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Rice, A., Cassidy, R., Jordan, P., Rogers, D., & Arnscheidt, J. (2021). Fine-scale quantification of stream bank geomorphic volume loss caused by cattle access. *Science of the Total Environment*, 769, 1-9. [144468]. <https://doi.org/10.1016/j.scitotenv.2020.144468>

[Link to publication record in Ulster University Research Portal](#)

Published in:
Science of the Total Environment

Publication Status:
Published (in print/issue): 15/05/2021

DOI:
<https://doi.org/10.1016/j.scitotenv.2020.144468>

Document Version
Author Accepted version

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Fine-scale quantification of streambank geomorphic volume loss caused by cattle access

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1 **Abstract**

2

3 Unrestricted cattle access to streams and rivers can be a significant source of
4 pollution in fluvial systems, contributing to bank erosion and fine sediment inputs.
5 Despite this pressure, observational data are scarce. This study quantified stream
6 bank geomorphic modifications caused by cattle access at fine scale using motion-
7 capture cameras and Terrestrial Laser Scanning (TLS) campaigns. Continuous
8 monitoring of rainfall, discharge, conductivity and turbidity further augmented this
9 dataset. The application of these techniques extended over a five-month grazing
10 period in agricultural sub-catchments with intensive cattle production. At low flow,
11 high-resolution water quality data showed that the frequency of cattle activity in and
12 around stream margins was associated with elevated turbidity signals downstream.
13 However, when elevated turbidity coincided with high flow events, it was not
14 possible to distinguish between local erosion and upstream sediment transfers. TLS
15 results indicated a loss of 0.141 m³ to 1.035 m³ stream bank material, which equates
16 to 0.067 m³ m⁻² to 0.092 m³ m⁻² of stream bank area (between 27 % and 41 % in the
17 <2 mm fraction) over the study period from sites with 130 to 1,154 discrete cattle
18 access hits. Multiple linear regression showed that the observed geomorphic volume
19 loss could not be explained by natural processes alone (hydrometeorology), but was
20 more significantly related to cattle-access frequency as the principal driver. The
21 geomorphic volume loss had the potential to impact 29 m² to 197 m² of stream bed
22 with fine sediment (<2 mm) from the three study sites. Grazing parcels adjacent to
23 streams in the study sub-catchments were enumerated at 18.4 parcels km⁻² and so the
24 results of this investigation potentially scale to a considerable fine sediment risk.
25 Regulations and time-limited incentives to exclude cattle access to stream channels

26 should therefore expect to reduce sediment pressures where these measures are
27 targeted at access points.

28

29 **Keywords:** water quality, sediment, cattle access, erosion, terrestrial laser scanning,
30 motion-capture cameras

31 **1. Introduction**

32 Among diverse point sources of nutrients or sediment, cattle access to rivers and
33 streams is considered a worldwide issue in grassland systems with field-based
34 livestock (see Miller et al., 2010 – Canada; Conroy et al., 2016 – Ireland; Hughes et
35 al., 2016a – New Zealand; Terry et al., 2014 – UK; Schwarte et al., 2011 – United
36 States). Key livestock pressures on the aquatic ecosystem include manure and urine
37 deposition instream, trampling and erosion of fields and stream banks and disturbance
38 of the river bed.

39

40 Cattle can be a significant cause of sediment inputs to river systems owing to their size
41 and powerful locomotive effort which drives erosional and incisional mechanisms
42 resulting in geomorphic alterations. This excessive soil damage, or ‘poaching’ effect
43 (Collins et al., 2010; O’Callaghan et al., 2019; Sear et al., 1995), disturbs the soil
44 surface, providing a source of material which can be mobilised either by rainfall or
45 livestock movement and can lead to high sediment inputs to surface drains, streams
46 and rivers (Belsky et al., 1999). Soil compaction (Sharrow, 2007), increased
47 sedimentation (Hansen et al., 2010) and a reduction in soil infiltration rates (Castellano
48 and Valone, 2007) can follow and lead to stream bank instability (Zaimes and Schultz,
49 2011). This instability is of particular concern during high streamflow, when cattle
50 access has caused localised damage to banks leading to selective patches of bare land
51 more vulnerable to further erosion. This can facilitate substantial volumes of sediment
52 being released into the stream network (Evans et al., 2006; Magner et al., 2008).

53

54 Seasonally low soil cover and direct stream bank erosion have been cited as major
55 sources of sediment loss from land to water in agricultural catchments (Sherriff et al.,

2015). The latter provides a source in grassland catchments where direct soil surface erosion can be limited (Sherriff et al., 2018). Livestock access points are likely to be more discrete erosion sources, but the majority of previous research has focused on determining the effects in semi-arid regions. This includes Australasia and Canada, particularly dairy farms (Amy and Robertson, 2001; Miller et al., 2018) and the United States, focusing mainly on rangelands (Neal and Anders, 2015; Zaimes and Schultz, 2015). In NW Europe, particularly in regions such as Ireland and areas of the UK where grassland-based livestock farming dominates, studies have focused on the biological and chemical impacts of livestock access on water quality (e.g. Conroy et al., 2016; O’Sullivan et al., 2019a, b; Wilson and Everard, 2018). Indeed, Ireland will exclude cattle from water courses through fencing in early 2021 as a statutory policy for the most intensive livestock farms (SI 605, 2017). Other time-limited incentives for riparian fencing have been included in environmental management schemes in Scotland (Scottish Government, 2019) and Wales (Welsh Government, 2017). Despite this, there has been limited research on the geomorphic stream bank impact of cattle access and consequently, little is known on the extent to which cattle access points add to sediment inputs or how they influence bank erosion and destabilisation. Furthermore, there is a knowledge gap on whether these landforms are significant sources of sediment transfers relative to other forms of disturbance such as flooding.

There are numerous methodologies employed to measure river bank stability (e.g. long-term in channel morphology changes - Ziliani and Surian, 2012; turbidity fluctuation monitoring - Mitchell et al., 2003; in-situ shear stress tests - Micheli et al., 2002; erosion pins - Henshaw et al., 2013). However, applications have been limited by difficulty in utilisation, resolution of measurements and the timeframe of interest,

81 and by operator bias (Nasermoaddeli and Pasche, 2008; Resop and Hession, 2010).
82 One emerging tool that can be employed to mitigate these limitations is terrestrial laser
83 scanning (TLS). TLS has demonstrated the capability to generate high-resolution
84 digital terrain models (DTMs) by producing a detailed 3-D point cloud describing the
85 topographic surface being investigated to sub-centimetre grid resolution in a variety
86 of environmental systems (Day et al., 2013; Longoni et al., 2016). For example, it has
87 been previously applied to observe a wide variety of geomorphological phenomena in
88 aeolian (e.g. Cornwall et al., 2018), glacial (e.g. Prantl et al., 2017) and fluvial
89 (Brasington et al., 2012) environments. Despite some studies employing TLS to
90 investigate river bank structure and change over time (Teruggi et al., 2011; Prosdocimi
91 et al., 2015) none have quantified bank erosion rates caused by cattle access to stream
92 channels. Therefore, in an economic climate of agricultural intensification (Melland
93 et al., 2018) this study aimed to increase knowledge of cattle impacts on rivers and
94 determine how this interaction affects bank erosion and destabilisation.

95 The objectives were to:

- 96 i. Determine whether the frequency of cattle access to rivers from adjacent
97 grazing land at vulnerable sites had links to conductivity/turbidity impacts.
- 98 ii. Determine the importance of cattle access and hydrometeorological pressures
99 on stream bank geomorphic volume loss.

100

101 **2. Methodology**

102 2.1 Site selection and characterisation

103 The study area was located in grassland sub-catchments of the intensively farmed
104 Upper Bann river catchment in Northern Ireland (Figure 1). The wider catchment,
105 which is 220 km² in area to the downstream monitoring point at Banbridge (50m
106 Ordnance Datum), rises in the Mourne Mountains in the south (630 m Ordnance
107 Datum) and flows north toward Lough Neagh (surface area 392 km²). Key
108 physiographic features are sandstone and shale greywacke metasedimentary (Silurian)
109 geology, overlain by glacial till in the form of drumlins and ribbed moraines. Soils are
110 mostly gleyed with areas of brown earth, peat and alluvial deposits of silt, sand, and
111 gravel. The landscape has a high drainage density (mean 1.44 km km⁻²); annual mean
112 precipitation over the period 1975 – 2016 was 600–800 mm in the lowlands and
113 increasing to 800–1200 mm in the uplands (National River Flow Archive, 2016).

114

115 Three stream bank study sites (Figure 1) were selected in two sub-catchments (Bx and
116 By) with second order streams, one under intensive management (Bx) and the other
117 less intensive (By). Soils located at Site 1 (Bx) comprise of groundwater gley on
118 alluvium with Sites 2 and 3 (By) consisting of brown earth on sandstone till (1:50,000
119 General Soil Map of Northern Ireland, AFBI, 2009). Other physiographic and land
120 use/land cover details for the study sub-catchments and wider catchment are
121 summarised in Table 1.

122

123 **Figure 1.**

124 **Table 1.**

125

Study sites in the sub-catchments were routinely grazed by livestock and were selected for investigation based on management practice, including grazing patterns of beef and dairy cattle. The three sites centred on cattle access points to the stream channel, at trampled zones which showed signs of regular disturbance, each between 2.0 and 7.5 m in length. The timeframe for this investigation was set between 18th July and 11th December 2018 due to grazing taking place from mid-summer (July) to early winter (December) with one stream bank at each site remaining unfenced for the duration of the investigation (lasting between 120 to 150 days depending upon sampling location). Livestock unit (LU) herd sizes with access to the stream points were twenty-eight beef cattle at Site 1 and eighty-five dairy cattle at Sites 2 and 3. As is normal in these agricultural settings, access points were left undisturbed prior to the start of grazing and exposed only to normal rainfall and river discharge events.

Stream gradients at each location were similar in profile with channel widths ranging from 2.05 – 4.15 m with low, steep-sided and vertical banks (Table 2). Discharge rate was measured at 5-minute intervals at the catchment outlets using a rated flat-v weir in conjunction with an OTT Orpheus Mini pressure transducer located > 1 m upstream of the weir installed within a stilling well. Daily rainfall data were obtained from an automatic UK meteorological rain gauge located at Katesbridge, Co. Down (+54°.297 N, -6°.110 W), approximately 2.67 km from the nearest sampling point and 8.5 km from the farthest point (Figure 1).

Table 2.

2.2 Monitoring cattle instream activity

151 The frequency and impact of cattle access to the stream channel were captured using
152 a Victure HC200 motion-activated camera with infrared night vision, positioned at an
153 elevated vantage point at each location. Each camera recorded images at a resolution
154 of 1080 psi and offered a 120 ° detection angle with a trigger distance of up to 30 m,
155 thus providing adequate coverage of the study areas.

156

157 Images were routinely downloaded and inspected for numbers of cattle entering the
158 stream. A definite ‘hit’ was determined when one or more body parts was visible in
159 the stream (illustrated by three animals recorded instream, Figure S1). Time-stamped
160 hits were then grouped for analysis based on the frequency of access between
161 subsequent TLS surveys. Therefore, the model parameter ‘cattle access’ was measured
162 as the sum of recorded times cattle gained access to the channel over the specified
163 time interval (i.e. between TLS surveys).

164

165 2.3 Monitoring of water quality parameters

166 Automated multi-parameter water quality sondes were deployed downstream from the
167 cattle access points at Sites 1 and 3 throughout the investigation (Figure 1). Turbidity
168 and conductivity data were recorded at 15-minute intervals using a YSI 6920 V2-2
169 sonde placed 15 m from the cattle access point at Site 1. Similarly, turbidity and
170 conductivity (reference temperature 25 °C) were also recorded at Site 3 at the same
171 data collection interval using an AquaTROLL 600 located 25 m from the access point
172 (Figure 1). Water quality measurements were then synchronised and plotted against
173 instream cattle access observations to determine if there was any association between
174 instream access and water quality.

175

176 2.4 Terrestrial laser scanner: data acquisition and processing

177 To quantify the volumetric change of bank erosion taking place before, during and
178 after cattle access to the stream channel TLS surveys were carried out between 18th
179 July and 11th December 2018. At each sample point between four and six successive
180 topographic surveys were conducted throughout the campaign depending upon
181 sampling location.

182

183 The TLS data were captured using a FARO Focus^{3D} X330 single return terrestrial laser
184 scanner operating at a laser beam wavelength of 1550 nm (FARO, Lake Mary, FL,
185 USA). Between four and six reference spheres were deployed as ground control points
186 for each scan, enabling multiple scans to be stitched together for each survey. This
187 procedure of attaching retroreflective spheres to the same stationary position as in
188 previous surveys, allowed all surveys to be referenced to these common reference
189 points in order to identify change.

190

191 The annually calibrated FARO instrument has a scan distance range between 0.6 mm
192 and 330 m encompassing a manufacturer specified ranging error of ± 2 mm at 10 m
193 and a ranging noise error of 0.3 mm with 90% reflectance and 0.4 mm with 10 %
194 reflectance. However, with greater distances, error and noise estimates increase.
195 Therefore, for this investigation, all measurements were collected approximately 0.5
196 - 2 m from the cattle access point, well within the 10 m distance error estimates
197 outlined and capturing an average 28 million data points per scan depending upon the
198 distance away from the instrument.

199

200 Processing of the terrestrial laser scanning data included: a) preprocessing and data
201 filtering, b) scan registration c) point cloud creation d) data cleaning and e) 3D mesh
202 creation. Steps a-c were carried out using Faro SCENE[®] software (FARO
203 Technologies UK LTD, Warwickshire, UK) and steps d and e were completed using
204 3DReshaper[®] software. Additionally, to identify areas of surface change
205 CloudCompare v2.10; (<http://www.cloudcompare.org>) software was used in
206 conjunction with the Multiscale Model to Model Cloud Comparison (M3C2) plugin
207 algorithm. The M3C2 method is used to detect topographic change through analysing
208 and computing differences between the repeated TLS point cloud scans at each site.
209 Once preprocessing was completed, individual scans were then co-registered with the
210 stationary retroreflective spheres. This consolidation or alignment is undertaken to
211 assure all scans are in a single and universal coordinate system.

212

213 Following vegetation correction by digital removal of remnant data obscuring bare
214 earth data (Day et al., 2013; Resop et al., 2012), meshing of the 3D point clouds was
215 used to generate a surface model of the scene in 3DReshaper[®] resulting in a full 3D
216 high-resolution mesh of the cattle access points and subsequent erosional points. Final
217 overall geomorphic volume change observed at each study site was determined by
218 calculating the difference in surface volume change between the first and last TLS
219 based on ensuring low mean target distance errors (mean < 5.32 mm – Table S1). A
220 workflow of these steps is shown in Figure S2.

221

222 2.5 Stream bank characteristics

223 Following Das et al. (2018), material was collected from the stream bank face at a
224 depth of approximately 30 cm across the bank profile at each site. Ten samples were

225 collected from each study location, composited and air-dried at room temperature,
226 disaggregated using a pestle and mortar, and sieved (2 mm). Using a subsample of
227 material for each location, particle size distribution was determined to quantify the <2
228 mm fraction as well as percentages of clay (<4 μm), silt (>4 to <62.5 μm) and sand
229 (>62.5 to <2000 μm) (Ministry of Agriculture Fisheries and Food, 1986).

230

231

232 2.6 Statistical analysis

233 The pressures on stream bank erosion and hence geomorphic changes were assumed
234 to be due to the magnitude of cattle access but with added pressures relating to
235 hydrometeorology. Therefore, multiple linear regression analysis was undertaken to
236 determine the relationship between geomorphic volume change as the dependent
237 variable and cattle access frequency, rainfall and stream discharge as the predictors.
238 All statistical analysis was undertaken with R 3.6.0 in the ‘glm’ library and ‘stats’
239 package (R Core Team, 2019). Variations of model predictors were tested and levels
240 of significance used to infer model strength.

241

242

243 **3. Results**

244 3.1 Instream cattle access observations

245 A combination of field observations and analysis of digital images indicated that cattle
246 were present at the study sites for 122, 14 and 5 days for Sites 1, 2 and 3 respectively.
247 Throughout the investigation, a total of 1905 images were downloaded from the
248 cameras and enumerated for cattle activity in and around the streams. Across all three
249 study sites 1579 of the examined images were classified as hits with evident instream
250 access. The remaining 326 images were determined to be either false triggers (e.g.
251 vegetation, wildlife or rainfall) or images without confirmed cattle instream access
252 and were therefore omitted. Site 1 had the highest frequency of instream activity with
253 a total of 1154 confirmed observations with Sites 2 and 3 having 295 and 130 hits,
254 (Table 3), i.e. each animal accessed the stream an average of 41.2, 3.5 and 1.5 times
255 throughout the study period, respectively.

256

257 **Table 3**

258

259 3.2 Associations between instream cattle activity and water quality

260 The photographic data revealed that, once a lead animal entered the stream channel,
261 others tended to follow in rapid succession, resulting in clusters of instream access
262 leading to focused trampling activity. While instream, the majority of cattle remained
263 stationary for extended periods usually during periods of drinking or grazing riparian
264 vegetation. For typical channel access by small groups of two to six animals, cattle
265 spent between 30 seconds and 6 minutes trampling the stream bed and banks. These
266 movements affected the amount of sediment entering the water as a result of direct
267 access to the stream bank or via resuspension from the bed.

268

269 Periods of access to the stream bank and bed were captured by turbidity and
270 conductivity time series data during periods of low stream discharge. Despite some
271 gaps in data collection due to power failures, data collected downstream from access
272 points at Site 1 showed that water quality parameters were closely associated with
273 instream cattle counts. For example, this association was particularly strong from 24th
274 September 2018 to 12th October 2018 at Site 1 with a period of relatively high turbidity
275 (up to 133 NTU from a base line average of 9 NTU) and conductivity (up to 626 $\mu\text{S cm}^{-1}$
276 cm^{-1} from a base line average of 392 $\mu\text{S cm}^{-1}$) during and after extensive instream
277 access beginning at 9th October 2018 (Figure 2a). While elevated readings of water
278 monitoring parameters occurred during periods of cattle access, turbidity responded
279 with even higher increases during periods of storm discharge where conductivity
280 decreased through dilution. These processes are shown in Figure 2b at Site 1 during
281 the period from 23rd October 2018 to 20th November 2018 where a period of excessive
282 cattle access during low stream flows showed increased turbidity (to > 100 NTU) and
283 conductivity (up to approximately 800-1,200 $\mu\text{S cm}^{-1}$). Storms during mid-November,
284 however, increased turbidity to >1,500 NTU, diluted conductivity to approximately
285 400 $\mu\text{S cm}^{-1}$ and indicated increased turbulence and hydrological energy as the
286 strongest agents of turbidity (and hence sediment) change. These periods do not,
287 however, discriminate between the turbidity impacts of storm erosivity originating
288 from the immediate cattle access points or those originating from wider sub-catchment
289 diffuse sources.

290

291 **Figure 2**

292

293 3.3 Soil texture, bank erodibility and TLS

294 Soil analysis determined that stream banks across all three study sites comprised
295 predominantly of material with a particle size > 2 mm in diameter with 62 %, 73 %
296 and 59 % at Sites 1, 2 and 3 (i.e. 38 %, 27 % and 41 % fine sediment < 2 mm,
297 respectively). For the latter fraction full particle size analysis subsequently indicated
298 soil textural classes of clay loam, sandy silt loam and sandy loam (Table S2).

299

300 Surface change which occurred before and after instream cattle access (e.g. between
301 first and last TLS surveys) is shown in Figure 3 and highlights areas of significant
302 detectable change (See Figure S3-S5 for TLS detected change in each interval between
303 TLS surveys). Modelling of surface retreat indicated concentrated erosion along the
304 top and vertical face of the bank at Site 1 as depicted by erosional hotspots illustrated
305 in red. Sites 2 and 3 indicated more stability with regard to surface vertical change as
306 depicted by the M3C2 algorithm (Figure 3b and c). Geomorphic change calculated
307 from the difference between first and last TLS survey showed that Site 1 had a total
308 cut volume (eroded material) of 1.035 m^3 with Sites 2 and 3 having cut volumes of
309 0.537 m^3 and 0.141 m^3 , respectively (Table 4). These volumes equate to $0.092 \text{ m}^3 \text{ m}^{-1}$
310 2 , $0.067 \text{ m}^3 \text{ m}^{-2}$ and $0.071 \text{ m}^3 \text{ m}^{-2}$ normalised by the area of impacted stream bank,
311 respectively. Using cattle access frequency data (Table 3) and LU sizes at each site,
312 the total cut volume losses also equate to $0.025 \text{ m}^3 \text{ LU}^{-1}$, $0.153 \text{ m}^3 \text{ LU}^{-1}$ $0.094 \text{ m}^3 \text{ LU}^{-1}$
313 1 , respectively, over the grazing period. Small volumes of accretion (fill) occurred on
314 all three sites, but this was material that had already been eroded upslope and was then
315 deposited downslope. Also shown in Table 4 are rainfall and stream discharge between
316 TLS surveys.

317

318 Based on these total cut volumes and the estimated percentage of material <2 mm
319 diameter, the losses equate to 0.393 m³, 0.145 m³ and 0.058 m³ fine sediment (0.035
320 m³ m⁻², 0.018 m³ m⁻² and 0.029 m³ m⁻² of eroded stream bank area), respectively.

321

322 **Figure 3**

323

324 **Table 4**

325

326 3.4 Factors influencing stream bank geomorphic change

327 Multiple linear regression was calculated to investigate the relationship between
328 geomorphic volume change, cattle access frequency, rainfall, and stream discharge.
329 Results from the analysis are presented in Table 5 for Sites 1 and 2. This analysis was
330 not performed for Site 3 due to insufficient data as no cattle presence was recorded for
331 the duration of TLS campaigns 3 and 4 at this site (Table 3).

332

333 Four linear models with variations in predictors showed that geomorphic change was
334 most strongly predicted by cattle access frequency at both Sites 1 and 2 ($p = 0.002$ and
335 0.003 , respectively). Linear models with variations including cattle access and
336 combinations of rainfall and stream discharge were insignificant additions to the
337 models. This was despite some small increase of significance in the coefficients of
338 determination when rainfall or stream discharge was included. Inclusion of all three
339 predictors similarly indicated cattle access as the only significant variable at Sites 1
340 and 2 ($p = 0.040$ and 0.028 , respectively), but the increase in the coefficient of

341 determination was not significant at either site (Site 1 R^2 0.922 to 0.935, $p = 0.096$ and
342 R^2 0.907 to 0.949, $p = 0.076$; Table 5).

343

344 **Table 5**

345

346

347 **4. Discussion**

348 This study used novel approaches to record instream cattle activity with motion
349 activated digital cameras and monitor geomorphic stream bank change through
350 campaigns of terrestrial laser scanning (TLS). Multiple linear regression models
351 (Table 5) indicated that the geomorphic volume change observed at each study site
352 could not be fully explained by rainfall and discharge processes alone. Indeed, the
353 most parsimonious predictor of volume change at Sites 1 and 2 was the frequency of
354 cattle access. Consistent with this relationship, the exclusion of cattle and resulting
355 paucity of observations for Site 3, which prevented the same analysis, may account
356 for the least amount of geomorphic volume loss being recorded at this site over the
357 study period. Therefore, in spite of differences in cattle access frequency, the general
358 pattern was consistent across all three sites that increasing stream bank volume loss
359 occurred after periods of high-frequency instream cattle activity and resulted in direct
360 modifications in stream bank morphology.

361

362 The monitored sites are representative of catchment areas whose stream bank slopes
363 exceed published values for angles of friction characteristic for their soil matrix (e.g.
364 US Forest Service 1994, p. 435). While this exceedance was rather small for Site 2
365 and Site 3, it was substantially larger for the bank slope angle at Site 1 (Table 2), which
366 is indicative of a more cohesive bank material. Notably Site 1 also experienced the
367 greatest volumetric loss. Therefore, bank slope as a likely factor contributing to
368 erosion by cattle impact would require consideration for catchment scale studies which
369 aim to compare bank erosion potential between different stream access sites. However,
370 beyond bank dimensions such a comparative analysis would also have to include the
371 investigation of numerous site specific soil properties and processes, whose complex

372 interaction defines the incipient motion of cohesive bank material (Knight et al.,
373 1998).

374

375 Other studies have also linked cattle access points to riparian zone deterioration and
376 stream bank destabilisation (e.g. Hughes, 2016b; Peppler and Fitzpatrick, 2005).

377 However, by using the results of the TLS campaigns (Table 4) in combination with
378 particle size analysis, this study was able to indicate more specifically that
379 approximately 27 - 41 % of stream bank lost through cattle access at the three sites
380 was in the <2 mm particle size. This is an important fraction for river biological
381 functioning and benthic ecological health. It impacts salmonid egg development by
382 impeding hyporheic exchange and thus causes deoxygenation of gravel redds (Pattison
383 et al., 2015; Sear et al., 2014). Downstream benthic impacts from access points could
384 therefore be anticipated (Braccia and Voshell, 2007; Conroy et al., 2016).

385

386 While elevated downstream turbidity data did indicate periods when cattle accessed
387 the study sites during low flow, increased turbidity in general was most prominent
388 during high flow events, when the combined influences of local erosion and upstream
389 sediment transfers could not be disentangled. O'Sullivan et al. (2019a) also found that
390 cattle access levels of sediment deposition were spatially limited to the access point
391 due to site characteristics and stream geometry. It is, therefore, difficult to predict the
392 extent of the downstream influence of <2 mm particle size transfer from these three
393 study sites in the Upper Bann. However, a useful first estimate based on fine sediment
394 volume lost at Sites 1, 2 and 3, and assuming a uniform sedimentation depth (2 mm),
395 the potential areal extent of stream bed impact is 196.7 m², 72.5 m² and 28.9 m²,
396 respectively, over the grazing season.

397

398 The spatial extent of this impact may be further compounded owing to the number of
399 field parcels used for grazing cattle that bordered the stream network in the wider
400 study area (147 in total in two sub-catchments – 64 % of the number of grazed field
401 parcels and equivalent to 18.4 parcels km⁻²), including field parcels with multiple
402 access points. Considering the Upper Bann catchment as a whole and similar livestock
403 dominated catchments, cattle access to streams and rivers may, therefore, act as
404 substantial sources of (fine) sediment supply. Previous investigations undertaken
405 within lowland agricultural catchments in the east of Ireland found that the number of
406 cattle access points was 7-8 points km⁻¹ of river (Jordan and Ryan, 2011; Jordan and
407 Smietanka, 2013 cited in Conroy et al., 2016). This spatial extent could limit some
408 fluvial sites to achieve acceptable ecological status owing to varying retention times
409 and small catchment sizes (Kavanagh and Harrison, 2014; O'Sullivan et al., 2019a;
410 Snell et al., 2014).

411

412 4.1 Management implications

413 A study by Zaimes and Schultz (2015) in the USA showed that removing cattle from
414 riparian areas for ten years led to improvement in stream bank stabilisation. Similar
415 investigations carried out by Laubel et al. (2003) in Denmark and Zaimes et al. (2008)
416 in the USA showed that restricting cattle access to streams for periods from 6 months
417 to three years reduced the potential of bank erosion considerably along with improving
418 bank vegetation and recovery of previously impacted riparian areas. As regulations
419 and time-limited incentives for excluding cattle from streams and rivers are
420 established elsewhere (e.g. SI 605, 2017; Welsh Government, 2017; DAERA, 2019),
421 the benefits of these services will be measured against expected water quality

422 improvements. This study at least indicates that cattle exclusion can potentially reduce
423 erosion of stream banks at cattle access points by $0.067 - 0.092 \text{ m}^3 \text{ m}^{-2}$ in a grazing
424 period, 27 – 41 % of which is in the fine fraction.

425

426 This provides a first estimate of the reduction in sediment pressure expected from
427 fencing measures in the Upper Bann and that can be used to scale up a volume of
428 ‘saved’ sediment when all field parcel access points are enumerated and fenced.

429 In exemplar catchments elsewhere with different soil characteristics and stocking
430 densities, the method presented here can be applied more widely and is wholly
431 transferable. It can be used as a tool for the reliable quantitative assessment of the
432 reduction in sediment pressure resulting from national and international regulations
433 and incentives to exclude cattle from direct access to streams.

434

435

436 **5. Conclusions**

437 Novel techniques of motion-capture and terrestrial laser scanning techniques
438 (augmented with rainfall, stream discharge and water quality data) and results from
439 multiple linear regression demonstrated that frequent cattle access to streams can
440 result in significant loss of fine material from stream banks. This may contribute to
441 localised instream sediment deposition and, while local in nature, the high number of
442 access points identified in some catchments may result in a substantial loss in overall
443 habitat quality.

444

445 Total and fine sediment (<2 mm) losses from the three stream bank areas in one
446 grazing season were $0.092 \text{ m}^3 \text{ m}^{-2}$, $0.067 \text{ m}^3 \text{ m}^{-2}$, $0.071 \text{ m}^3 \text{ m}^{-2}$, and $0.035 \text{ m}^3 \text{ m}^{-2}$,
447 $0.018 \text{ m}^3 \text{ m}^{-2}$, $0.029 \text{ m}^3 \text{ m}^{-2}$, respectively. This dataset and range give an indication of
448 what sediment can be ‘saved’ from areas of stream bank with cattle exclusion in new
449 or existing regulations or incentive schemes. The novel method presented here
450 provides a transferable accounting framework for increasing the dataset in this and
451 other catchment/soil types with similar livestock access issues.

452

453

454 **Acknowledgements**

455 This work was funded by a DAERA PhD Scholarship (A. Rice) with additional
456 resources from DAERA Evidence and Innovation project 16/4/03. We acknowledge
457 AFBI and Ulster University staff for field and laboratory support. We also thank
458 farmers and landowners for access to catchment study sites. We acknowledge use of
459 data (Station number 203033) from the National River Flow Archive (URL:
460 <https://nrfa.ceh.ac.uk/> accessed 10/09/20). Finally, we thank the anonymous

461 reviewers for their insightful comments and suggestions which helped to improve the
462 manuscript.

463

464

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716

717 **Figure and Table captions**

718 **Figure 1.** Study catchment and location of cattle access points within two sub-
719 catchments of the Upper Bann, Northern Ireland with ‘intensive’ (sub-catchment Bx:
720 Site 1) and ‘less intensive’ (sub-catchment By - Sites 2 and 3) agricultural
721 management. ‘Cattle present’ represents field parcels which have had cattle grazing at
722 some point over twelve months prior to the study.

723

724 **Figure 2.** Time series plots showing periods of instream cattle access, turbidity,
725 conductivity and stream discharge at Site 1 during a) low flow and b) a period of low
726 flow followed by a storm event. Turbidity (and conductivity to a lesser extent) show
727 short duration increases with cattle access during low flow – but with a more
728 pronounced increase in turbidity (and dilution of conductivity) during high flow in
729 early November 2018.

730

731 **Figure 3.** Terrestrial Laser Scanning (TLS) point clouds showing the progressive
732 geomorphic vertical change between first and last survey scans with areas in red
733 depicting areas of high erosional change at Site 1 (a), 2 (b) and 3 (c). In the legends,
734 colours with figures less than zero illustrate point differences where erosion is likely
735 to have occurred.

736

737 **Table 1.** Summary information on physiography and land use/land cover for the
738 Upper Bann catchment and two study sub-catchments.

739

740 **Table 2.** Morphological and hydraulic characteristics of study sites.

741

742 **Table 3.** Summary of instream cattle activity for study period 18th July to 11th
743 December 2018 based on analysis of images recorded by the Victure HC200 motion-
744 activated camera.

745

746 **Table 4.** Summary of bank geomorphic change recorded with the TLS, rainfall and
747 stream discharge and surface runoff as they accumulated in survey intervals for the
748 study period 18th July to 11th December 2018; surface runoff in mm as the quotient of
749 stream discharge and sub-catchment area. For reference, the nearest long-term (1975
750 –2019) discharge monitoring station downstream of the study sites (101.7 km²) has a
751 ten day Q50 mean daily surface runoff of 10.8 mm and a Q10 surface runoff of
752 55.2mm (NRFA, 2020).

753

754 **Table 5.** Summary of multiple linear regression analysis undertaken for Sites one
755 and two demonstrating the association between geomorphic surface change, cattle
756 access frequency, rainfall and stream discharge accumulated in periods between TLS
757 surveys.

Tables

Table 1. Summary information on physiography and land use/land cover for the Upper Bann catchment and two study sub-catchments.

Catchment	Area, km ²	Elevation, m	Land cover, %			Land use, %					Mean field area, ha	Mean drainage density, km km ⁻²
			Grass	Arable	Other	Beef	Dairy	Mixed livestock	Mixed livestock/arable	Sheep		
Upper Bann	220	50-630	95	3	2	26	13	32	11	18	0.94	1.04
Bx	3.8	54-300	60	30	10	12	29	35	18	6	1.83	1.36
By	4.2	60-630	90	5	5	37	21	32	0	10	0.93	2.03

Table 2. Morphological and hydraulic characteristics of study sites.

Site	Reach gradient (m km⁻¹)	Stream width (m)	Bank height (m)	Bank length (m)	Bank slope (°)
1	11	2.30	1.5	7.5	60
2	13	2.05	4.0	2.0	45
3	15	4.15	1.2	2.0	40

Table 3. Summary of instream cattle activity for study period 18th July to 11th December 2018 based on analysis images taken with the Victure HC200 motion-activated camera.

Site	Survey period in 2018	No. of days between TLS	Cattle access frequency
1	18/07 → 02/08	15	38
	03/08 → 21/08	19	287
	22/08 → 13/09	23	169
	14/09 → 09/10	26	73
	10/10 → 20/11	43	578
	21/11 → 11/12	21	9
	Total	150	1154
2	18/07 → 02/08	15	34
	03/08 → 21/08	19	9
	22/08 → 13/09	23	112
	14/09 → 09/10	26	45
	10/10 → 20/11	43	89
	21/11 → 11/12	21	6
	Total	150	295
3	14/08 → 13/09	31	130
	14/09 → 09/10	26	0
	10/10 → 20/11	42	0
	21/11 → 11/12	21	0
	Total	120	130

Table 4. Summary of bank geomorphic change recorded with the TLS, rainfall, stream discharge and surface runoff as they accumulated in survey intervals for the study period 18th July to 11th December 2018; surface runoff in mm as the quotient of stream discharge and sub-catchment area. For reference, the nearest long-term (1975 –2019) discharge monitoring station downstream of the study sites (101.7 km²) has a ten day Q50 mean daily surface runoff of 10.8 mm and a Q10 surface runoff of 55.2mm (NRFA, 2020).

Site	Survey period in 2018	No. of days between TLS	Volumetric Change (m ³)	Rainfall (mm)	Stream Discharge (m ³)	Surface Runoff (mm)
1	18/07 - 02/08	15	0.068	102.6	342	0.2
	03/08 - 21/08	19	0.321	37.0	1,974	0.5
	22/08 - 13/09	23	0.142	35.0	1,642	0.8
	14/09 - 09/10	26	0.066	23.0	414	0.6
	10/10 - 20/11	43	0.402	133.0	86,078	20.9
	21/11 - 11/12	21	0.036	80.8	183,418	41.8
	Total	150	1.035	411.4	273,868	69.0
2	18/07 - 02/08	15	0.089	102.6	42,450	10.4
	02/08 - 21/08	19	0.052	37.0	16,093	3.9
	22/08 - 13/09	23	0.144	35.0	22,108	5.4
	14/09 - 09/10	26	0.095	23.0	18,635	4.6
	10/10 - 20/11	43	0.104	133.0	241,169	59.1
	21/11 - 11/12	21	0.053	80.8	262,929	64.4
	Total	150	0.537	411.4	603,384	147.9
3	14/08 - 13/09	31	0.11	58.6	28,322	6.9
	14/09 - 09/10	26	0.016	23.0	18,635	4.6
	10/10 - 20/11	42	0.008	124.4	241,169	59.1
	21/11 - 11/12	21	0.007	87.8	262,929	64.4
	Total	120	0.141	293.8	551,055	135.1

Table 5. Summary of multiple linear regression analysis undertaken for Sites one and two demonstrating the association between geomorphic volume loss, cattle access frequency, rainfall and stream discharge accumulated in periods between TLS surveys.

Study sites			Coefficients	Standard error	t	Sig.	Multiple r ²	F-statistic	p-value
Site 1	Model 1: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall + Stream Discharge	Intercept	6.3 x 10 ⁻²	5.0 x 10 ⁻²	1.242	0.340	0.935	9.538	0.096
		Cattle	7.1 x 10 ⁻⁴	1.5 x 10 ⁻⁴	4.826	0.040*			
		Rain	-3.5 x 10 ⁻⁴	8.1 x 10 ⁻⁴	-0.430	0.709			
		Discharge	-7.6 x 10 ⁻⁸	4.3 x 10 ⁻⁷	-0.177	0.876			
	Model 2: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall	Intercept	6.3 x 10 ⁻²	4.1 x 10 ⁻²	1.518	0.226	0.934	21.115	0.017
		Cattle	7.2 x 10 ⁻⁴	1.2 x 10 ⁻⁴	6.129	0.009**			
		Rain	-4.2 x 10 ⁻⁴	5.7 x 10 ⁻⁴	-0.740	0.513			
	Model 3: Geomorphic Volume Loss ~ Cattle Access Frequency + Stream Discharge	Intercept	4.9 x 10 ⁻²	3.4 x 10 ⁻²	1.464	0.239	0.929	19.52	0.019
		Cattle	6.8 x 10 ⁻⁴	1.1 x 10 ⁻⁴	6.221	0.008**			
		Discharge	-1.7 x 10 ⁻⁷	3.1 x 10 ⁻⁷	-0.546	0.623			
	Model 4: Geomorphic Volume Loss ~ Cattle Access Frequency	Intercept	4.1 x 10 ⁻²	2.7 x 10 ⁻²	1.500	0.208	0.922	46.982	0.002
		Cattle	1.0 x 10 ⁻³	1.0 x 10 ⁻⁴	6.854	0.002**			

Site 2	Model 1: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall + Stream Discharge	Intercept	5.7×10^{-2}	1.2×10^{-2}	4.598	0.044 *	0.949	12.321	0.076
		Cattle	7.5×10^{-4}	1.3×10^{-4}	5.817	0.028 *			
		Rain	3.3×10^{-5}	1.9×10^{-4}	0.172	0.879			
		Discharge	-6.7×10^{-8}	6.4×10^{-8}	-1.047	0.405			
	Model 2: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall	Intercept	5.9×10^{-2}	1.3×10^{-2}	4.690	0.018 *	0.921	17.380	0.022
		Cattle	1.0×10^{-3}	1.3×10^{-4}	5.858	0.010**			
		Rain	1.0×10^{-4}	1.5×10^{-4}	-0.714	0.527			
	Model 3: Geomorphic Volume Loss ~ Cattle Access Frequency + Stream Discharge	Intercept	5.9×10^{-2}	0.8×10^{-2}	7.416	0.005**	0.948	27.314	0.012
		Cattle	1.0×10^{-3}	1.1×10^{-4}	7.107	0.006**			
		Discharge	-5.9×10^{-8}	3.9×10^{-8}	-1.535	0.222			
	Model 4: Geomorphic Volume Loss ~ Cattle Access Frequency	Intercept	5.2×10^{-2}	0.8×10^{-2}	6.756	0.003**	0.907	39.021	0.003
		Cattle	1.0×10^{-3}	1.2×10^{-4}	6.247	0.003**			

Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

a)

b)

Start: 18/07/18
End: 11/12/18

a)

Start: 18/07/18
End: 11/12/18

b)

Start: 14/08/18
End: 11/12/18

c)

Table S1. Accuracy of TLS surveys throughout the investigation as determined by the mean target distance errors. Each survey cluster had a mean target distance error of less than 5.32 mm. To calculate geomorphic volume loss, each survey cluster required registration to a benchmark survey, i.e. the first survey undertaken for each site.

Mean target distance error (mm)			
Survey dates	Site 1	Site 2	Site 3
02/08/2018	2.68	3.59	
21/08/2018	3.08	5.09	1.93
13/09/2018	4.99	5.32	2.18
09/10/2018	5.01	3.56	2.43
20/11/2018	4.74	4.65	2.97
11/12/2018	4.96	4.17	3.77

Table S2. Soil texture analysis (particle size <2mm)

Site	% Sand	% Silt	% Clay
1	47.2	29.8	23.0
2	50.1	36.9	13.0
3	67.2	23.4	9.4

1

2

3