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Acidification of previously limed upland pastures – An overlooked flood risk factor?

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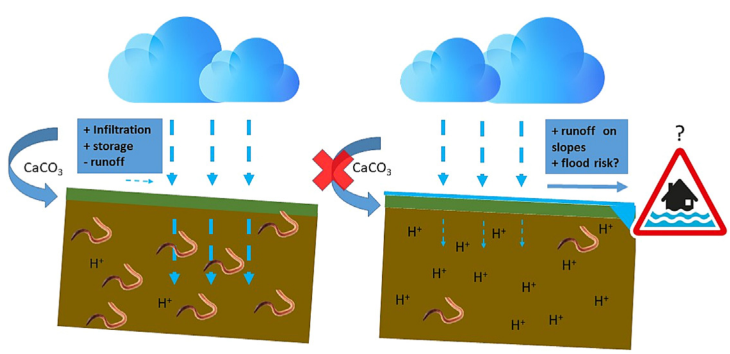
HIGHLIGHTS

- Liming of improved upland pastures in the UK has declined.
- Most such pastures are on steeper slopes prone to runoff.
- Without liming soil acidification reduces earthworm abundance and infiltration.
- Reduced infiltration can promote surface runoff on slopes and enhance flood risk.
- Catchment targeted support for maintenance liming may mitigate flood risk.

GRAPHICAL ABSTRACT



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ABSTRACT

In low-lying land, the impact of agriculture on flooding has focussed on soil compaction, whilst in the uplands there has been more interest in the influence of afforestation. The potential effect of acidification of previously limed upland grassland soils on this risk has been overlooked. The marginal economics of upland farms has led to inadequate lime application on these grasslands. In Wales, UK, agronomic improvement of upland acid grasslands with liming was widespread in the last century. The extent and topographical distribution of this land use in Wales was estimated and these characteristics were mapped in four catchments studied in more detail. Then 41 sites on improved pastures within the catchments were sampled, where lime had not been applied for periods of between two and 30 years; unimproved acid pastures adjacent to five of these sites were also sampled. Soil pH, organic matter, infiltration rates and earthworm populations were recorded. Grasslands at risk of acidification without maintenance liming were estimated to cover almost 20 % of upland Wales. The majority of these grasslands were located on steeper slopes (gradients >7°) where any reduction in infiltration would promote surface runoff and limit rainwater retention. The extent of these pastures varied markedly between the four study catchments. There was a 6-fold reduction in infiltration rates between high and low pH soils, and this trend was correlated with reductions in anecic earthworm abundance. The vertical burrows of these earthworms are important for infiltration and no such earthworms were present in the most acidic soils. Recently limed soils had infiltration rates similar to those of unimproved acid pastures. Soil acidification has the potential to exacerbate flood risk but further research is needed to assess the extent of any impact. Modelling of catchment specific flood risk should include the extent of upland soil acidification as an additional land use factor.

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1. Introduction

In common with many regions of the world the UK has experienced an increasing frequency and severity of flooding events associated with intense rainfall (Huntingford et al., 2014). Fluvial flooding causes serious economic losses and damage worldwide, and is projected to increase under climate change (Tanoue et al., 2021). Temporal trends in the frequency of extreme rainfall have been regionally divergent in the UK, though increases have often occurred in upland areas (Dodd et al., 2020). In mid and south Wales during 2019/20 storms, a substantial majority of catchments recording their highest peak flows over the last 50 years (Sefton et al., 2021).

Across Europe there has been notable interest in the extent to which soil compaction and broader agricultural management exacerbates flooding risk (Alaoui et al., 2018; Robinson et al., 2013), including some research on upland pastures (Marshall et al., 2014). But the main focus has been on lowland soils with less consideration of how existing upland grassland and its management affects flood risk.

Large-scale land-use change in the uplands, including afforestation, has been proposed as a strategy for the UK to meet its emission reductions in the Paris Agreement (UK Committee on Climate Change, 2020). In addition to carbon balances, there has been a particular interest in the potential of afforestation for flood mitigation via interception of rainfall and increased soil infiltration (Buechel et al., 2022).

In the second half of the 20th century large areas of the UK uplands were converted to more productive pasture to increase livestock production and support rural communities, encouraged by government incentives. This practice was particularly extensive in Wales where just over 200,000 ha or almost 20 % of uplands (> 250 m asl) is classed as improved pasture (JNCC, 2017). A key component of pasture improvement was raising soil pH by liming, commonly through the application of ground limestone, but existing surface organic/rooting layers were also disrupted by cultivations that exposed mineral soils. Withdrawal of support for maintenance liming and economic/practical constraints (Goulding, 2016) have led to reductions in the lime applications needed to maintain soil pH in the UK, in particular for upland soils. Liming of acid soils increases earthworm activity and therefore soil macro-porosity and temporary water storage (Bolan et al., 2003). Earthworm burrows, and the vertical systems of anecic species in particular, increase surface infiltration and reduce surface runoff (Blouin et al., 2013).

Acid sensitive improved pastures were expected to be present disproportionally on sloping land as this favoured better drainage and machinery access. It was hypothesised that, in the absence of maintenance liming, upland soils would acidify over time, anecic earthworm abundance would decline and surface water infiltration would decrease. If these responses to soil acidification were to occur over extensive areas within a catchment, there was a potential for accelerated surface runoff into river systems, especially where slope gradients are greater. The overall objective of the study was to establish whether there was a case to consider acidification of previously limed upland soils as a flood risk factor requiring further research. Its specific objectives were i. to estimate the areal extent and topographical distribution of these soils in Wales, UK; ii to assess whether acidification was associated with declines in soil infiltration rates; iii to investigate whether changes in infiltration attributable to acidification could be explained by trends in earthworm populations.

2. Methods

The research involved two linked phases. Firstly, the extent and topographical distribution of target grasslands in Wales were determined; detailed land use maps were created for four fieldwork catchments. Secondly, field investigations of soil properties were undertaken in the context of lime application history within the selected catchments.

2.1. Land cover and topography

Habitat data from the Wales Terrestrial Phase 1 habitat map (Blackstock et al., 2010) were accessed via Wales Map Portal (Lle Welsh Government 2020 https://lle.gov.wales/home) and used alongside Ordnance Survey Terrain Map topography data from Digimap (EDINA, 2020 https://digimap.edina.ac.uk) to estimate coverage of improved upland pasture in different slope classes in Wales and in the study catchments; the catchment data were used to create maps of improved and unimproved grassland in these slope classes along with other upland habitats. Potential hydrological impacts of improved grassland condition would be catchment specific, taking account of these land cover factors. The spatial distribution of these grasslands would also influence their hydrological impact via the potential buffering effect of adjacent habitats. Slope angle classes (< 7^o, 7 - 11^o and > 11^o) used in this study followed those in the UK Agricultural Land Classification (ACL) system. Although this classification is based primarily on land management factors, it also recognises the risk of soil erosion and therefore variations in run-off (MAFF, 1988). Maps of habitat and slope data for each of the studied catchments were created using QGIS (QGIS version 3.10.1 Development Team, 2020) in order to investigate these variations in potential risk factors between catchments.

2.2. Field investigation

Fieldwork was based on four upland grassland farms stocked with sheep in mid- and north Wales, UK catchments. Farms were selected based on access and availability of reliable records of land management, in particular liming practices, rather than to represent this land use generally. Co-operating farmers were promised anonymity so geolocations provided indicate catchment rather than sampling locations. At site a) Dulas (52 21 53 N 3 49 47 W) elevation varied ca. 350 m asl, at site b) Pwllpeiran (52 36 39 N 3 50 22 W) ca. 230 m asl, at site c) Clywedog (52 56 26 N 3 45 21 W) ca. 340 m asl, and at site d) Tryweryn (53 5 54 N 3 27 9 W) ca. 375 m asl. Unimproved soils were acidic, free draining fine loams developed over Palaeozoic mudstone, siltstone or slate often with an organic surface horizon (Manod series – Chromic Mollic Endoskeletic Umbrisol);at higher elevations soil graded into Hafren series (Endoskeletic Histic Stagnic Albic Podzol) permeable loams over Palaeozoic slaty mudstone and siltstone rock with a wet peaty surface horizon and bleached subsurface horizon (ferric stagnopodzol) (Rudeforth et al., 1984). Where applied, liming rates were set to achieve a soil pH of 6, based on agronomic recommendations for grassland productivity (Goulding, 2016). Liming generally involved the application of ground limestone. Where practiced, maintenance treatments are typically applied at rates of 3–4 t ha^{-1} every 4–5 years; rates varied depending on soil characteristics and land use. Sites had a maritime climate with annual precipitation >1500 mm (Bendelow and Hartnup, 1980). A total of 41 points on improved pasture with a range of liming histories were sampled; points were located at random, avoiding any obvious anomalies such as around gates or feeding areas. An additional 5 topographically similar points on adjacent unimproved grassland s were sampled; these may have been affected slightly by liming wind drift. Duplicate or triplicate measurements (infiltration, soil and earthworm sampling) were made at each sampling location from within a 2 m by 2 m plot.

For the relative infiltration measurement, a single (40 cm diameter) ring method was used (Walsh and McDonnell, 2012). The difficult terrain and limited access to water made deployment of the more widely used double ring method logistically impractical. It is recognised that the single ring measurement is liable to give higher values than double-ring methods due to lateral flow but the method used was applied consistently across all points giving robust relative measures of water ingress. The ring was secured to a standard 3 cm depth into soil (increasing stoniness with depth precluded a greater, consistent placement) and filled with water to a mean 10 cm depth. If water leakage around the edge of the ring was observed, the ring was reset. The ring was then refilled to 10 cm depth at 2-minute intervals over a total of 20 min and the total volume of water used for these refills converted to a relative infiltration rate. Measurements

Table 1
The extent of improved pasture in different slope categories in catchments sampled and for Wales (UK) as a whole.

Catchment	a) Dulas	b) Pwllpeiran	c) Clywedog	d) Tryweryn	Wales
% total area as upland improved grassland					
	17.0	7.5	0.6	47.3	9.7
% improved grassland in different slope categories					
% improved <7°	16.1	36.3	47.6	7.5	48.8
% of improved >7°	83.9	63.7	52.4	92.5	51.2
% of improved >11°	66.4	34.1	0.0	23.7	24.9

were taken when soils were close to field capacity based on prior rainfall conditions and during grazing by sheep.

At each sampling location, earthworms were collected from two or three points using a combination of hand-sorting of excavated soil (30 by 30 cm to 30 cm depth block) and application of a mustard vermifuge extractant to the base of the excavated pit to extract earthworms below this depth. Adult anecic species (*Lumbricus terrestris* L. and *Aporrectodea longa* Ude) numbers were recorded after preservation in ethanol and identified morphologically (Sherlock, 2018). Samples of excavated soil were taken for measurement of pH (1:2.5 soil:water) and oven dried samples were tested for loss on ignition (20 h @ 400 °C – modification of Ball, 1964).

2.3. Data analysis

One-way ANOVA was used to investigate differences in earthworm abundance and infiltration between the different soil pH classes. Mean data for each sampling site were used in all analyses. Data were assessed for normal distribution using Shapiro-Wilk test and for equal variances using Levene's test. Regression analysis was used to investigate further the potential relationships between different factors. *P* values <0.05 were considered statistically significant and individual mean differences were assessed based on the Tukey range test. All data analyses used SPSS Statistics (IBM, USA).

3. Results

Uplands classed as improved pasture represented almost 10 % of Wales overall and 20 % of uplands, with just over half of these occurring on slopes >7° (Table 1) where surface water is likely to run off rather than pond. In the study catchments, excluding Clywedog catchment where the improved grassland extent was limited, this slope class varied from 64 to 92 %, whilst the extent of improved grassland on slopes greater than 11° varied between 34 and 66 % cover. The proportion of improved grasslands varied between the four catchments investigated (from <1 to >47 % Fig. S1), with forests, bogs and a range of other upland habitats constituting the remainder. Improved grassland occurred in topographical 'blocks' (Fig. S1 a-d) in the catchments sampled, limiting the potential of surrounding habitats to mitigate runoff.

Soils on the field sites had been limed last between 2 and 30 years previously and showed a linear decline in the pH as time since liming increased ($R^2 = 0.634$ $p < 0.001$ $n = 41$). There was a gradual increase in organic contents (mean +/− standard deviation) in the 0–10 depth from 12.0 % (+/− 2.32) in regularly limed grasslands to 17.9 % (+/− 3.89) in the grasslands limed 30 years previously. There was a significant decline in

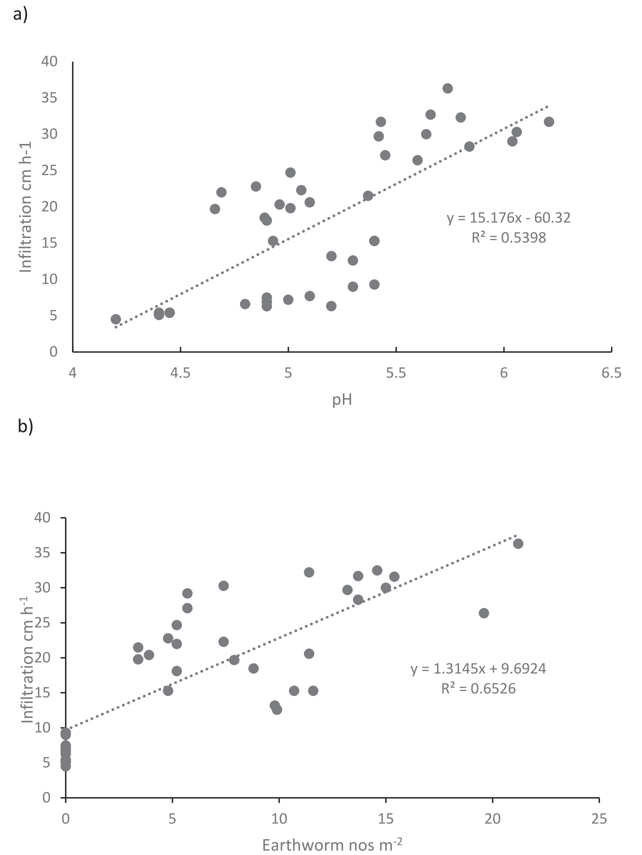

Fig. 1. Relationships between a) pH and b) anecic earthworm abundance and infiltration rate ($n = 41$) - excluding unimproved pastures.

infiltration rates in more acidic soils (Table 2 and Fig. 1a) and this decline was closely related (Fig. 1b) to reductions in abundance of anecic earthworms; these species were absent from the most acidic class of previously improved soils and from 42 % and 19 % of soils with a pH 4.5 to 4.99 and 5 to 5.49 respectively (Table 2). Infiltration rates were most variable in the intermediate soil pH classes, and this variation aligned to a degree with patchy distribution of anecic earthworm abundance within these classes (0–14.7 m^{-2}). Adjacent, unimproved soils had mean pH levels similar to those of the more acidic improved soils, with some anecic earthworms, and infiltration rates were close to those of the most recently limed improved soils (Table 2); the pH of these unimproved soils may have been affected by some wind drift of fine particles during liming of nearby (< 100 m) improved sites. There was no evidence of the more acidic, previously improved soils regaining the hydrological function of unimproved soils, probably because of their limited accumulation of surface organic matter even 30 years after previous lime applications.

4. Discussion

Acidification of improved grasslands was associated with a very marked reduction in infiltration rates which in turn were closely related to declines in earthworm abundance. The links between earthworms and soil acidity

Table 2
Mean (standard deviation) soil pH, infiltration rate and anecic earthworm abundance by pH class for soils on improved and unimproved pastures. Soils with a common letter suffix (infiltration and earthworms) do not differ $p < 0.05$.

Land/pH	Site numbers	pH	Infiltration cm^{-h}	earthworm nos.m^{-2}
Improved/<4.5	5	4.4 (0.12)	5.16c (0.39)	0
Improved/4.5–4.99	12	4.9 (0.12)	14.3b (6.78)	4.14b (3.893)
Improved/5–5.49	15	5.3 (0.18)	18.6b (7.78)	7.90b (5.234)
Improved/>5.5	9	5.8 (0.21)	30.8a (0.21)	16.16a (6.206)
Unimproved	5	4.8 (0.14)	30.2a (3.35)	6.89b (2.530)

(e.g. Syers and Springett, 1984) and between earthworm activity and infiltration rates (Blouin et al., 2013) are well established. Values of pH close to or below 4.5 are considered limiting to *L. terrestris* (e.g. Baker and Whitby, 2003), a finding consistent with those reported here. Deep burrowing anecic species have a particularly important role promoting water infiltration (Bouché and Al-Addan, 1997) as their burrows provide a system of connected transmission pores. The positive association between anecic earthworm abundance and infiltration in the present study supports this view. A field study on arable soils by van Schaik et al. (2014) found close correlations between anecic earthworm abundance and surface infiltration; the distribution of infiltered water within soil profiles was also linked to burrowing. Some of the variation in infiltration rates found here, unexplained by earthworm abundance, may be attributable to differences in preceding weather conditions affecting earthworm burrowing activity (Andriuzzi et al., 2015) and to time lags between the loss of an earthworm and destruction of its burrow system. Although earthworms play an important role in recovery from treading damage (Drewry, 2006), heterogenous treading by sheep prior to sampling may also have contributed to varied infiltration rates.

In addition to the role in surface water infiltration of their burrows, earthworms affect soil aggregation, porosity and hydrology in general. Earthworm activity increases soil water holding capacity, although the extent of these effects varies with ecotype and soil texture (Hallam and Hodson, 2020). Inter-aggregate large capillary (< 2 mm) pores, created by earthworm activity (Blouin et al., 2013), also provide some temporary retention and slow release of infiltered rainfall; the effectiveness of these processes depends strongly on transfers between preferential flow channels (e.g. burrows) and the soil matrix (van Schaik et al., 2014).

The flood risk and more general hydrological implications associated with soil acidification have received little attention. Here we demonstrate that reduced liming of improved upland grasslands may contribute to enhanced flooding risk by limiting rainwater capture and storage. We also show that these grasslands cover almost 20 % of upland Wales, that overall a majority are on steeper sloping land and that there are large variations between different catchments in the extent of these flood risk factors. Although runoff generation is affected by interactions between slope gradient and microtopography (Caviedes-Voullième et al., 2021), in general increasing gradients will facilitate rapid surface runoff when infiltration is exceeded,

Agricultural improvement of previously acid grassland soils included ploughing that destroyed the well-developed organic AO horizon (Smith et al., 2007), typical of these podzolic soils. The high organic contents of this horizon would have previously facilitated infiltration and moisture retention (e.g. Yang et al., 2014), consistent with our data on unimproved soils. With cultivation and liming this hydrological function supported by earthworm burrows. The loss of earthworms from these grasslands may represent a hydrological tipping point, since their recolonization post restorative liming may take decades, especially where there are no source populations present in adjacent land. Even under favourable conditions rates of population spread may be <5 m per annum (Baker et al., 2006). Abandonment of maintenance liming, allowing soil acidification and natural upland grassland hydrology to re-develop is not a short-term option. Our data show no evidence of any recovery in infiltration even 30 years after previous liming. The failure to recover previous infiltration characteristics is likely due to the slow rate of re-forming a well-developed organic AO horizon. Although organic contents showed an upward trend with time since liming this increase was small in the context of similar unimproved soils, with for example typical Hafren series surface soils having organic matter concentrations of 40 % or higher (Smith et al., 2007). High levels of anecic earthworm activity in limed soils would have prevented surface accumulation of organic residues (e.g. Lorenz and Lal, 2005). No such accumulation was apparent during fieldwork and in other studies of similar soils where liming was discontinued (Pavlů et al., 2021).

Meteorological drivers are the main factors affecting flood risk and this risk is likely to increase with climate change (Tanoue et al., 2021). Modelling of Welsh catchments (Harvey et al., 2022) under a severe climate change scenario suggest a strong seasonal change in river flows, with increased Spring and reduced Autumn flows. Land management, and its topographical distribution, can either mitigate or enhance these climate driven risks via differences in the extent and duration of water retention in soils. If current trends for reduced lime applications continue (Goulding, 2016) this acidification of previously limed soils may further exacerbate flood risks.

Dadson et al. (2017) note that whilst the benefits of natural flood management measures are well understood in principle, uncertainty remains in quantifying their potential to reduce downstream flood hazards, especially in large catchments and for major floods. Prolonged and extreme rainfall events can override increased soil infiltration and storage capacity, limiting its potential to mitigate major flood events (Robinson et al., 2013). Nevertheless, substantial reductions in infiltration rates would inevitably contribute to some increase in flood risk and reduce climate change hydrological resilience, particularly at a local scale (Alaoui et al., 2018; Robinson et al., 2013). Also, at a local scale, changes to streamflow characteristics may impact river ecology. These effects are likely to be of practical significance only if soil acidification occurs over a large proportion of a catchment (Buechel et al., 2022) and on predominantly sloping land, as in most of the catchments sampled here.

The extent to which variations in surface infiltration affect peak river flow depends also on the capacity of soils to store infiltered water and the timing of its release. Many of the soils on sites studied here are relatively shallow, but they are developed on permeable parent materials (e.g. scree) so their temporary storage capacity for infiltered rainwater may be large; the timing of release of stored rainfall into streams is unclear. In addition to impacts on flood hydrology, effective infiltration may support base river flow by capturing and slowly releasing intense summer rainfall during otherwise dry periods, in contrast to the negative impacts predicted with afforestation (Buechel et al., 2022). The relationships between infiltration, topography and river flow are complex and to a degree catchment specific. In Wales and elsewhere in the UK there is a need to establish the proportion and topographical location of previously improved grasslands where pH management is inadequate, as a first step in investigating impacts on river flows.

Many previously limed upland grasslands in Central Europe (Merunková and Chytrý, 2012), in central France (Lochon et al., 2019) and in northern Spain (Mijangos et al., 2010) have levels of soil acidity found in our study to reduce earthworm populations and therefore the hydrological functions they support. So, soil acidification may reduce resilience to climate change and contribute to flood risk at least in temperate uplands on a continental scale. With upland grasslands globally at risk of acidification, information on its extent and hydrological impact would inform modelling of catchment level flooding impacts, as undertaken for afforestation (Buechel et al., 2022). The potential mitigation of flood risk by liming upland grasslands may be lost if this results in excessive animal stocking densities (Marshall et al., 2014).

UK policy on land management aims to deliver a broad range of environmental services (Marriott et al., 2004). Managing acidification of previously limed grasslands is consistent with broader approaches based on catchment scale flood mitigations including varying land use, temporary flood storage and decoupling of the timing of flows from different tributaries (Lane, 2017) aiming to reduce rapid runoff on hillslopes and to increase temporary water storage, including that within soil profiles (Environment Agency, 2021). Data reported here indicate the need to consider soil acidification as a potential factor in flood risk in this context.

5. Conclusions

Where liming of improved upland grasslands prevented soil acidification, infiltration rates were similar to those of unimproved acid grassland. Where these soils acidified, earthworm abundance and infiltration declined markedly. Improved grasslands are extensive in upland Wales and often located on slopes where rapid surface runoff is likely if infiltration is exceeded. On this basis acidification presents a potential to exacerbate flood risk. However, the catchments sampled showed marked differences in land use-slope gradient combinations so further research is needed to establish the wider hydrological context and to estimate the extent of liming deficit alongside its topographical distribution. If acidification proves to affect flood risk, targeted agri-environment support for liming of previously improved grassland could mitigate this risk and would promote wider ecosystem services, including collateral water quality improvements (Adams and Evans, 1989) and increased food resources for farmland birds (e.g. McCallum et al., 2016). There is a need for a more nuanced debate on the role of upland pastoral agriculture in the delivery of environmental services.

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CRediT authorship contribution statement

Caroline Freeman: investigation, data analysis, Writing - Original Draft. Osian Gwyn: investigation, data analysis, Writing - Original Draft. Dylan Gwynn-Jones: supervision, conceptualization, Writing - Review & Editing. Katie Medcalf: data analysis, Writing - Review & Editing. Hefin Williams: data analysis Writing - Review & Editing. John Scullion - supervision, conceptualization, Writing - Original Draft, Writing - Review & Editing.

Data availability

Data will be made available on request.

Declaration of competing interest

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

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