the contribution of landslides to erosion rates.

To address this, a bespoke coastal landslide inventory is needed. This should incorporate;

- Systematic mapping and classification
- Integration of historical and contemporary data,
- The use of remote sensing and UAV monitoring.

Without such datasets, it is not possible to robustly quantify coastal landslide activity or assess how it may change under future climate conditions.

5.2 Topographic surveys

A fundamental limitation in landslide research in Ireland is the lack of consistent, high-resolution topographic data for detecting and quantifying geomorphic change. The collection of an all-Ireland baseline topographic data set (e.g., LiDAR) (Farrell and Bourke, 2019) is needed with a repeat collection cycle within two years. Such datasets would support the development and refinement of landslide inventories and enable detailed analysis of landslide geomorphology across a range of environments. Monitoring representative sites over time is essential for understanding slope response to both current and projected climate conditions, and for improving landslide susceptibility assessments.

Recent advances in remote sensing technologies have made this increasingly feasible. High-resolution digital elevation models (DEMs), derived from LiDAR and UAV-based surveys, provide new opportunities for detecting and monitoring landslides, particularly in remote or inaccessible coastal areas (Gonzalez-Ollauri and Mickovski, 2021). The increasing accessibility and reduced cost of these technologies present a viable method for mapping and monitoring of coastal slope instabilities in difficult to access terrains.

We recommend the implementation of national topographic monitoring program supported by:

- Repeat surveys to quantify topographic change
- Targeted monitoring of representative sites
- Integration of UAV and remote sensing methods

5.3 The role of rainfall

Rainfall is identified as the primary trigger of landslides in Ireland. However, there is limited quantitative understanding of the thresholds at which failure occurs. This represents a key gap in the context of climate change, where increases in rainfall intensity and variability are expected to alter triggering conditions.

A particular challenge lies in the role of small-scale spatial variability in precipitation, which is not captured by current monitoring networks but may be critical in explaining the apparent variability of landslide occurrence at the catchment scale (Von Ruette *et al.,* 2014). Robust identification of rainfall thresholds therefore requires event-scale analyses, linking landslides to rainfall intensity, duration, and timing (Segoni *et al.,* 2018). In Ireland, this is constrained by limited data availability. Only a small number of stations record hourly rainfall, and many landslides occur at distances exceeding 10–50 km from the nearest gauge. This hinders a robust quantification of the role of rainfall intensity. Nevertheless, we suggest a retrodictive analysis of landslide events of known dates where the appropriate high resolution rainfall records exist.

Traditional approaches for deriving rainfall thresholds for landslide initiation have adopted the approach proposed by (Caine, 1980) which uses the expression of a power law between rainfall event duration and mean intensity or event rainfall (the total rainfall accumulated over event duration). There have been calls to move beyond this approach as it is perhaps too simplistic. In particular, intensity–duration thresholds do not consider antecedent rainfall conditions. This is important where the rainfall event that coincides with the failure may be the final trigger (as may be the case in some of the 2020 landslides described above). Some suggest that a hydro-meteorological threshold, which combines rainfall with catchment water storage (e.g., soil moisture), may be a better approach (Bogaard and Greco, 2018). However, these require high-resolution spatial and temporal datasets that are not yet widely available.

To address these issues, we recommend targeted studies to develop rainfall and hydro-meteorological thresholds for Irish conditions. These include:

- Retrodictive analysis of landslides with known timing
- Integration of high resolution rainfall and soil moisture data
- Evaluation of antecedent conditions alongside event rainfall

5.4 Effects of SLR and storm waves

A key gap in current understanding is the limited integration of sea-level rise and storm-driven processes. Much of the research undertaken to date has examined the effect of SLR or the effect of storms on coasts. Few studies have attempted to predict erosion under the combined conditions (Vousdoukas *et al.,* 2020).

Global studies indicate that up to 15% of sandy beaches may experience severe erosion by 2050, increasing to 35–50% by the end of the century (Vousdoukas *et al.,* 2020). These estimates do not include the impact of infrequent storm-driven shoreline retreat. In Ireland, model projections suggest that changes in storm surges and wave climate will significantly influence coastal morphology (Kandrot *et al.,* 2016; Slott *et al.,* 2006). In addition, recent storm events and clusters (e.g., Storms Darwin (2014), Desmond (2015), Ophelia (2017), Eleanor (2018), Elsa (2019) highlight the need to consider the combined effects of individual storms and storm clusters on both coastal and inland slope stability.

The global mean sea level has increased at an accelerated rate during the past 25 years (Nerem *et al.,* 2018) and is projected to continue to do so with future climate change (Horton *et al.,* 2020). While the response of sandy coastlines to sea-level rise is relatively well studied, cliffed coasts both Quaternary and rock remain less understood, and it is recognised that there is no single response to SLR.

Coastal response is highly variable and controlled by local factors including morphology, sediment supply, sediment transport, and nearshore dynamics. The varied response of sandy coastlines to SLR may include landward migration, recession, overstepped or prograde (see Cooper *et al.,* 2020 for discussion).

The same can be stated for Quaternary and rock coastlines with cliffs, however these are less studied and understood. Recent work suggests that retreat rates may increase substantially under future sea-level rise, potentially by up to an order of magnitude by 2100 (Shadrick *et al.,* 2022).

In Ireland, regional variability further complicates projections, with evidence that relative sea-level rise in locations such as Dublin and Cork may exceed global averages due to local factors including isostatic adjustment and anthropogenic subsidence (Pugh *et al.,* 2021; Shoari Nejad *et al.,* 2022). Current estimates suggest that 20% of the Irish coast is at risk for coastal erosion. We suggest that based on the work of Shadrick *et al.* (2022) this figure will be significantly higher when rock coasts are included.

To address these gaps we recommend:

- Combined assessment of wave, surge, and sea-level forcing
- Assessment of the effects of storms and storm clusters.
- Targeted studies of cliffed coast response to sea-level rise and storm forcing, particularly for rock coasts

5.5 The contribution of rainfall to coastal landslides.

Rainfall triggered coastal landslides are likely to make a significant but currently unquantified contribution to the recession of 'soft' coastal cliffs. Under-representation of rainfall triggered coastal landslides makes it difficult to quantify their role in coastal erosion, both at present and under future climate conditions. Indeed, the accuracy of landslide susceptibility maps depends on the precision of the NLD (Gaidzik and Ramírez-Herrera, 2021) which should be representative of the distribution, type and patterns of all past landslides (Braun, 1991; Guzzetti *et al.,* 2021; Malamud *et al.,* 2004).

A recent study by Cullen *et al.* (2024) which leveraged a Citizen Science approach for reporting of coastal landslides, noted multiple rainfall triggered slope failures (flows), some of which occurred behind rock armour coastal defences.

Higher temporal resolution monitoring of coastal landslides is needed to determine rainfall thresholds for failure and the relative contribution of rainfall triggered coastal landslides to current and future rates of coastal erosion.

We recommend:

- Improved temporal resolution of event detection
- Identification of rainfall thresholds for coastal landslides
- Assessment of coastal landslide contribution to coastal erosion rates

5.6 Long-term studies

A key limitation in understanding landslide activity and coastal erosion in Ireland is the lack of long-term datasets capable of resolving cumulative and lagged responses to environmental forcing. Even where high-resolution data exist, relationships between cliff recession and marine or subaerial drivers are often weak or unclear (Masselink *et al.,* 2020; Vann Jones (Née Norman) *et al.,* 2015). This is further complicated by the expected increase in basal erosion and groundwater levels along coasts as a result of SLR (Crozier, 2010).

The winter storms (2013–2014) caused significant geomorphic change to large sections of Ireland's coastline and the December 2013 to February 2014 is noted as the stormiest period in the 150 years of the instrumental record in both Ireland and northwestern Europe (Matthews *et al.,* 2014). A limited number of studies have demonstrated the immediate coastal response of the 2013-14 storms (Cox *et al.,* 2018; e.g. Kandrot *et al.,* 2016. However, the longer-term adjustment of coastal systems remains poorly understood, with some coastlines exhibiting recovery or reworking over decadal timescales.

This lack of temporal perspective limits the ability to distinguish between short-term event-driven change, the cumulative impacts of storm sequences and longer-term geomorphic adjustment.

Establishing rates and volumes of landslide activity and coastal erosion over a range of spatial and temporal scales should be a priority. For example, a better understanding of the cause of coastal erosion by landslides is needed to determine the efficacy of various hard and soft coastal protection measures and more accurate risk assessments are to be made for coastal infrastructure. More broadly, the contribution of landslides to coastal sediment flux remains poorly constrained, despite evidence that rock coast inputs to the ocean may be more significant than previously recognised. For Europe, the sediment flux is only three times lower than the fluvial sediment (Regard *et al.,* 2022). We agree with the recommendations of Regard et al (2022) who suggest that monitoring all coastal sedimentary sources will permit a better assessment on the effect on the geochemical ocean budget.

The land-sea transition zone allows research on scientific questions around anthropogenic and climate forcing. Key to facilitating the understanding of processes within the coastal area and their interactions with regional and global environmental changes are the global network of coastal observatories (Zielinski *et al.,* 2022). There have been calls for Ireland to join the Global network of Coastal observatories (e.g. in Northern Ireland, Cooper and Jackson, 2018). Ireland and Northern Ireland has a dearth of information on how its coast works (e.g. rates of change, sources of coastal material, patterns of sand movement, impact of storms, post-storm recovery) along most of the coastline. These data are needed to address the absence of adequate information for effective coastal management. The establishment of coastal observatories are necessary to support decision-making today and in the development of any future strategic approach for effective coastal management.

To address these gaps we recommend long term, multiscale monitoring and analysis of coastal and landslide processes using the following approaches:

- Quantification of erosion rates and landslide volumes across spatial and temporal scales
- Evaluation of longer-term recovery and adjustment following extreme events

This should be supported by the development of coastal observatories to provide sustained, high-resolution datasets. Expanding Ireland's participation in international coastal observation networks would address current data gaps and support improved process understanding and coastal management.

Conclusion

This review demonstrates that many of the climatic conditions associated with landslide activity in Ireland are projected to intensify under future climate change. Evidence from the wider literature, the all-Ireland landslide inventory, and the case studies presented here supports the conclusion that rainfall is the dominant climatic control on slope failure, particularly in peatland environments. Failures are associated with a range of hydrometeorological conditions, including prolonged wet periods, intense rainfall events, and heavy rainfall following antecedent drying.

Projected increases in rainfall intensity and greater variability between wet and dry periods are therefore likely to increase landslide susceptibility across Ireland. Coastal landslides remain particularly understudied despite the potential combined effects of sea-level rise, storm activity, wave action, and rainfall on slope instability along Ireland's coastline.

A major limitation identified in this review is the lack of long-term, high-resolution monitoring data needed to robustly assess climate–landslide relationships. Future research should prioritise improved landslide inventories, repeat topographic surveys, high-resolution rainfall analysis, long-term monitoring, and dedicated investigation of coastal landslides and climate-driven coastal change.

Although uncertainties remain, the available evidence supports the conclusion that climate change is likely to increase landslide hazard in Ireland, highlighting the need for coordinated research, monitoring, and improved hazard assessment.

Acknowledgements

This work was enabled in part by funding provided by the GSI Short Call 2015-sc-076.

Author contributions

All authors contributed to the study conception, design, material preparation, data collection and analysis. The manuscript was written by NC and MB. All authors read and approved the final manuscript.

Statements and Declarations

Each authors confirm that this manuscript has not been previously published and is not currently under consideration by any other journal. There are no financial or non-financial interests that are directly or indirectly related to this work that would represent a conflict of interest.

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