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Sherriff, Sophie; Rowan, John; Fenton, Owen; Jordan, Phil; O hUallachain, Daire

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RESEARCH ARTICLE

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Influence of land management on soil erosion, connectivity, and sediment delivery in agricultural catchments: Closing the sediment budget

Sophie C. Sherriff[1,2,3] | **John S. Rowan**[1] | **Owen Fenton**[2] | **Phil Jordan**[3,4] | **Daire Ó hUallacháin**[2]

[1] Geography and Environmental Sciences, University of Dundee, Dundee DD1 4HN, Scotland, UK

[2] Crops, Environment and Land Use Programme, Teagasc, Johnstown Castle, Wexford Y35 TC97, Ireland

[3] Agricultural Catchments Programme, Teagasc, Johnstown Castle, Wexford Y35 TC97, Ireland

[4] School of Geography and Environmental Sciences, Ulster University, Coleraine, Co. Derry BT52 1SA, UK

Correspondence

S. C. Sherriff, Geography and Environmental Sciences, University of Dundee, Dundee, DD1 4HN, UK

Email: s.c.sherriff@dundee.ac.uk

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Abstract

Agricultural land, and arable farming in particular, is commonly associated with increased soil erosion risk. Such systems are most vulnerable during low groundcover periods, but downstream delivery is ultimately controlled by connectivity. This study provides a catchment-scale sediment budget integrating three discrete but complementary investigations spanning different temporal and spatial scales. The first gives details on suspended sediment fluxes at the catchment outlet (2009–2012). The second provenances sources of fluxes using quantitative sediment fingerprinting. The third sets recent data in a multidecadal (60-year) context using radiometric (^{137}Cs) field-scale soil loss estimates. The catchment observatory (11 km^2) is low relief with predominantly well-drained soils and dominated by spring-sown cereal cropping through the study period. Modelling ^{137}Cs inventory losses across 30 fields provided a catchment-wide mean soil loss of 2.0 Mg ha^{-1} yr^{-1}. Although such rates are not atypical of intensively managed agriculture across Europe, they are considerably higher than contemporary sediment export yields of 0.12 Mg ha^{-1} yr^{-1} of which fingerprinting revealed that contemporary slope erosion contributed less than 25% (0.03 Mg ha^{-1} yr^{-1}). No evidence of floodplain or in-channel sediment storage was consistent with disconnectivity. Instead, it is hypothesised that soil loss is associated with coextraction from root crop harvesting of previously widespread sugar beet crops. Considering that the highest mass-specific ^{137}Cs concentration occurred during the 1960s, there appears to have been significant depletion of the cumulative ^{137}Cs inventory where root crop harvesting occurred as compared with atmospheric fallout 'reference sites.' The study highlights the value of multiple methodologies when seeking to understand legacy issues within agricultural catchment settings.

KEYWORDS

connectivity, cultivation, land management, sediment, sediment budget, soil erosion

1 | INTRODUCTION

Changes in agricultural land use and management can have both positive and negative effects on soil, which in turn can impact downstream aquatic ecosystems (Mueller et al., 2012). Scaling up to Atlantic Europe, soil sustainability (incorporating soil erosion, soil organic carbon, contamination, and compaction) is identified as a key environmental challenge (Amundson et al., 2015; Creamer et al., 2010; Louwagie, Gay, Sammeth, & Ratinger, 2011). Soil erosion can remove carbon- and nutrient-rich topsoils, resulting in a subsequent need to rebuild soil fertility, structure, and carbon content (Powlson et al., 2011; Quinton, Govers, Van Oost, & Bardgett, 2010). Where sediment and associated nutrients are hydrologically connected and delivered in excessive quantities to watercourses, physical damage to aquatic habitats and species, eutrophication, and reduced light penetration can occur, resulting in a deterioration in the quality of aquatic ecosystems (Kemp, Sear, Collins, Naden, & Jones, 2011; Kjelland, Woodley, Swannack, & Smith, 2015). Successful management of soil erosion and sediment delivery must, therefore, consider the spatial variability and magnitude–frequency relationships of particle detachment, conveyance, and delivery mechanisms—a process spectrum termed 'sediment connectivity' (cf. Bracken, Turnbull, Wainwright, & Bogaart, 2015).

Sediment connectivity is generally controlled by climate, physiography, lithology, and land management, which impact the availability and transfer dynamics of sediment within a catchment sediment cascade (Bracken & Croke, 2007). Physically, catchments possess a quasi-constant set of "boundary conditions," determined by topography, geology, soil texture, and topsoil–subsoil, subsoil–geology transitions. These conditions characterise the likelihood of water and sediment storage, preferential flow paths, or impeded horizontal and/or vertical water movement. For example, following rainfall, catchments underlain by geology featuring efficient primary and/or secondary permeability (e.g., karst landscapes) support subsurface hydrological pathways thereby reducing surface sediment connectivity (Schmidt & Morche, 2006; Mellander et al., 2013). In contrast, rainfall on catchments with impeded vertical permeability may encourage sediment connectivity as water emerges at the soil surface and subsequently moves over ground (Mellander et al., 2012).

Agricultural land management influences soil erosion rates by, for example, increased erodibility and efficiency of runoff on bare or low groundcover soils (Kirkby et al., 2004). On arable land, connectivity varies seasonally according to crop type, drilling date, and post-seeding establishment of groundcover in relation to rainfall characteristics and soil moisture conditions (Boardman & Favis-Mortlock, 2014). Permanent crop cover in pasture-based systems is more commonly associated with reduced sediment connectivity through interception of runoff and increased infiltration and organic matter build-up (Regan et al., 2012). However, channel bank erosion and compaction of soils by grazing livestock in fluvial corridors can also contribute to sediment fluxes (Lefrançois, Grimaldi, Gascuel-Odoux, & Gilliet, 2007). On the hillslope, landscape features can both concentrate (in-field tracks and tramlines) and intercept or attenuate (hedgerows and buffer strips) flow pathways, respectively, increasing and decreasing the likelihood of sediment connectivity between field systems and the channel network (Lacoste, Michot, Viaud, Evrard, & Walter, 2014; Thomas et al., 2017). Furthermore, in agroecosystems where agricultural productivity is inhibited by saturated field soils, extensive artificial surface and/or subsurface drainage systems and the modification and maintenance of the river network aim to reduce field water storage, which may both positively and negatively impact sediment connectivity (Shore et al., 2013).

The amount of water available for routing through catchments is driven by climate. In NW European latitudes, antecedent conditions prior to rainfall events (which themselves vary in duration, magnitude, intensity, and frequency) are a strong determinant of sediment connectivity at the event scale (Perks et al., 2015; Sherriff et al., 2016). Improving the understanding of sediment connectivity is challenged by the spatial and temporal heterogeneity of processes and high resource demands for data collection. However, the benefits of understanding and managing connectivity and disconnectivity to reduce the impacts of agroecosystems on downstream water resources make assembling an evidence-base essential to classify current behaviour and explore the influence of land management and climatic behaviour. Sediment budgeting, assembled through integration of complementary field-based techniques, quantifying losses and gains across a catchment, has been suggested as an essential framework for sediment management (Walling & Collins, 2008).

In this study, radiometric-based soil loss estimates were combined with existing downstream suspended sediment flux measurements to assemble a sediment budget to investigate temporal variations in hydrological and sediment disconnectivity. This was undertaken in a highly monitored, intensively managed, productive, and long-term predominantly arable mesoscale headwater catchment observatory with well-drained soils in Ireland (Melland et al., 2012). Sediment monitoring at the catchment outlet since 2009 has indicated a relatively low annual average suspended sediment yield of 0.12 Mg ha^{-1} yr^{-1} (Sherriff et al., 2015). Sediment fingerprinting of the yield showed that field topsoils are not the primary source, contributing, on average, 24% of sediment compared with 53% from subsoils and channel banks and 24% from damaged road verges (Sherriff, Rowan, Fenton, Jordan, & Ó hUallacháin, 2018). Quantification of seasonally averaged channel sediment storage indicated relatively low storage, approximately equivalent to 1 year of sediment yield (Sherriff et al., 2016). Using a LiDAR-based hydrologically sensitive area model, Thomas et al. (2016) indicated limited connectivity (7% of catchment area) during upper quartile rainfall–runoff events and highlighted the influence of microtopographically driven flow sinks, on catchment disconnectivity. The results were attributed to high permeability soils and fractured bedrock which dominate the catchment and support subsurface hydrological pathways; these reduce surface hydrological and sediment connectivity. However, high interannual variability of annual suspended sediment yield (0.03–0.23 Mg ha^{-1} yr^{-1}) and the high magnitude of event-scale sediment export following extreme rainfall, and likely efficient sediment connectivity, suggest periodic risks from this and similar catchments (Sherriff et al., 2016). A challenge is to quantify the extent and proportionate times of these apparent low sediment delivery rates with periods of high risk in the absence of long time series data.

The ^{137}Cs-based soil loss forensic approach was considered here to give a medium-term (approximately 60-year) time-integrated estimate to compare against short-term high-resolution sediment flux measurements at the catchment outlet. The basis of the technique is to use loss or gain of fallout ^{137}Cs inventory (Bq m^{-2}) in a soil profile relative to the inventory in a noneroding reference site to infer the amount of soil lost by erosion or, conversely, gained through deposition (Lacoste et al., 2014; Porto, Walling, & Ferro, 2001; Walling & Quine, 1990). The ^{137}Cs methodology for soil erosion assessment is subject to ongoing debates regarding the spatial variability of ^{137}Cs fallout and transfer to soil and the reliability of converting sampled inventories into soil erosion rates (Parsons & Foster, 2011, 2013). Mabit, Meusburger, Fulajtar, and Alewell (2013) review the existing and future strategies to minimise the potential impact of such uncertainties which are consequently an important consideration for future study. With these considerations in mind, the aim of the study was to assemble a catchment sediment budget to identify the relative importance of soil erosion and sediment (dis)connectivity on the low sediment delivery rates. This information can help inform catchment management strategies in this and similar catchment types.

The objectives were to (a) quantify field-scale soil erosion and sediment redistribution in a highly productive arable catchment based on slope and land use using ~60-year field-based ^{137}Cs soil loss estimates; (b) drawing on existing recent flux and channel source and storage measures, estimate the catchment sediment budget; and (c) evaluate the sediment connectivity implications for management.

2 | MATERIAL AND METHODS

2.1 | Study site

The 11.2-km^2 Castledockrell study catchment observatory is located in Co. Wexford, Ireland (52°34′N, 6°36′W). The catchment has been extensively described elsewhere (Sherriff et al., 2015, 2016), and a summary is provided below. Hillslope soils are predominantly well-drained, shallow Brown Earths, underlain by a fine loamy drift with siliceous stone subsoil. In the stream corridor and towards the eastern parts of the catchment, smaller areas of poorly drained Groundwater Gleys are present (Figure 1; – Melland et al., 2012). The underlying geology is characterised by slate and silt stones of the Oaklands Formation creating a poorly productive aquifer (Tietzsch-Tyler et al., 1994); however, secondary permeability occurs through bedrock fissure flow.

The dominant land use in the catchment is arable farming (54%), primarily cultivated on well-drained soils with spring barley, and the remainder of land is predominantly pasture-based for beef/dairy cattle and sheep grazing which primarily occurs on poorly drained soils. Two tributaries comprise the stream network flowing west–east and north–south which also drain a limited proportion of artificial drainage which is located in the poorly drained soils (stream linear density 1.3 km km^{-2}). The present average field size is 3.2 ha, and the areal density of hedgerows is 0.011 km^2 km^{-2} (Sherriff et al., 2015). A trend of increasing field size and decreasing density of hedgerows was likely over the soil redistribution decadal monitoring period as agricultural intensification was supported by large-scale adoption of machinery and the introduction of production orientated policy support, that is, the Common Agricultural Policy. Catchment rainfall, discharge, and suspended sediment yield in hydrological years (October 1 to September 30) of 2009, 2010, 2011, and 2012 were 1,240 mm, 750 mm, and 0.17 Mg ha^{-1} yr^{-1}; 763 mm, 366 mm, and 0.02 Mg ha^{-1} yr^{-1}; 1,102 mm, 517 mm, and 0.05 Mg ha^{-1} yr^{-1}; and 827 mm, 473 mm, and 0.12 Mg ha^{-1} yr^{-1}, respectively.

Monthly 60-year rainfall data (1954–2014) from the Johnstown Castle, Co. Wexford, national synoptic station (52°17′N, 6°29′W) were used to infer the temporal distribution of rainfall (CSO, 2016). Contributions from snow and subsequent snowmelt hydrology were minimal (less than 2 days yr^{-1} with snow lying as recorded at Rosslare synoptic station, Co. Wexford; Met Éireann, 2017). Field-scale land use data were collected as part of the wider monitoring programme (Wall et al., 2011). A longer term land use record (Land Parcel Information System), available from 2000 to 2013, was used to infer cultivation practices in the study catchment (DAFM, 2013).

2.2 | Data collection

For individual fields, mean field slope (°) and maximum downslope field length (MDFL, m) were derived from a 2-m resolution resampled LiDAR digital terrain model (DTM) for all catchment fields (n = 278). Low, medium, and high mean slopes, of <3°, 3–5°, and >5°, respectively, divided fields into three categories. The influence of slope length on sediment redistribution was minimised by selecting fields with the lowest deviations (either positive or negative) from the mean MDFL value of all fields (231 m). Within each slope category, 10 fields with the lowest MDFL deviation were selected for subsequent ^{137}Cs budgeting. Land use was evaluated; fields on an arable rotation termed 'cultivated' and 'permanent pasture,' which broadly represented well-drained and poorly drained soil types, respectively, and of a similar proportion to the catchment-scale land use breakdown (Figure 2).

Field cores for ^{137}Cs analysis were collected during September 2014 using a percussion drilled soil corer (diameter 60 mm and maximum depth 570 mm). A transect of cores was collected along a representative field section at equidistant downslope locations in each study field: top, upper-mid, mid-slope, lower-mid, and bottom, which reached within 3 m of upper and lower field boundaries (Walling, Porto, Zhang, & Du, 2014; Walling, Zhang, & Parker, 2005). At each hillslope location, cores were collected in triplicate on, and 3 m either side of, the central transect line perpendicular to the transect direction (Figure 2). Triplicate cores were bulked into one integrated sample to represent spatial variability resulting in 150 cores for analysis (Parsons & Foster, 2011; Zhang, 2015). Reference cores for background ^{137}Cs

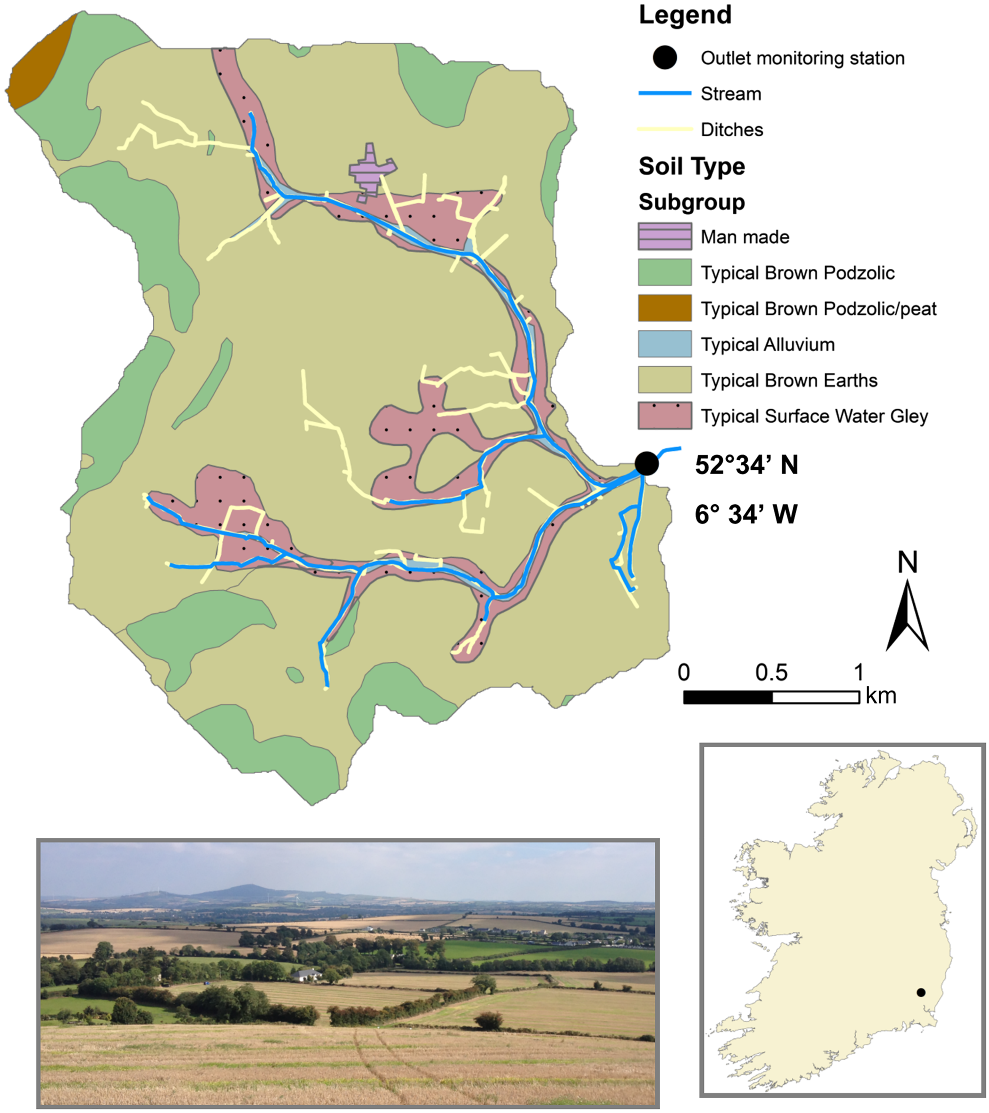

FIGURE 1 Map of the Castledockrell catchment, showing river channels, ditches, outlet location, and soil types. (inset) Map of Ireland with Catchment location (bottom right) and photograph of catchment showing fields with spring barley (bottom left) [Colour figure can be viewed at wileyonlinelibrary.com]

concentrations were collected at two locations with minimal soil disturbance (no evidence of fluvial or overland sediment redistribution or location under an established tree canopy). One site was located in a nonproductive area adjacent to a cultivated field; the second was located in a residential garden. At each location, nine cores were collected in a 1-m^2 grid resulting in 18 cores to establish a reference inventory. Reference cores were collected in 2014 at one site and during an additional campaign in 2017 at the second (with a 38.5-mm-diameter percussion drilled soil core). Further sectioned cores, subsampled into 2-cm increments indicating the vertical distribution of ^{137}Cs, were collected in 2017. Additional sectioned cores were collected from a cultivated field (in 2014 at 5-cm increments) and a grassland field (in 2017 at 2-cm increments) to determine mixing depth due to soil overturning associated with tillage and or reseeding of improved grassland fields. Chernobyl ^{137}Cs deposition was considered low (<2.3 kBq m^{-2}), as relatively low rainfall, <10 mm, occurred in 48 hr following the 1986 Chernobyl cloud passing south-east Ireland (McAulay & Moran, 1989).

2.3 | Laboratory analysis

Soil cores were oven dried at 105°C for greater than 48 hr, mechanically disaggregated, and sieved to 2 mm. Subsamples of 900 g, with consistent sample geometry, were analysed for ^{137}Cs at 661 keV on a low background ORTEC HPGe detector gamma spectrometer (ORTEC, Oak Ridge, USA) at the University of Dundee with count times over 30,000 s (mean error: 15%). Specific surface area (mg kg^{-1}) was estimated using a Malvern Mastersizer 2000G with autosampler unit following organic matter removal and chemical dispersal (Fenton et al., 2015).

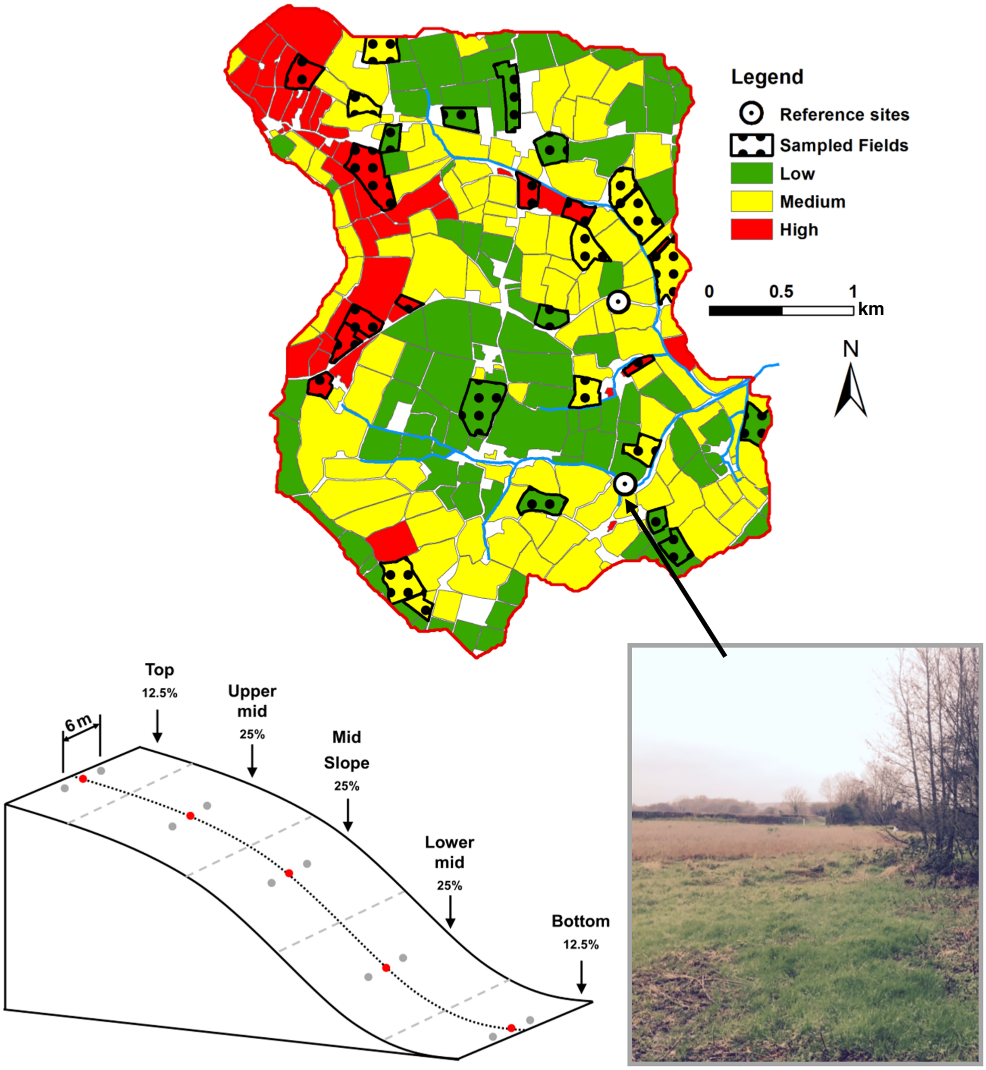

FIGURE 2 Field slope map based on defined categories (low <3°, medium 3–5°, and high >5°) and sampled fields in the study catchment (top); schematic representation of transect-based sampling strategy and spatial representation of sampling points (bottom left); and photo of reference site in foreground (bottom right) [Colour figure can be viewed at wileyonlinelibrary.com]

2.4 | Data analysis

Caesium-137 activity concentrations (Bq kg^{-1}) were converted to areal activity inventories (Bq m^{-2}) using total <2-mm bulked core mass and respective core surface areas (Porto et al., 2001). The Mass Balance 2 (MB2) model (FAO/IAEA, 2013) was used to calculate gross soil erosion rates (Mg ha^{-1} yr^{-1}) from bulked field cores and the field-scale net erosion (Mg ha^{-1} yr^{-1}) and sediment delivery ratio (field-SDR%; Walling & He, 1997) using all bulked cores within a specific field which were weighted to represent their spatial representativeness (top, 12.5%; upper-mid, 25%; middle, 25%; lower-mid, 25%; bottom, 12.5%; Figure 2). The MB2 model includes a vertical mixing component to represent cultivation; this was used for all fields with vertical ^{137}Cs distribution by ploughing, that is, for cultivated fields or reseeding for permanent pasture fields. The 2000–2013 land use record and sectioned cores indicated this was highly likely across the catchment (Figure 3). Cultivated fields were defined as those which supported arable crops in the available land use record (*n* = 24), and the remaining sampled fields were defined as permanent pasture (*n* = 6), whereby vertical ^{137}Cs mixing was possible but at a lower temporal frequency. Mechanical cultivation was assumed limited due to low permeability soils, small field sizes, or restricted accessibility for machinery. The MB2 model used the following parameters: tillage depth (115 kg m^{-2}) defined by the mass depth of ^{137}Cs from the incremental core (Figure 3); the proportion factor (1), accounting for the accumulation of ^{137}Cs during major rainfall preceding the cultivation in the catchment; and the relaxation depth (4 kg m^{-2}) as defined in agricultural fields in the United Kingdom (Walling & He, 1997). The stronger affinity of ^{137}Cs to clay particles between mobilised sediments and the original soil volume in both models was corrected using the particle size factor (average ratio 0.99) based on specific surface area (Dalgleish & Foster, 1996; Walling, Zhang, & He, 2007).

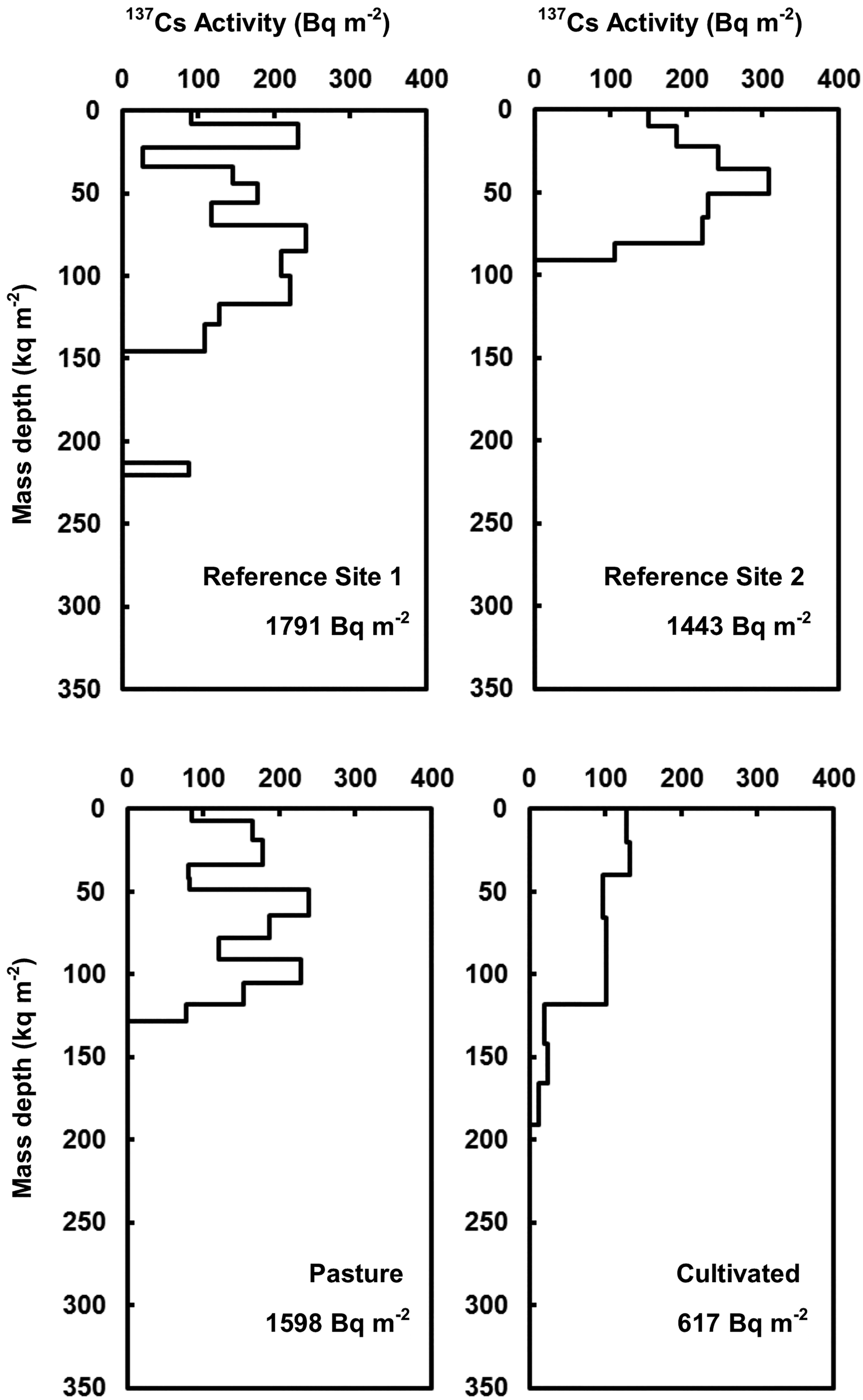

FIGURE 3 Depth profiles and total ^{137}Cs content of the two reference sites and fields under permanent pasture and cultivated rotations

3 | RESULTS

The ^{137}Cs reference inventory of 1,679 ± 96 Bq m^{-2} (standard deviation 408 Bq m^{-2}, n = 18) was exceeded in 64 of 150 field samples (Figure 4). The mean reference inventories from the two sites, 1,610 and 1,765 Bq m^{-2}, were not statistically different (Mann–Whitney U Test, p = .796) but vertical mixing, as indicated by sectioned cores, was identified at both sites (Figure 3). Samples from cultivated fields had significantly higher ^{137}Cs activity inventories than permanent pasture fields (p < .05, independent t test, SPSS v18). The models confirmed that 62% of individual core points were erosional with a maximum inferred erosion rate of 29.4 Mg ha^{-1} yr^{-1} and a maximum

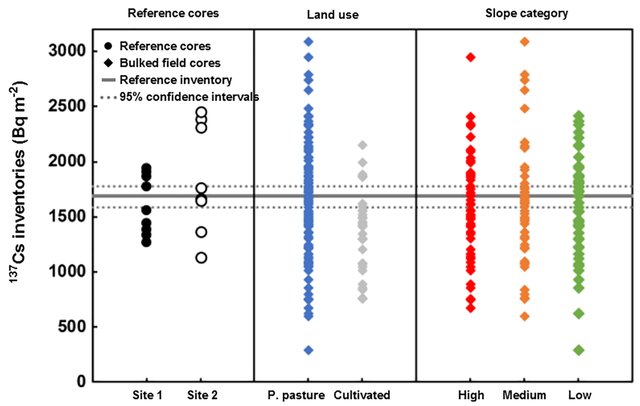

FIGURE 4 Activity concentrations of field and reference cores according to land use and slope categories (low <3°, medium 3–5°, and high >5°). P. Pasture, permanent pasture [Colour figure can be viewed at wileyonlinelibrary.com]

deposition of 14.1 Mg ha^{-1} yr^{-1} (Figure 5). No consistent trends in erosion or deposition coincided with field profile positions in either cultivated or permanent pasture fields (Figure 5) or spatially across the catchment (Figure 6a).

Field-scale soil erosion rates showed greater gross erosion, net erosion, and sediment delivery ratios from high and medium mean slope field classes relative to low, but these were not statistically significant (Table 1). The mean estimated field-scale gross soil loss rates of 2.8 Mg ha^{-1} yr^{-1} (range 0.0–13.0 Mg ha^{-1} yr^{-1}) and net soil erosion

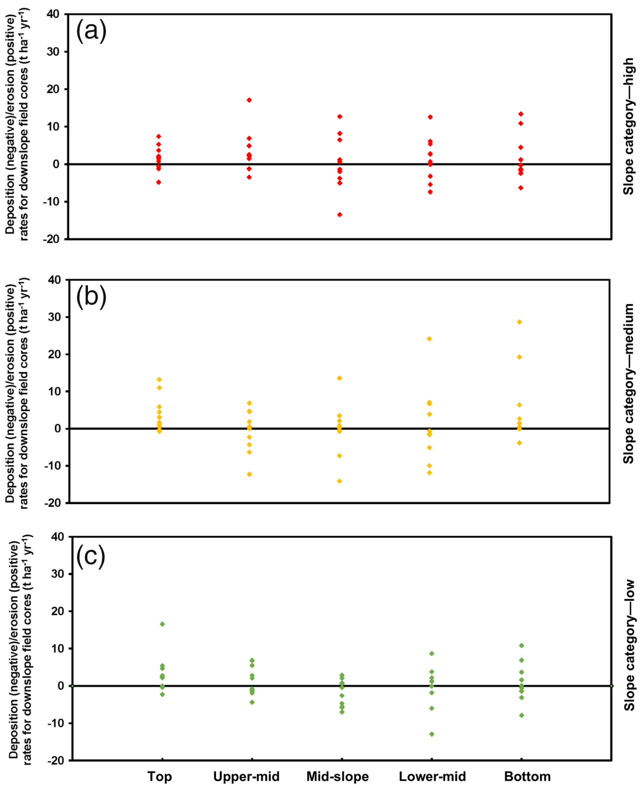

FIGURE 5 Downslope gross erosion/deposition trends in fields separated by slope group: (a) high (>5°), (b) medium (3–5°), and (c) low (<3°). Lines represent individual fields within each group [Colour figure can be viewed at wileyonlinelibrary.com]

rate of 2.0 Mg ha^{-1} yr^{-1} resulted in an average field-SDR of 55% for all fields (Table 1). Soil losses from permanent pasture fields were greater than cultivated, but no spatial trends were evident across the catchment (Figure 6b).

To understand the influence of cultivated crop type on soil erosion mechanisms, land use data from 2000 to 2005 in the Castledockrell catchment show 57% of cultivated fields were used for root crops and the maximum proportion was 15% of the catchment area (Figure 7a). After 2005, there was a decline overall in root crops, most notably sugar beet and greater uptake of grains. Across the wider Co. Wexford region, Figure 7b showed the greatest areas 10,000–14,000 ha of cultivated root crops from 1954 until the early 1970s. An overall increase in the area of sugar beet occurred from 1954 to 2000 from approximately 2,000 to 7,000 ha. Monthly rainfall data from 1954 to 2014 show annual average monthly rainfall contribution is highest in October to January at over 10% compared with February to September (Figure 8a). During the years of greatest ^{137}Cs fallout (1954–1964), annual rainfall was within 15% of the 30-year average annual rainfall (1,041 mm) for 8 years. Two years, 1958 and 1960, had annual rainfall of 1,366 and 1,318 mm, respectively, which were above 25% greater than the 30-year average annual rainfall.

The average net soil erosion rates of cultivated and permanent grassland fields relative to their respective catchment areas (cultivated, 874 ha; permanent grassland, 106 ha) estimated a medium-term net soil erosion rate of 1,777 Mg yr^{-1} or 1.8 Mg ha^{-1} yr^{-1} for the whole catchment. This represented maximum possible sediment input to the down-catchment sediment cascade and field-scale sediment retention (731 Mg yr^{-1}) and gross-soil erosion (2,508 Mg yr^{-1}) assembled for a 60-year average sediment budget (Figure 9). Recent data for annual average yield combined with quantified bed sediment storage and source provenance data indicate the contemporary sediment budget (Figure 9). In this case, the annual average suspended sediment yield of 0.12 Mg ha^{-1} yr^{-1} equated to 124 Mg yr^{-1}. The contemporary sediment fingerprinting data suggest, on average, 24%, 53%, and 24% were derived from field topsoils, channel banks, and road verges, respectively, which corresponds to 34, 78, and 34 Mg yr^{-1} in Figure 9 (Sherriff et al., 2018). As measured seasonal channel bed storage was relatively consistent, this was assumed not to cause fluctuations in the catchment yield between years (Sherriff et al., 2016).

4 | DISCUSSION

Field core ^{137}Cs concentrations above and below the reference inventory showed both erosional and depositional processes were present in the Castledockrell catchment. The depth profiles of both reference locations showed vertical disturbance. In intensive catchments with 93% agricultural utilisation (Sherriff et al., 2015), identification of physically undisturbed areas of soil was problematic. The two reference sites are, however, based on low-risk soils for run-on and runoff, in marginal areas (edge of field unproductive area and a private

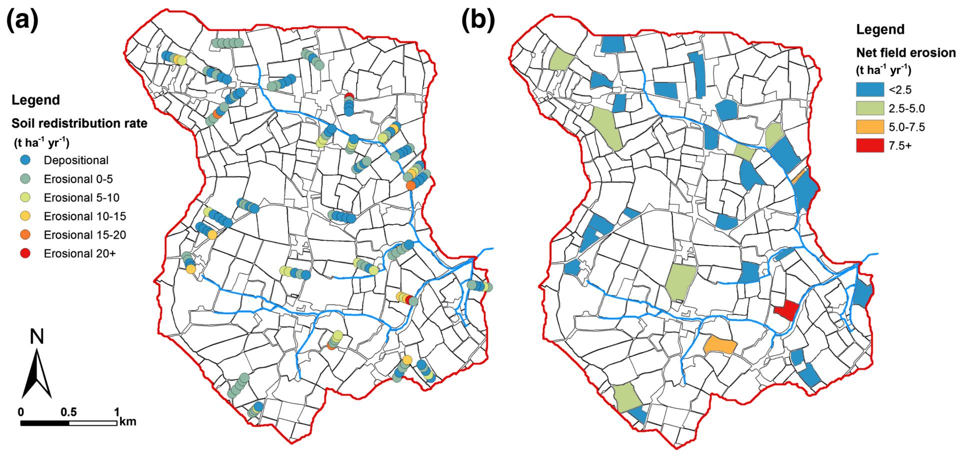

FIGURE 6 (a) Estimated soil redistribution rates of individual cores and (b) estimated field-scale net erosion rates of sampled fields using ^{137}Cs in Castledockrell [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary statistics for ^{137}Cs-based net soil erosion and sediment redistribution measurements using the Mass Balance 2 model in Castledockrell Catchment for all fields, slope categories, and long-term land use

Field category	*N*	Gross erosion (Mg ha^{-1} yr^{-1}) Mean	Range	Net erosion (Mg ha^{-1} yr^{-1}) Mean	Range	Sediment delivery ratio (%)
All	30	2.8	0.0–13.0	2.0	0.0–13.0	55
Slope categories						
High	10	3.0	0.9–5.5	2.4	0.0–5.5	68
Medium	10	3.0	0.0–13.0	2.2	0.0–13.0	68
Low	10	2.4	0.3–6.4	1.5	0.0–6.4	43
Long-term land use						
Cultivated	24	2.3	1.6–13.0	1.5	0.0–6.4	55
Permanent pasture	6	4.7	0.0–13.0	4.4	1.0–13.0	48

Note. Positive values represent erosion, negative values represent deposition.

garden) and were assumed to be valid reference sites relative to the field sampling locations.

The depletion of ^{137}Cs inventories from upper slope positions and downslope enrichment has been widely demonstrated (Govers, Quine, Desmet, & Walling, 1996; Verheijen, Jones, Rickson, & Smith, 2009). These inventories are the foundation for positive relationships between slope position and soil erosion rate and are influenced by tillage erosion. However, no consistent patterns of diverging depletion in upper slope positions or augmented ^{137}Cs inventories in lower slope positions were evident, suggesting downslope soil redistribution due to surface pathways being not significant in this catchment or, at least, not detectable relative to other erosional processes influencing the ^{137}Cs inventory (Figure 5). These data also indicate areas of elevated erosion may occur at a single hillslope location and are often not consistent, likely due to slope geometry and anthropogenic influences such as trafficking routes across fields. This supports previous work suggesting predominantly well-drained catchment soils underlain by fractured bedrock promoting infiltration and resulting in subsurface hydrological pathways (Mellander et al., 2016; Sherriff et al., 2016, 2015; Thomas et al., 2016). Thus, the likelihood for surface runoff driven erosion and sediment transport pathways is, at best, intermittent and confined to the most extreme rainfall events and/or localised areas of saturation excess or infiltration excess overland flow on poorly drained gleyic soils in the river corridor (Sherriff et al., 2016).

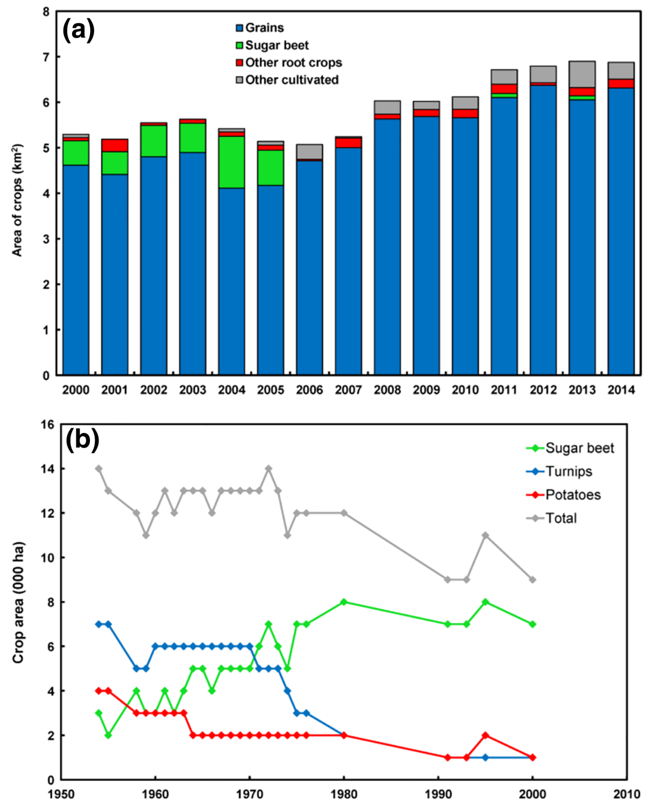

FIGURE 7 (a) Arable crop type in the Castledockrell Catchment from 2000 to 2013 (DAFM, 2013); (b) total and specific root crop (sugar beet, turnips, and potatoes) area in Co. Wexford from 1954 to 2000 (CSO, 1997, 2002) [Colour figure can be viewed at wileyonlinelibrary.com]

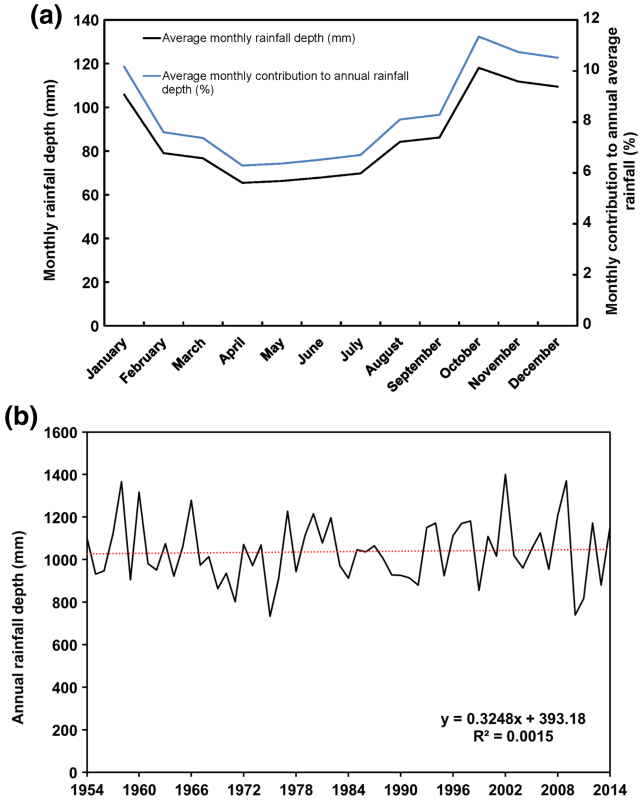

FIGURE 8 (a) Average monthly rainfall depth and average contribution of average monthly rainfall to annual average rainfall depth and (b) annual rainfall totals (1954–2014) [Colour figure can be viewed at wileyonlinelibrary.com]

Although soil loss rates are lower than estimates of 4.5–38.8 Mg ha^{-1} yr^{-1} from tilled agriculture across Europe and within the range of estimates for arable land in Ireland of 1.3 and 4.4 Mg ha^{-1} yr^{-1}, reported gross and net erosion rates have still exceeded normative ranges of tolerable soil erosion rates (cf. 0.3–1.4 Mg ha^{-1} yr^{-1}; Verheijen et al., 2009; Cerdan et al., 2010; Regan et al., 2012; Panagos et al., 2015). Estimated soil losses from permanent pasture fields in this catchment are greater than estimated for European soils and significantly greater than cultivated fields (Cerdan et al., 2010). These permanent pasture fields are frequently located on steeper, poorly drained soils in the river corridor. Therefore, despite the interception of surface hydrological pathways by vegetation, greater surface hydrological connectivity elevates the likelihood of soil erosion and particle entrainment, that is, sediment connectivity (Cerdan et al., 2004; Sherriff et al., 2018; Vannoppen, Vanmaercke, De Baets, & Poesen, 2015). These clay-dominated gleyic soils have also been shown to bind radiocaesium more strongly than coarser soil textures (Okumura et al., 2018). Greater affinity of ^{137}Cs to finer particles which are preferentially eroded relative to coarser fractions, particularly during surficial soil erosion, may indicate actual soil loss rates from permanent pasture fields are lower than estimated here.

From a connectivity perspective, the estimated catchment soil erosion rate highlights a major anomaly of 60-year field-scale soil loss rates with high field-SDRs and recent suspended sediment yields (2009–2013) of 0.12 Mg ha^{-1} yr^{-1} (Sherriff et al., 2015). Sediment fingerprinting completed in this catchment over 2 years indicates only 24% (0.03 Mg ha^{-1} yr^{-1}) of the suspended sediment yield can be attributed to field topsoils. This indicates an extremely low field-to-outlet SDR of 2%. Low catchment SDRs are not unexpected in catchments dominated by subsurface hydrological pathways as areas of hydrological connectivity are spatially and temporally limited (Thomas et al., 2016). This would suggest conveyance losses occur further along the sediment cascade as particles are transported from the field, into, and through the river network to the catchment outlet (Walling, Collins, Jones, Leeks, & Old, 2006; Walling, Russell, Hodgkinson, & Zhang, 2002).

Compiling a catchment sediment budget for the present day, channel sediment storage in the stream or ditch networks cannot account for the discrepancy between soil loss and sediment yield, and geomorphological evidences of extreme channel resuspension and flushing events are similarly absent (Keesstra, Bruijnzeel, & van Huissteden, 2009). Sherriff et al. (2016) estimated the seasonally averaged fine (<125 μm) bed sediment storage was 128 Mg across the river network which accounted for 7% of the annual average net soil erosion from fields. Additionally, Shore, Jordan, Mellander, Kelly-Quinn, and Melland (2015) reported 58% of ditches in this catchment were net transfer zones of sediment, whereas only 13% showed accumulation. Field surveys since the establishment of water quality monitoring in 2009 have also shown infrequent floodplain inundation is limited to lower reaches of the catchment and, therefore, is unlikely to account for the discrepancy in sediment volumes. This is supported by high agricultural utilisation which has created minimal opportunity for sediment deposition in the narrow riparian corridors (Sherriff et al., 2018).

Methodologically, assumptions underlying the ^{137}Cs-based soil loss estimations have been challenged resulting in the debate regarding the reliability of estimated rates (Mabit et al., 2013; Parsons & Foster, 2011). Transfer of ^{137}Cs intercepted by vegetation to the soil and nuclide binding to soil particles was assumed complete and not formally quantified. However, in this study, implementation of an established protocol, with standard analytical capabilities, and an enhanced field sampling programme was designed to minimise uncertainties in spatial ^{137}Cs deposition and ensure robustness of the collected data. Therefore, in terms of understanding current patterns of connectivity, there is a fundamental mismatch in the catchment. The medium-term net field losses inferred from ^{137}Cs modelling suggest (a) that the potential for additional processes impacting soil and ^{137}Cs removal is not captured in the modelling approach and (b) that modern sediment yield values are not consistent with the medium-term average.

Land management is a fundamental variable not comprehensively included in ^{137}Cs conversion models but likely to have a significant impact on both soil erosion and the functioning of ^{137}Cs as a soil erosion tracer. Figure 7a indicates that sugar beet was cultivated in Castledockrell until 2006 when the Irish sugar industry collapsed in response to the EU sugar policy reform (OJEU, 2006). Sugar beet cultivation in Co. Wexford prevailed since 1926 showing an established,

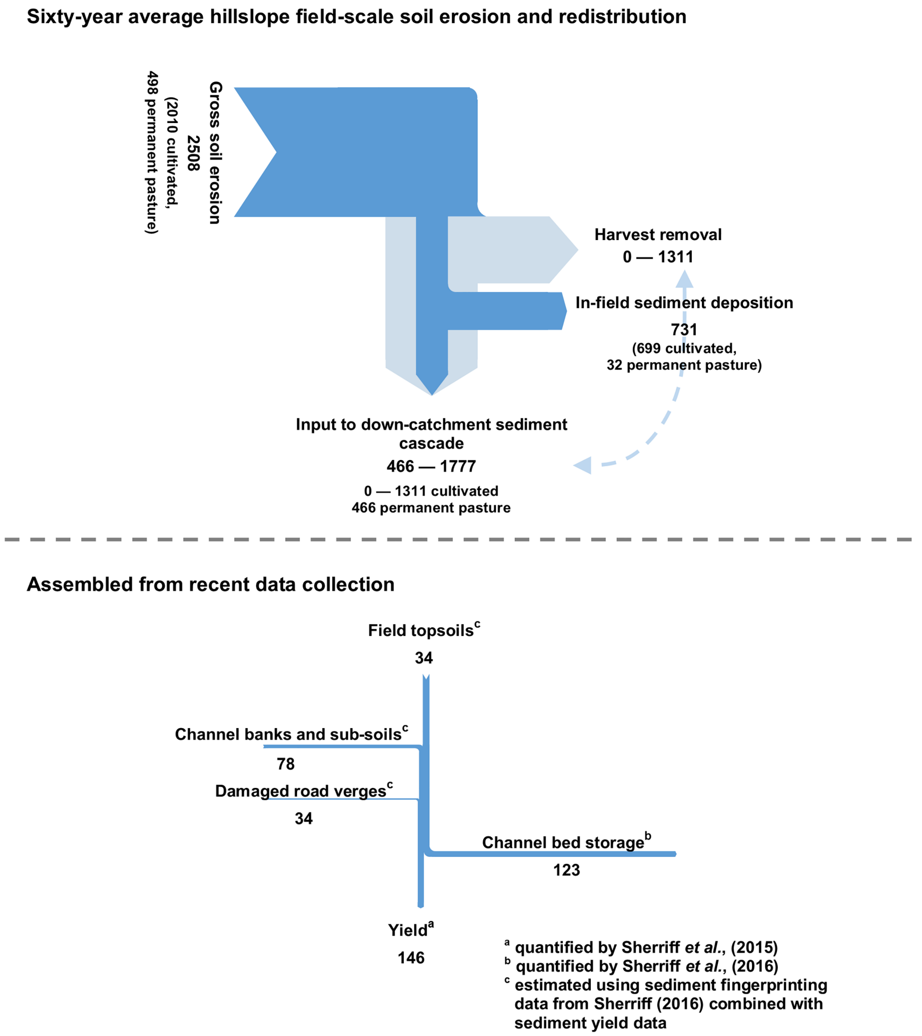

FIGURE 9 Annual sediment budget for the Castledockrell catchment in Mg combining 60-year averaged data (upper) and recent (lower) sediment flux, fingerprinting, and channel storage data. The blue dashed arrow represents the estimated components of the sediment budget whereby an increase/decrease in one component represents a corresponding change in the other within the limits stipulated on the diagram. Channel bed storage is not subtractive and assumed inputs equal outputs on an annual time step [Colour figure can be viewed at wileyonlinelibrary.com]

long-term cropping rotation which predated the initial ^{137}Cs fallout (Figure 7b). The soil series showing the greatest productivity across Co. Wexford represents 75% of the catchment area (Lee & O'Connor, 1976; Lee & Ryan, 1966). The extent and magnitude of root crop cultivation were restricted by one in 3-year rotation of sugar beet to control nematodes which subsequently restricted the potential spatial extent of harvest associated soil loss and ^{137}Cs removal (Hbirkou et al., 2011). However, anecdotal evidence suggests all fields on a cultivated rotation are likely to have supported root crops in the past. This was consistent with the trend in the area root crops over time which suggests there was previously a greater proportion of fields supporting root crops (Figure 7b). Uptake of caesium into the plants themselves must also be considered. On loam soils, a consistent texture with the cultivated catchment soils, radiocaesium uptake by cereals and root crops has been estimated at 1.4×10^{-2} Bq kg^{-1} (range 4.5×10^{-4}–4.2×10^{-1} Bq kg^{-1}) and 5.7×10^{-2} Bq kg^{-1} (range 1.5×10^{-3} – 9.0×10^{-1} Bq kg^{-1}), respectively, which is a small proportion of the field core activity values (Zhu & Smoulders, 2000). Additionally, hydrological redistribution of the recorded inventory through diffusion and convection processes is possible and have been reported elsewhere by He and Walling (1997). However, the same study and others acknowledge that cultivation and erosion dominate for vertical soil distribution due to the high affinity, up to 93%, of ^{137}Cs to particles (Yamashiki et al., 2014).

Lake cores from a small (141 ha) catchment in Sweden with similar proportions (62%) of cereal and sugar beet agriculture reconstructed suspended sediment yields of approximately 2.5 Mg ha^{-1} yr^{-1} from 1950 to 1979 due to severe erosion predominantly associated with overland flow on 'open' or bare soils (Dearing et al., 1987). Similar sediment yield reconstructions in the Castledockrell study catchment were not possible as lakes are absent from the area. Crops such as sugar beet, turnips, and potatoes are associated with harvest soil erosion, whereby soil losses in the range of 3.8–11.8 Mg ha^{-1} per harvest have been reported (Poesen, Verstraeten, Soenens, & Seynaeve, 2001;

Ruysschaert, Poesen, Verstraeten, & Govers, 2004, 2007; Tuğrul, İçöz, & Perendeci, 2012), and it follows that soil-bound ^{137}Cs is coextracted and removed from the catchment fallout inventory (Bq m^{-2}) attached to crop roots (cf. van Oost et al., 2003; Walling et al., 2005; Golosov et al., 2017).

To estimate the maximum possible rate of harvest soil erosion, a catchment sediment budget was constructed based on the assumption that all sediment not retained in-field are lost to harvest erosion. The maximum possible rate of 1.5 Mg ha^{-1} yr^{-1} appears justifiably at the lower end of published rates, as coarser loam soil textures, such as the Brown Earths, which dominate the cultivated catchment soils, are less likely to adhere to root crops relative to clay-dominated soils (Ruysschaert et al., 2004). Harvest soil erosion will subsequently coextract adsorbed ^{137}Cs which was likely greatest during periods of highest ^{137}Cs deposition in the mid-1960s. This process is not represented in standard conversion models but is likely to artificially reduce the ^{137}Cs inventory in the affected fields and potentially inflate the estimated soil erosion losses reported above (van Oost et al., 2003).

The variability in sediment connectivity over time must also be considered. Cultivation of sugar beet, in terms of the agricultural calendar, likely increased the historical frequency and spatial extent of sediment connectivity and sediment yield from the catchment which is not captured in the available sediment yield data. Late autumn/early winter harvesting of sugar beet crops coincided with the main annual rainfall period (October to January) which likely increased the 'window of opportunity,' that is, efficiency of water erosion, entrainment, and transport compared with a spring cereal-dominated catchment whereby post-harvest, soils are unmanaged and crop residues provide some stability to the soil profile and are drilled, on average, during drier months (Boardman & Favis-Mortlock, 2014). Significant event suspended sediment fluxes (flow-weighted mean suspended sediment concentration, 1,256 mg L^{-1}) have been reported in this catchment when extreme rainfall and low groundcover combine which exceeds the equivalent metric in catchments with higher annual average suspended sediment yields (Sherriff et al., 2016). These events were likely more frequent under past land use configurations which is supported by anecdotal evidence from catchment landowners and cannot be attributed to changes in rainfall. Field amalgamation due to mechanisation over time, resulting in increased field size and reduced hedgerows, likely increased hillslope soil erosion risk and modified hydrological pathways (Thomas et al., 2016). However, the impact of cropped field positions on modelled mean suspended sediment yield versus the window of opportunity effect has been reported as 22% and 100%, respectively (Smith et al., 2018). This suggests the gradual amalgamation of fields is likely to have a minor impact on soil erosion and sediment delivery, particularly considering the low connectivity of the majority of catchment soils.

Using the time-averaged ^{137}Cs data, the minimum estimated hillslope sediment loss of 466 Mg yr^{-1} does not include sediment delivery from cultivated fields. This value was likely higher (and compensated in the sediment budget by a reduction in the maximum possible harvest soil erosion rate) but challenging to estimate and would have impacted in-field redistribution of sediment, channel sediment storage, and sediment export values but not significantly enough for observations of legacy sediment at the present day. The present estimate of field-derived sediment (indicated by sediment fingerprinting) suggests more than 69% of the minimum possible 60-year 'input to down-catchment sediment cascade' volume is lost in conveyance to the river network (Figure 9). Large-scale sediment retention is not supported by geomorphic evidence suggesting that estimated soil erosion results from direct soil removal from the field, that is, coextraction, or efficient erosion and transport of eroded soils through the catchment. However, using field methodologies with contrasting timescales to estimate conveyance losses (soil redistribution and sediment fingerprinting) and the catchment SDR (soil redistribution and suspended sediment yield) to infer catchment behaviour is problematic. As previously discussed, shifts in land management alter sediment connectivity and undermine the representativeness of relatively short-term datasets and corresponding metrics.

Bringing together all the evidence to explain apparent sediment disconnectivity in this catchment based on land use, associated land management, and the spatial/temporal extent of hydrologically sensitive areas, the ^{137}Cs data offer new insights. High average soil erosion rates and low in-field sediment retention over the last 60 years, yet the apparent lack of such processes during the present day, suggest the soil erosion and sediment delivery were historically augmented. This matches with land use records of sugar beet which was harvested during wetter winter periods and subjected the catchment to harvest soil erosion which is responsible for loss soil from the surface of affected fields. Nevertheless, this disconnection, reduced sensitivity or function, apparently provided by current (spring crop and grassland) land cover, is likely to be undermined with reconfigurations to cropping patterns that expose soil redistributions to winter rainfall–runoff processes (Smith et al., 2018). Policies which could result in significant changes in crop type and land management windows must consider the potential impact of soil erosion, sediment connectivity, and the influence of these potentially augmented processes on soil and aquatic ecosystems (Keesstra et al., 2009). Sediment budgets, constructed using soil erosion, sediment connectivity, and sediment delivery studies, must fully consider the appropriateness of combining contrasting methodologies and complete a full appraisal of processes over space and time to support interpretations of collected data (Parsons, 2011). Combining soil erosion and sediment measurement with modelling expertise may offer a crucial future strategy to resolve discrepancies and explore the influence of anthropogenic or natural changes on catchment sediment yields across a variety of timescales (Smith et al., 2018).

5 | CONCLUSIONS

Soil core and field-scale soil redistribution rates of cultivated and permanent pasture fields were quantified using a forensic ^{137}Cs approach in an arable catchment observatory to estimate catchment soil erosion and assess sediment (dis)connectivity by constructing a sediment budget. Collating data from three discrete methodologies with contrasting timescales revealed fundamentally divergent systems of soil erosion and sediment delivery which could not be explained by sediment connectivity. The assembled sediment budget suggested that 60-year average soil loss rates contradicted contemporary basin processes, consequently raising the importance of land use (change) and land management in the catchment.

The main findings were (a) the 60-year gross soil erosion from all fields (average 2.8 Mg ha^{-1} yr^{-1}) was higher than tolerable soil erosion rates despite dominance of well-drained soils in the catchment; (b) net soil erosion from permanent pasture fields, 4.4 Mg ha^{-1} yr^{-1} (on predominantly low permeability soils), was greater than from cultivated fields, 1.5 Mg ha^{-1} yr^{-1} (on predominantly high permeability soils), due to the greater likelihood of overland flow initiation; and (c) net soil erosion rates from cultivated fields could not be validated by sediment yield, riparian attenuation, or in-stream bed suspended sediment storage during the present day, indicating a 2% catchment sediment delivery ratio. Sediment removal from the arable catchment fields was likely due to the combined influence of coextraction from historical harvest soil erosion associated with root crops combined with increased efficiency and transport of water erosion when low groundcover periods coincided with, on average, wetter periods (compared with solely spring sown crops) and this fits with recollections from catchment farmers.

In conclusion, the reduced sensitivity of sediment export risk (i.e., disconnectivity) offered by high soil permeability and a low extent of hydrologically sensitive areas is also linked to land use. In this study, historical field-scale erosion rates were likely to have been highly influenced by winter-sown sugar beet crops and harvest erosion. This now appears reduced by spring-grown cereal crops which are harvested without removal of the root system (and associated soil). Permanent pasture land management on low permeability soils is a consistent high risk for soil erosion despite the limited extent in the catchment. This has implications for other catchments sensitive to sediment export risk and where land use configurations may mitigate or augment that risk now and under future policy driven land use change.

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ORCID

Sophie C. Sherriff https://orcid.org/0000-0003-2579-7696

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