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Field-based determination of controls on runoff and fine sediment generation from lowland grazing livestock fields

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ABSTRACT

Compared with arable land, there is a paucity of field-based measurements of erosion rates and controls for lowland temperate grassland supporting ruminant agriculture. Despite this evidence gap, reducing diffuse fine sediment pollution from intensively farmed grassland has been recognised as essential for improving compliance with water quality targets. Improved information on erosion rates and controls within intensively managed lowland grazing livestock systems are prerequisites for informing best management practices for soil and water resource conservation.

Accordingly, this study assembled such information using the North Wyke farm platform in south west England where flow, suspended sediment concentration, rainfall and soil moisture are monitored quasi-continuously in 15 hydrologically-isolated (1.54–11.12 ha) catchments. This region of the UK is representative of temperate lowland ruminant grazing landscapes with semi permeable soil drainage.

Catchment area was the major control on both water and sediment flux. When normalised to catchment area, sediment yields were controlled by the erodibility of the catchment’s soils. Ploughing for re-seeding of grass swards was the major factor that affected this. Whilst total rainfall had a small effect on sediment yields, slope and the damage of soils by livestock had no significant effects. This finding may be due to the overriding effects of ploughing and re-seeding of some fields during the study period.

Detachment by impacting raindrops mobilised sediment particles across the entire field with diffuse saturation-excess overland flow responsible for their transport. The majority of erosion occurred during the rising limbs of storm events when there is an abundance of easily detached soil particles. Given that erosion and sediment transport are driven mechanistically by processes affecting the entire field areas, a reduction in sediment yield through the implementation of highly spatially-targeted in-field management such as that for feeder ring use, troughs, poached tracks or gateways would likely be very challenging. Instead, stocking density and grazing regime management, as well as carefully planned ploughing and re-seeding will be more beneficial for erosion control.

1. Introduction

Soil erosion and the resulting diffuse fine sediment pollution from agriculture has been identified as a leading cause of the degradation of freshwater habitats (Berkman and Rabeni, 1987; Wood and Armitage, 1997; Kemp et al., 2011). Diffuse agricultural sediment has resulted in significant off-farm costs; for example, Collins and Zhang (2016) calculated that maximum environmental damage costs of £523 M yr$^{-1}$ are incurred in the UK due to detrimental effects of agriculturally-related sediment pollution on ecosystem goods and services. To mitigate these effects and achieve compliance with water quality targets it has been estimated that sediment loads from agriculture will have to be reduced by up to 20% (Collins and Anthony, 2008). Such an achievement may be challenging, however, since Zhang et al. (2017a) recently estimated that best-case future on-farm management interventions costing a median of £13,000 km$^{-2}$ yr$^{-1}$ are only likely to deliver a median 25% reduction in agricultural sediment loss under business-as-usual. In the context of this management challenge, it is necessary to target on-farm mitigation on the basis of robust data on pollution losses and key controls to deliver optimum cost-benefit (Ockenden et al., 2012). Erosion rates and controlling processes must therefore be understood in a range of different agricultural landscapes. Accordingly, this study focuses on assessing the magnitude of sediment loss from intensively managed lowland grassland in a UK setting. Grasslands represent a significant proportion of land internationally. Nationally in the UK, grassland represents 67% of the total agricultural land area (Defra,
Soil erosion on grasslands is generally less severe than on cultivated land due to its near continuous vegetation cover (O’Connor, 1956; Patto et al., 1978; Bilotta et al., 2007a; Evans, 2010), and, as a result, until recent decades, most monitoring studies in the UK have focussed on assembling data on erosion rates and key controls in arable settings (Evans, 1988, 1990a; Boardman et al., 2009; Boardman, 2013, 2015). However, a decline in aquatic habitat quality and non-compliance with...
Many studies into soil erosion rates and key controls have historically been conducted at plot scale (Mutch et al., 1994). It is questionable, however, if such results can be reliably upscaled to field or catchment scale (Evans, 1988; Lane et al., 1995; Seyfried and Wilcox, 1995), despite these scales being fundamental units for land management by farmers and for water quality compliance reporting in the context of policy-driven environmental objectives. Previous UK-based field scale studies into soil erosion rates have focussed on measuring visible rill and gully erosion and estimating sheet wash on cultivated land rather than assembling data for intensively managed grasslands (Evans, 1988; Boardman, 2003). It has also been identified that the prediction of erosion rates and processes through modelling is more challenging for smaller catchments when compared to large catchments (De Vente et al., 2013). Therefore, there remains a paucity of field scale information on soil erosion and its major controls within grassland landscapes. In this context, the aim of this study was to determine how scale information on soil erosion and its major controls within grassland landscapes is likely to compound many of these factors. Slope has also been shown to be a major control on erosion rate (Ekern, 1955; De Ploey and Savat, 1968), which is linked with the fact that erosion has been shown to be directly related to runoff velocity (Moss, 1988; Kinnell, 1990a, 1990b). Field topography has also been linked to increased erosion with saturation-excess overland flow developing in the topographic convergence of valley axes (Dunne and Black, 1970; Anderson and Burt, 1978).
containing a perforated drainage pipe backfilled to the surface with 20–50 mm clean granite, carbonate free, stone chips) range from 1.54 ha for Flume 15 to 11.12 (subsequently reduced to 7.75 on 13/08/2013) ha for Flume 4 (Table 1). Many of the catchments are steeply sloping with the highest individual mean (Catchment 5, Table 1) being 12.25°; however, some catchments have a mean slope as low as 4.17° (Catchment 14, Table 1). The fields generally have a slowly permeable slightly stony clay loam topsoil (~36% clay) prone to seasonal water-logging, which overlies a mottled stony clayey poorly permeable subsoil (~60% clay) derived from the underlying Carboniferous Culm rocks (Harrod and Hogan, 2008). The dominant soils (Fig. 1) have been soil (~60% clay) derived from the underlying Carboniferous Culm logging, which overlies a mottled stony clayey poorly permeable subsoil (~36% clay) prone to seasonal water-logging. The percentage of total water and sediment flux taking place under each percentile flow rate in Flume 4.

3. Material and methods

3.1. Data collection

The drains from each catchment on the NWFP converge on a pre-collection chamber where samples of the runoff are extracted for measuring pollutant (e.g. sediment) content. Runoff then passes to an open channel where flow is recorded at 15-min intervals using H-flumes (designated for a 1 in 50-year runoff event) equipped with Tracom flow height gauges, and Teledyne ISCO bubbler flow-meter devices (ISCO Open channel flow measurement handbook, 2001). Turbidity is also measured at 15-min intervals using YSI multiparameter sondes (6600V2, YSI) inserted into stainless steel bypass flow cells. The latter are necessary to ensure that the multi-parameter sondes do not become vulnerable to drying out during the absence of field runoff. The sondes are calibrated quarterly for turbidity measurements using a two-point calibration; 0 (RO water) and 124 formazine nephelometric turbidity units (FNU). Automatic water samplers (ISCO) are used for the routine collection of water samples for developing the suspended sediment concentration-turbidity ratings for the turbidity sensors.

Recorded turbidity was converted into suspended sediment concentration (SSC) using ratings developed using 100 ml samples of runoff from the flumes sampled over a range of flow conditions. These samples were filtered through 0.7 μm pore size glass fibre paper and oven dried at 105 °C for 60 min (Equation (1); Bilotta et al., 2008). For Flumes 2, 8, 14 and 15 it was found that the relationship between SSC and turbidity changed after ploughing in mid-2013. As such, a new rating (Equation (2)) was developed from the relationship shown in Supplementary Fig 1 and this was applied during the post-plough period, defined as the time spanning from ploughing till the end of the first winter (March 31st) post plough.

\[
\text{SSC} = 1.1804_{-0.0472}^{+0.7116}(r^2 = 0.75) \\
\text{SSC} = 0.7664_{-5.7116}^{+5.7116}(r^2 = 0.91)
\]

Fig. 2. The percentage of total water and sediment flux taking place under each percentile flow rate in Flume 4.

Fig. 3. Flow, rainfall and SSC time series for Flume 4 from the 23/12/2012 to the 31/12/2012.
It was not possible to obtain a measurement of turbidity during flows of less than 0.0002 m$^3$s$^{-1}$ due to inadequate water depth; the intercept value of the SSC-turbidity relationships was therefore used for these periods in the runoff records.

An Adcon SM1 soil moisture station and an ADCON RG1 tipping bucket rain gauge with 0.2 mm resolution have been installed in the centre of each catchment. The soil moisture station records percentage moisture using capacitance at depths of 10, 20 and 30 cm. Both soil moisture and rainfall are recorded at 15-min intervals.

The particle size distributions of the < 2 mm fraction of soils within each catchment were quantified using a composite sample of 10–33 individual topsoil samples collected to a depth of 10 cm using a steel...
The total rainfall in each catchment and percentage of rainfall delivered to the catchment outlet during the study period.

| Flume  | Total rainfall (mm) | Percentage of rainfall delivered to the catchment outlet |
|--------|---------------------|--------------------------------------------------------|
| Flume 1 | 2085                | 71.90                                                  |
| Flume 2 | 2140                | 51.95                                                  |
| Flume 3 | 2030                | 59.05                                                  |
| Flume 4 | 2030                | 58.08                                                  |
| Flume 5 | 1897                | 64.65                                                  |
| Flume 6 | 1919                | 51.57                                                  |
| Flume 7 | 2247                | 51.84                                                  |
| Flume 8 | 2178                | 53.75                                                  |
| Flume 9 | 2061                | 42.60                                                  |
| Flume 10| 2054                | 45.58                                                  |
| Flume 11| 2178                | 42.28                                                  |
| Flume 12| 2086                | 34.34                                                  |
| Flume 13| 2025                | 41.15                                                  |
| Flume 14| 2118                | 58.11                                                  |
| Flume 15| 2138                | 77.38                                                  |

Data analysis comprised three stages. In stage one, the temporal trends in sediment and water flux were explored. Here, the percentage of the total sediment and water flux which occurred under each percentile of total flow rate in 5th percentile increments (0–5th, 5th–10th, etc) was determined to identify under what conditions the majority of export occurred. A time series of high flow events in Flume 4 (the largest catchment) was then examined to compare the temporal relationships between rainfall and sediment flux. The time series for the entire study period was also examined for the catchment which had the most complete soil moisture dataset (Flume 10) to determine the effect of soil moisture (%) on water and sediment fluxes. As part of this analysis, the relationships between flow and SSC were examined during saturated and non-saturated soil conditions. Finally, the relationships between flow and SSC were examined both before and after ploughing in Flume 8 which had the highest overall sediment export.

In stage 2, fluxes of water and sediment were examined to determine their controlling factors. The differences between total rainfall in each flume were first compared to determine how spatially variable the quantities of water delivered to the catchments were. It was also determined what percentage of the rainfall delivered to each catchment reached the corresponding flume outlet. The data time series was then divided into three categories based upon flow condition; rising limb, falling limb and baseflow. Where there was an increase in flow from the previous measurement the 15-min time period was classified as the rising limb, where there was a decrease it was classified as the falling limb, and where flow was at a rate less than 5% of the maximum value recorded in each flume the time period was classified as under baseflow conditions. This threshold was determined through a visual inspection of the flow time series; the 5% threshold was judged to best separate the rapidly rising or falling high flow peaks from flat or gently falling flow rates which characterised periods with little rainfall. The flow condition category was only changed from the previous if it lasted for longer than 1 h to minimise the noise of short duration fluctuations in flow. The total water and sediment fluxes were calculated for each flow condition as well as the total for the entire study period. It was then determined what percentage of the water and sediment fluxes and percentage of the study period duration occurred under each flow condition. The sediment and water export for each flume were compared to catchment characteristics (described at the end of this section) and the mean SSC of the flume runoff to determine their controlling factors.

In the final part of the analysis, the water and sediment fluxes were normalised to catchment area and the total duration of each flow condition to generate water and sediment specific yields (m³ ha⁻¹ yr⁻¹; t ha⁻¹ yr⁻¹). The yields were compared to catchment characteristics and the mean SSCs in the runoff of each flume to determine their controlling factors. A Pearson correlation matrix was finally used to summarise all of the correlations between catchment variables and sediment and water fluxes and yields.

The catchment characteristics compared to sediment and water fluxes and yields comprised: rainfall (mm), measured by the tipping bucket rain gauges; the percentage of time livestock were present, determined through farm management records; the percentage of soil area damaged by livestock and the total area of damaged soil (m²), identified manually using an 5 cm resolution aerial photograph and NDVI in ARCGIS 10.5; rainfall reaching each catchment outlet (%), calculated by multiplying the total rainfall by the catchment area and dividing by the measured water flux at the corresponding flume; catchment area (ha); mean catchment slope (°), measured using a 5m resolution Ordinance Survey Terrain 5 DEM in ARCGIS 10.5; rising limb water flux...
In almost all flumes, over half of the water flux took place between the 90th and 100th percentile flow rate despite this covering only 4% of the monitoring period duration (see example using Flume 4 in Fig. 2). The proportion of time spent in the rising limbs of all storm events across the study period; percentage of time spent in the falling limbs of all storm events across the study period.

4. Results

4.1. Temporal trends in runoff and sediment generation

In almost all flumes, over half of the water flux took place between the 90th and 100th percentile flow rate despite this covering only 4% of the monitoring period duration (see example using Flume 4 in Fig. 2). In excess of 90% of the total sediment flux took place between the top 5th percentile of flow conditions, indicating that the short periods of very high flow dominate sediment fluxes from the catchments (see example using Flume 4 in Fig. 2). The proportion of the study period where sediment was transported in concentrations exceeding background was using Flume 4 in Fig. 2). The proportion of time spent in the rising limbs of all storm events across the study period; percentage of time spent in the falling limbs of all storm events across the study period.

| (m³) | falling limb water flux (m³) | baseflow water flux (m³), calculated using the flume measurements; maximum flow accumulation in each catchment (m³), calculated using a 5m resolution DEM and the flow accumulation tool in ARCGIS 10.5; total water flux (m³); percentage of time spent in the rising limbs of all storm events across the study period; percentage of time spent in the falling limbs of all storm events across the study period.

| (b) Flow (%) | Rising Limb | Falling Limb | Baseflow | Rising Limb | Falling Limb | Baseflow |
|-------------|-------------|-------------|----------|-------------|-------------|----------|
| Flume 1     | 25.47       | 30.25       | 44.28    | 48.92       | 34.01       | 17.10    |
| Flume 2     | 34.54       | 30.85       | 34.62    | 66.45       | 18.43       | 15.13    |
| Flume 3     | 36.90       | 32.36       | 30.74    | 69.81       | 13.88       | 16.32    |
| Flume 4     | 33.55       | 37.12       | 29.33    | 69.30       | 16.62       | 14.09    |
| Flume 5     | 39.04       | 30.00       | 30.86    | 65.84       | 14.23       | 19.92    |
| Flume 6     | 29.88       | 18.57       | 51.55    | 65.74       | 21.16       | 13.11    |
| Flume 7     | 33.52       | 18.27       | 48.21    | 68.46       | 16.04       | 15.51    |
| Flume 8     | 41.18       | 32.10       | 26.72    | 49.06       | 10.81       | 14.29    |
| Flume 9     | 37.88       | 28.41       | 33.70    | 56.17       | 35.99       | 7.83     |
| Flume 10    | 28.82       | 10.89       | 60.28    | 69.67       | 19.57       | 10.66    |
| Flume 11    | 34.64       | 12.36       | 52.97    | 72.38       | 16.18       | 11.47    |
| Flume 12    | 41.93       | 12.50       | 45.59    | 72.24       | 19.06       | 8.70     |
| Flume 13    | 32.36       | 13.33       | 54.33    | 65.66       | 17.63       | 16.77    |
| Flume 14    | 34.22       | 16.97       | 48.81    | 49.56       | 16.88       | 12.24    |
| Flume 15    | 23.38       | 35.31       | 41.30    | 53.87       | 14.56       | 11.94    |

Fig. 3). This trend was present for most large storm events in most flumes and was most pronounced in the flumes with the highest SSCs in an event. Further rainfall during the same high flow event often resulted in turbidity rising again. For example, the event on the 24/12/2012 (Fig. 3) experienced an hour of heavy rainfall after the initial peak in SSC had fallen which resulted in a second peak in SSC. Fig. 3 demonstrates that the rise in SSC occurs prior to the rise in flow suggesting that sediment mobilisation and transport can occur with only small quantities of overland flow. This pattern was common to most catchments where a high SSC occurred (see Supplementary Fig. 3).

All flumes were characterised by a reduction in soil moisture during the summer of 2013 due to a period of low rainfall and high evapotranspiration (Fig. 4). During this dry period large rainfall events did not result in any appreciable flows or sediment generation. The high rainfall of mid-October 2013 increased soil moisture but it remained lower than that during the previous winter until the end of the study period. This had a large effect on the capacity of the catchments to generate sediment. After October 2013, there was a far lower SSC for a given flow in each flume than prior to the reduction in soil moisture in April 2013 (Fig. 5).

The ploughing and re-seeding of the fields draining to Flumes 8, 14 and 15 caused a significant increase in the mean SSC for a given flow rate in the post-plough period. This increase was most pronounced in Flume 8, where SSC for a given flow rate could be over 7 times higher than before ploughing despite soil moisture content being lower during this transition period (Fig. 6; plots for the other ploughed catchments are provided in Supplementary Fig. 4). Ongoing work is exploring explanations for the differing responses to ploughing. The SSC for a given flow rate increased under all flow conditions but was most significant during higher flows.
4.2. Fluxes of water and sediment

4.2.1. Temporal patterns of flow

When the flow time series were divided into the rising limb, falling limb and baseflow for all flumes, baseflow conditions (<5% of maximum flow) were present for the vast majority of the study period. In only the largest catchment (Flume 4) was less than 90% of the monitoring period spent under baseflow conditions. For all flumes, the mean percentage of time spent in the rising limb and falling limbs were comparable at 2.21% and 2.63%, respectively. There was, however, some variation between flumes with, for example, 6.97% of time spent in the rising limb for Flume 15 and only 0.25% for Flume 12 (Supplementary Table 1).

Mean precipitation during the study period for all flumes was 2079 mm (Table 2). Flumes 7, 8 and 11 had the highest rainfall with 99–168 mm more than the mean whereas Flumes 5 and 6 had the lowest at 182 and 160 mm less than the mean, respectively. There is a general spatial trend of the south east catchments experiencing the most rainfall and the south west the least. This spatial pattern is likely to reflect the orographic effect of winds from the south west having to transverse more of the neighbouring Dartmoor upland than winds from the south east. When the total rainfall inputs to each flume were compared to the monitored total water yields of the corresponding catchments (Table 2), Flumes 1 and 15 had the highest proportion of rainfall delivered to the flume outlet at 72% and 77%, respectively, compared to an overall mean of 53% for all flumes. Rainfall intensity when quantified using a histogram of daily rainfall totals is related to total rainfall with Flumes 4, 5 and 6 in the south west having 44, 44 and 52 days with rainfall exceeding 10 mm, compared with a mean of 62.5 days for the other flumes (Supplementary Fig. 5).

4.2.2. Water and sediment flux

For all flumes, a mean of 33.82% of the total water flux occurred during the rising limbs of storm events, 23.95% in the falling limbs and 42.4% during baseflow conditions (Table 3). A significantly higher proportion of sediment movement took place during the rising limbs of high flow events, with a mean of 62.87% for all flumes, compared with 19.00% in the falling limbs and 13.67% in baseflow conditions. It is therefore apparent that the ~2% of time spent in the rising limbs of storm events are most important for sediment erosion and transport to the edge-of-field flumes.

There was a strong linear relationship between the area of each catchment and its total water flux with an $r^2$ of 0.85 (Fig. 7a). The relationship was found to be strongest ($r^2$ of 0.90) when the catchment area is plotted against water flux in the rising limb only, compared to either the falling limb ($r^2$ of 0.78) only, or baseflow ($r^2$ of 0.75) only, reflecting the strong clockwise sediment hysteresis patterns observed. The total sediment flux was found to be more weakly correlated with catchment area with an $r^2$ of 0.56 (Fig. 7b), most likely reflecting the effect of soil erodibility which was primarily impacted by ploughing. For the rising limb only, the corresponding $r^2$ was 0.64, compared with 0.81 for the falling limb or 0.53 for baseflow only. The high $r^2$ for the falling limb is likely due to its longer duration in larger catchments. Flume 8 is the outlier in these relationships with a high sediment flux (Fig. 8). The water and sediment fluxes were normalised to catchment area and subsequently re-seeded, providing a likely explanation for this result. When this flume and Flumes 14 and 15, which were also ploughed and had high SSC for their area, were removed from this part of the analysis, the $r^2$ for the relationship between total sediment flux and catchment area increased to 0.73.

When comparing the total sediment flux to the mean SSC of runoff sampled in each flume (Supplementary Table 2), the relationship was weaker ($r^2$ of 0.39) than that with catchment area or water flux (Fig. 8). The highest mean SSCs were recorded in Flumes 2, 7, 8, 14 and 15 which when combined were found to have an overall mean of 10.43 mg l$^{-1}$ compared to a corresponding mean of 4.62 mg l$^{-1}$ for the remaining flumes (Supplementary Table 2). Of these flumes, all but Flume 7 were ploughed in mid-2013.

4.3. Water and sediment yields normalised to catchment area and partitioned by flow

The water and sediment fluxes were normalised to catchment area and the duration of each flow condition (rising limb, falling limb and baseflow) to calculate partitioned water and sediment yields. Water
yields ranged from approximately 4000 to 10000 m$^3$ ha$^{-1}$ yr$^{-1}$ (Table 4). Flumes 1, 4 and 15 had the highest total specific water yields and Flume 12 the lowest. This flume was also found to have lowest percentage of rainfall delivered to the flume outlet (Table 2).

Table 4: Total specific water and sediment yields for each flume, partitioned by flow.

| Flume   | Water yield (m$^3$ ha$^{-1}$ yr$^{-1}$) | Sediment yield (t ha$^{-1}$ yr$^{-1}$) |
|---------|----------------------------------------|--------------------------------------|
|         | Rising limb | Falling limb | Baseflow | Total | Rising limb | Falling limb | Baseflow | Total |
| Flume 1 | 6363 | 9779 | 3683 | 9000 | 3.74 | 1.61 | 0.03 | 0.18 |
| Flume 2 | 6087 | 7588 | 2175 | 8673 | 5.44 | 3.92 | 0.03 | 0.33 |
| Flume 3 | 7196 | 7881 | 2225 | 7197 | 9.04 | 1.49 | 0.06 | 0.38 |
| Flume 4 | 5890 | 5698 | 3786 | 10155 | 6.83 | 0.89 | 0.05 | 0.37 |
| Flume 5 | 7912 | 8740 | 2149 | 7362 | 7.25 | 1.43 | 0.05 | 0.32 |
| Flume 6 | 8901 | 204381 | 2120 | 5941 | 5.36 | 2.78 | 0.02 | 0.14 |
| Flume 7 | 11891 | 305943 | 2186 | 6994 | 27.43 | 12.99 | 0.09 | 0.68 |
| Flume 8 | 6685 | 80144 | 1978 | 7028 | 14.59 | 3.02 | 0.11 | 0.71 |
| Flume 9 | 6682 | 89228 | 1515 | 5271 | 5.95 | 1.62 | 0.03 | 0.22 |
| Flume 10 | 160332 | 564717 | 1811 | 5621 | 9.86 | 7.47 | 0.02 | 0.16 |
| Flume 11 | 166578 | 305943 | 2186 | 6994 | 27.43 | 12.99 | 0.09 | 0.68 |
| Flume 12 | 150212 | 635945 | 1299 | 4300 | 10.76 | 10.79 | 0.01 | 0.14 |
| Flume 13 | 160332 | 564717 | 1811 | 5621 | 9.86 | 7.47 | 0.02 | 0.16 |
| Flume 14 | 159042 | 428680 | 1848 | 7389 | 14.59 | 3.02 | 0.11 | 0.71 |
| Flume 15 | 90011 | 50321 | 4535 | 9933 | 18.21 | 1.78 | 0.07 | 0.66 |

Fig. 9. The relationships between the total water yield and percentage of rainfall delivered to the catchment outlet (a) and the total specific sediment yield and mean SSC sampled for the flume catchments (b).
Table 5
Pearson correlation coefficients of catchment, flow and sediment variables, values in bold are significantly correlated (p < 0.05).

|                | Rainfall | Percent time with animals | Rising limb water flux | Falling limb water flux | Baseflow water flux | Total water flux | Percentage time rising | Percentage time falling | Rainfall reaching outlet | Damaged soil area | Percent of soil area damaged | Water yield | Maximum flow rate | Mean SSC | Sediment flux | Sediment yield | Mean slope | Max flow accumulation |
|----------------|----------|---------------------------|------------------------|------------------------|--------------------|------------------|----------------------|----------------------|------------------------|------------------|----------------------------|-------------|-------------------|-----------|--------------|---------------|-----------|---------------------|
| Rainfall       |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Percent of time with animals |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Rising limb water flux |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Falling limb water flux |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Baseflow water flux |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Total water flux |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Percentage time rising |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Percentage time falling |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Rainfall reaching outlet |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Damaged soil area |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Percent of soil area damaged |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Water yield |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Maximum flow rate |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Mean SSC |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Sediment flux |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Sediment yield |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |
| Mean slope |          |                           |                        |                        |                    |                  |                      |                      |                        |                  |                             |             |                  |           |              |               |           |                     |

Correlation coefficients and p-values are presented. Significant correlations are bolded (p < 0.05).
5. Discussion

Three primary geographical components control water and sediment generation from the 15 study catchments monitored on the NWFP. First, and most importantly, catchment area is highly correlated with sediment concentration (Table 2) with several response characteristics, namely: total water flux \(r = 0.93\) and its associated partitioning \(r = 0.87 - 0.95\), maximum flow rate \(r = 0.96\), maximum flow accumulation \(r = 0.55\) and sediment flux \(r = 0.75\). The primary effect of area is that larger catchments have more land which can release water and sediment, with the increased flow being of more minor importance with regards to sediment generation than drainage area.

Secondly, the mean SSC of the runoff sampled for each flume and catchment specific sediment yield are strongly correlated \(r = 0.91; \text{Table 5}\). SSC is also significantly correlated with sediment flux \(r = 0.63; \text{Table 5}\); however, this is a weaker relationship than with sediment yield. SSC is controlled by the capacity of each unit area of the hydrologically-isolated catchments to generate sediment. Most importantly, ploughed and re-seeded catchments generated a significantly higher mean SSC than undisturbed long-term permanent pasture catchments. Equally importantly, a higher SSC was generated for a given flow when soils are saturated compared to when dry. It is noteworthy that SSC was not strongly correlated with catchment area \(r = 0.20; \text{Table 5}\) suggesting that the greater runoff, slope length and flow accumulation from the larger catchments is not causing a proportional increase in SSC as might happen if concentrated flows were initiating rill or gully erosion rather than lateral wash.

Thirdly, total rainfall was found to be correlated, albeit relatively weakly \(r = 0.52; \text{Table 5}\) with sediment yield, indicating that the amount of net erosion taking place in a given area increases with rainfall. Field walking during storm events suggested that the majority of sediment was eroded and transported during active rainfall with such processes ceasing rapidly with the end of precipitation inputs. The percentage of rainfall reaching each catchment outlet was correlated with water flux and specific yield but was not correlated with sediment flux nor yield, indicating that these particular aspects of hydrological response are unlikely to be key controlling factors on the amount of erosion and sediment export taking place. Recent work has reported some statistically significant shifts in rainfall patterns for some sites with long-term records elsewhere in the UK with aspects of these changes involving higher mean rain totals on rain days and more back-to-back days delivering in excess of 30 mm of precipitation (Burt et al., 2016). Although such analysis was not reported for the south west of England in conjunction with the work reported here, the relatively strong correlation \(r = 0.52; \text{Table 5}\) between rainfall and sediment yield suggests that such changes would potentially be significant for increasing sediment loss and associated on-site and off-site consequences in environmental settings similar to that represented by the NWFP. Here, it is noteworthy that recent papers have also reported the growing likelihood of weather extremes across the UK, including the unprecedented risk of higher rainfall (Thompson et al., 2017) and the importance of large-scale atmospheric-ocean oscillations (Mellander et al., 2018).

The finding that catchment area is the key control on sediment flux has the implication that either the entire area of each hydrologically-isolated catchment is eroding or that the greater catchment area is resulting in a larger quantity of runoff which is concentrating into high velocity flows which, in turn, cause more erosion. A higher flow accumulation in each catchment was shown to increase sediment fluxes and yields; however, these correlations were weak (Table 5). Additionally, Flume 2 was ploughed and flow accumulation was more concentrated than in the unploughed Flume 7, yet it did not have a higher sediment yield. Instead, Flume 7 with the higher rainfall (Table 2) experienced the higher total specific sediment yield (Table 4). As catchment area is more strongly correlated with sediment flux than maximum flow accumulation (Table 5) it is likely that erosion is occurring across the entire catchment areas. This is in contrast to the findings of Parsons et al. (2006) who found that sediment yield decreased with increasing plot length once a threshold of 7m length is passed because of the limited travel distance of individual particles.

It was found that SSC decreased sharply and rapidly when rainfall stopped, indicating that the action of rainfall is eroding the sediment subsequently reaching the edge-of-field flumes. It was also found that a thin layer of surface runoff covered almost the entire field areas during the latter stages of storm events. It is therefore proposed, on the basis of the analysis of the monitoring data herein and associated field observations, that raindrop impact is the primary agent of soil detachment and that saturation-excess surface runoff transports the detached particles to the edge-of-field where they are intercepted by the network of French drains. During the latter stages of a high-intensity storm event on the 26th of November 2018 it was observed that the turbidity of runoff decreased significantly after rainfall stopped, confirming the observations made using the turbidity records. It was also observed that concentrated high velocity flows over disturbed and trampled earth were insufficient to entrain soil particles (Supplementary Fig. 8). It is possible that during the early stages of storm events there is a greater concentration of easily detached particles and this erosion mechanism is of importance. However, no significant detachment of particles by concentrated overland flows have yet been observed on the site, even on heavily trampled soil.

This mechanistic conceptualisation centred on raindrop-impacted saturation-excess overland flow erosion is supported by the findings of previous work. Raindrop impact and splash have been identified as important components of rain-induced soil erosion (Zhang et al. 2017b, 2019; Hao et al., 2019). Here, the impact of the raindrops is responsible for two important processes increasing the propensity for soil erosion; topsoil aggregate breakdown and instigation of soil fragment movement (Legout et al., 2005; Warrington et al., 2009). Several studies have reported that raindrop impact can break down soil aggregates to help initiate soil erosion (Ekern, 1951; Kinnell, 1990a, 1990b; Van Dijk et al., 2002; Wang et al., 2014). Here, aggregate breakdown can be attributed to slaking, physico-chemical dispersion or differential clay swelling (Le Bissonnais, 1996; Levy et al., 2003). Whilst the observational work on the study site is not currently investigating or appportioning the principal mechanisms of aggregate breakdown experimentally, it is feasible to assume that raindrop impact is the first stage of soil erosion. A rapid decline in soil erosion in field settings where soil wetting is fast has been attributed to a dominant role of slaking in aggregate breakdown (Grant and Dexter, 1990; Ramos et al., 2003; Zaher and Caron, 2008), but targeted experimental work is clearly required at our study site to confirm or counter this, even though sediment responses were observed to be rapid. Regardless, published work has previously reported soil erosion by raindrop impact and subsequent transportation by raindrop-impacted overland flow (Young and Wiersma, 1973; Meyer et al., 1975; Kinnell, 2005). Similarly, previously reported studies have underscored that sediment transport by overland flow is greatly enhanced by raindrop impact (Foster, 1982; Singer and Walker, 1983; Guy et al., 1987) and that raindrop-impacted overland flow soil erosion is a detachment-limited process (Lattanzi et al., 1974; Meyer et al., 1975). Again, these findings point to our conceptualisation of soil erosion at the study site on the basis of sediment monitoring and field observations. This conceptualisation is reinforced by the fact that soil moisture was identified as a key control on temporal trends in sediment flux, with rainfall during the dry summer period of 2013 resulting in little flow and sediment flux. Even when soil moisture had recovered close to its pre-summer levels later in 2013, sediment flux continued to be significantly lower than when the soil was fully saturated (Fig. 4). It has been identified in catchments elsewhere globally that raindrop impact is the primary mechanism for soil detachment where overland flows are the dominant transport mechanism (Ellison, 1945; De Ploey and Savat, 1968; Young and Wiersma, 1973; Moss et al., 1979; Parsons et al., 1994).
This work identified a rapid and sharp decline in erosion after rainfall ceases. It has been identified (Ellison, 1945) that the reduced availability of loose detachable soil particles in the latter stages of a storm event can also cause the same reduction of sediment transport in the falling limbs of events as observed in this study. The cultivation of fields clearly has the effect of removing the protective grass sward and breaking up the soil structure, thereby increasing the quantity of loose detachable particles prone to mobilisation and delivery in saturation-excess overland flow in the catchments. Here, a reduction in erosion in the latter stages of high flow events may also be linked to the presence of the surface water. A thin layer of water up to that of the raindrop diameter has been shown to increase erosion because of turbulence in the water film (Palmer, 1963, 1965), but deeper surface water reduces erosion by providing a protective barrier against more detachment by raindrops, therefore resulting in eventual exhaustion of the supply of readily mobilised soil particles (Dunne et al., 2010). This links well with the soil particle detachment-limitation noted above.

Mean catchment slope was weakly negatively correlated with total rainfall and mean SSC (Table 5) suggesting that slope also plays only a minor role in the generation of sediment from the NWFP. In much published research, slope has been shown to have an important effect on rain splash erosion with dislodged particles being preferentially pushed in a down-slope direction (Dunne and Dietrich, 1980). Froehlich and Slupik (1980) and McCarthy (1980) showed that steeper slopes were characterised by a significant increase in soil detachment by rain splash. These studies were, however, over a range of gradients between 0°–25° and 0°–20° and it is therefore possible that the range of mean gradients for the hydrologically-isolated catchments on the NWFP (4.17°–12.25°; Table 1) is insufficient to show an effect in the analysis reported herein. It has also been shown that other factors such as raindrop size, vegetation cover and soil mobility have a larger effect than slope gradient (Dunne et al., 2010). Equally, other field-based studies in the UK have detected little relation between slope and the severity of soil erosion (Morgan, 1977; Evans, 1990b; Evans and Brazier, 2005), raising concerns about the prominent role slope plays in the computations by many erosion models.

An increased percentage of time with livestock present in each catchment resulted in a larger area of damaged soil. Larger catchments also had larger areas of damaged soil, possibly due to the livestock congregating in a small area of the field e.g. in conjunction with the regular moving of feeder rings. Neither the total area or percentage of the catchment area with damaged soil were, however, correlated significantly with sediment flux or yield (Table 5). It is possible that the small effect of ruminant livestock related soil damage is masked by the large impacts of the ploughing and re-seeding in some catchments. It is also noteworthy that even in the most damaged catchment, only 4.1% of the total field area was bare and damaged by poaching during the study period, again limiting the impact of such features of the pastures. This specific finding is potentially important for the management of soil loss from lowland grazing more generally in the UK, since the targeting of on-farm mitigation measures for erosion control has frequently focussed on measures such as regular movement of feeder rings before excessive trampling damage occurs, installation of concrete bases to protect soils beneath and surrounding drinking troughs, re-siting gateways away from high risk areas and the resurfacing of heavily poached gateways and cattle tracks (Collins et al., 2016). The findings from the study herein, however, suggest that such mitigation is unlikely to deliver substantial benefits for erosion management, highlighting the importance of using high resolution data to develop mechanistic (e.g. hydrological) understanding for guiding management interventions, rather than being informed by purely visual evidence alone. In this case, the monitoring data and analysis suggest that more general grazing management (e.g. reducing field stocking rates when soils are wet) will be more important (Kemp and Michalk, 2007), although since the NWFP aims to follow best practice, the scope for significant changes to the stocking density and grazing regime is small, especially in the context of the need for productive agriculture.

6. Conclusions

This research highlights the importance of particle detachment by raindrop impact and saturation-excess surface runoff for sediment mobilisation and delivery. The significant control imparted by catchment area suggests that connectivity within the studied fields is extremely high. This is likely due to widespread saturation-excess overland flow as driven by the local soils, although the network of French drains installed for the hydrological-isolation is a factor in the connectivity between the fields and flumes.

This study was conducted in an area of the UK for which it has recently been reported that a scenario of future projected uptake (rate = 95%) of on-farm mitigation measures might feasibly result in a reduction in sediment delivery to river channels from agricultural land by 39%. The modelled work suggested that much of this reduction could likely be achieved through targeted source control rather than delivery control (Zhang et al., 2017a). The findings reported in this paper support X.C. Zhang et al. (2017b) as the ploughing and re-seeding of some of the catchments resulted in a significant increase in sediment generation due to the entire field areas being exposed to raindrop impact and sediment transport by saturation-excess runoff. However, further research is needed into the effects of ploughing and re-seeding in lowland grazing systems on erosion rates and processes. One catchment on the NWFP had an extremely strong response to ploughing whilst another experienced very little increase in sediment flux. Understanding the geographical factors controlling these differences observed for fields in the same locality is key for reducing soil erosion and excess sediment loads exported to aquatic environments in lowland grazing landscapes. The ongoing work on the NWFP will provide the opportunity to answer these questions on the basis of mechanistic understanding provided by a combination of high resolution quasi-continuous monitoring and information for both intrinsic and management factors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109365.

References

Anderson, M.G., Burt, T.P., 1978. The role of topography in controlling throughflow generation. Earth Surf. Process. 3, 331–344. https://doi.org/10.1002/esp. 1290330402.
Avery, B.W., 1980. Soil Classification for England and Wales: Higher Categories. Soil Survey of England and Wales, Harpenden Technical Monograph No 14.
Berkman, H.E., Rabeni, C.F., 1987. Effects of siltation on stream fish communities. Environ. Biol. Fish. 18, 285–294. https://doi.org/10.1007/BF00448811.
Bilotta, G.S., Brazier, R.E., Haygarth, P.M., 2007a. Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: erosion. Hydrox. Process. 21, 115–139. https://doi.org/10.1002/hy.660.
Bilotta, G.S., Brazier, R.E., Haygarth, P.M., 2007b. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands.
Evans, R., 2010. Land use and accelerated erosion soil erosion by water in a small
S. Pulley and A.L. Collins
De Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A.,
Defra, 2015. Defra Agriculture in the United Kingdom 2014. London, UK.
Evans, R., 1997. Soil erosion in the UK initiated by grazing animals: a need for a national
Evans, R., 1988. Water Erosion in England and Wales 1982–1984. Report for Soil Survey
Dunne, T., Malmon, D.V., Mudd, S.M., 2010. A rain splash transport equation assimilating
Environmental Protection Agency, 2019. Report on the environment: land use. Available online at:www.epa.gov/report-environment, Accessed date: 2 July 2019.
Ekern, P.C., 1951. Raindrop impact as the force initiating soil erosion. Soil Sci. Soc. Am. J.
Boardman, J., 2015. Extreme rainfall and its impact on cultivated landscapes with par-
Boardman, J., 2013. Soil erosion in Britain: updating the record. Agric. 3, 418
Bilotta, G.S., Brazier, R.E., Haygarth, P.M., Macleod, C.J.A., Butler, P., Granger, S.,
Krueger, T., Quinton, J., 2008. Rethinking the contribution of drained and undrained grasslands to sediment-related water quality problems. J. Environ. Qual. 37,
Foster, G.R., Romkens, M.J.M., 1975. Source of soil eroded by water from
Moss, A.J., Walker, P.H., Hutka, J., 1979. Raindrop stimulated transportation in shallow
Meyer, L.D., Foster, G.R., Romkens, M.J.M., 1975. Source of soil eroded by water from
Lane, L., Nichols, M., Paige, G., 1995. Modeling erosion on hillslopes: concepts, theory and data. In: International Congress on Modelling and Simulation Proceedings (Agriculture, Catchment Hydrology and Industry), vol. 1. pp. 1–17.
Lattanzi, A.R., Meyer, I.D., Baumgärtner, M.F. 1974. Influence of mulch rate and slope steepness on interrill erosion. Soil Sci. Soc. Am. Proc. 38, 946–950.
Legout, C., Leguedois, S., Le Bissonnais, Y., Malam Issa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124 (3), 279–292.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Legout, C., Leguedois, S., Le Bissonnais, Y., Malam Isa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124 (3), 279–292.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Kemp, D.R., Michalk, D.L., 2007. Towards sustainable grassland and livestock manage-
J. Agric. Sci. 145 (6), 543–564. https://doi.org/10.1017/S00218784067707253.
Kemp, P., Bear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. 25, 1800–1821. https://doi.org/10.1002/hyp.7940.
Kinnell, P.L.A., 1990a. Modelling erosion by rain-impacted flow. Catena Suppl. 17, 55–66.
Kinnell, P.L.A., 1990b. The mechanics of raindrop induced flow transport. Aust. J. Soil Res. 28, 497–516.
Kinnell, P.L.A., 2005. Raindrop impact induced erosion processes and prediction: a re-
view. Hydrol. Process. 19, 2815–2844.
Lane, L., Nicholls, M., Paige, G., 1995. Modeling erosion on hillslopes: concepts, theory and data. In: International Congress on Modelling and Simulation Proceedings (Agriculture, Catchment Hydrology and Industry), vol. 1. pp. 1–17.
Lattanzi, A.R., Meyer, I.D., Baumgärtner, M.F. 1974. Influence of mulch rate and slope steepness on interrill erosion. Soil Sci. Soc. Am. Proc. 38, 946–950.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Legout, C., Leguedois, S., Le Bissonnais, Y., Malam Isa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124 (3), 279–292.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Legout, C., Leguedois, S., Le Bissonnais, Y., Malam Isa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124 (3), 279–292.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. Eur. J. Soil Sci. 47 (4), 425–437.
Palmer, R.S., 1963. The influence of a thin water layer on waterdrop impact forces. Int. Assoc. Sci. Hydrol. Publ. 65, 141–148.
Palmer, R.S., 1965. Waterdrop impact forces. Trans. ASAE (Am. Soc. Agric. Eng.) 8, 69–70.
Parsons, A.J., Abrahams, A.D., Wainwright, J., 1994. Rainsplash and erosion rates in an interrill area on semi-arid grassland, Southern Arizona. Catena 22, 215–226. https://doi.org/10.1016/0341-8162(94)90003-5.
Parsons, A.J., Bruijnzeel, L.A., Rosewell, C.J., 2002. Rainfall intensity-kinetic energy relationships: a critical literature appraisal. J. Hydrol. 261, 1–23.
Walling, D.E., Webb, B.W., Shanahan, J., 2008. Investigations into the use of critical sediment yields for assessing and managing fine sediment inputs into freshwater ecosystems. In: Natural England Research Report NERR007. Natural England, Sheffield.
Wang, L., Shi, Z.H., Wang, J., Fang, N.F., Wu, G.L., Zhang, H.Y., 2014. Rainfall kinetic energy controlling erosion processes and sediment sorting on steep hillslopes: a case study of clay loam soil from the loess plateau, China. J. Hydrol. 512, 168–176.
Warrington, D.N., Mamedov, A.I., Bhardwaj, A.K., Levy, G.J., 2009. Primary particle size distribution of eroded material affected by degree of aggregate slaking and seal development. Eur. J. Soil Sci. 60 (1), 84–93.
Wind, G.P., Schotthorst, C.J., 1964. The influence of soil properties on suitability for grazing and of grazing on soil properties. In: Proceedings of Eighth International Congress of Soil Science. Romania, Bucharest.
Wood, P., Armitage, P., 1997. Biological effects of fine sediment in the lotic environment. Environ. Manag. 21, 203–217. https://doi.org/10.1007/s106600000019.
Young, R.A., Wiersma, J.L., 1973. The role of raindrop impact in soil detachment and transport. Water Resour. Res. 9, 1629–1630. https://doi.org/10.1029/WR009i006p01629.
Zaher, H., Caron, J., 2008. Aggregate slaking during rapid wetting: hydrophobicity and pore occlusion. Can. J. Soil Sci. 88 (1), 85–97.
Zhang, Q., Wang, Z., Guo, Q., Tian, N., Shen, N., Wu, B., Liu, J., 2019. Plot-based experimental study of raindrop detachment, interrill wash and erosion-limiting degree on a clayey loessal soil. J. Hydrol. 575, 1280–1287.
Zhang, Y., Collins, A.L., Jones, J.I., Johnes, P.J., Inman, A., Freer, J.E., 2017a. The potential benefits of on-farm mitigation scenarios for reducing multiple pollutant loadings in prioritised agri-environment areas across England. Environ. Sci. Policy 73, 100–114. https://doi.org/10.1016/j.envsci.2017.04.004.
Zhang, X.C., John, Wang, Z.L., 2017b. Interrill soil erosion processes on steep slopes. J. Hydrol. 548, 652–664.