RESEARCH ARTICLE

Simulated event-scale flow and sediment generation responses to agricultural land cover change in lowland UK catchments

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Abstract

Agricultural land use can increase runoff and erosion leading to detrimental downstream impacts. This paper examines the impact of agricultural land cover change on runoff and sediment generation at event scales using a model-based approach. SHETRAN, a physically based, spatially distributed model, was applied in two southwest England catchments to represent: (a) changes in the land cover (cropland extent and spatial arrangement), (b) changes in crop type, and (c) use of riparian buffer strips. A total of 84 simulated events within a 4-year period were used to quantify impacts on flow and sediment generation. We found past changes in land cover resulted in significant differences in sediment yield ($p < 0.05$). Linear regression showed an increase in flow and sediment yield proportional to increases in arable crop area ($p < 0.001$). The spatial arrangement of cropped fields and riparian buffer strips produced no significant differences in event flow or sediment yield ($p > 0.05$). However, buffer strip scenarios compared with the base run showed sediment load reductions for specific events, up to 20% and 15% for woodland and grass riparian buffers, respectively. When comparing crop types with and without the use of post-harvest cover crops, we observed non-significant differences for event flow and sediment yield. However, large reductions in modelled sediment yields occurred for some events (e.g., up to 60% for winter cereals, 50% for maize and 74% for spring cereals). For these scenarios, examination of rainfall event magnitude emphasized the importance of ground cover in mitigating soil erosion for maize and spring cereals, but not for winter cereals. Our findings indicate that significant changes in sediment delivery at the event scale over a multi-year period are associated with variations in cropland extent and crop types, depending on rainfall magnitude, but not on the spatial arrangement of cropped fields or the use of riparian buffer strips.

KEYWORDS

catchment modelling, agricultural land cover, scenario simulation, runoff and sediment yield, event-scale, SHETRAN.

1. INTRODUCTION

Agricultural land use intensification and increases in crop cultivation have been related to global increases in soil erosion (Borrelli *et al.*, 2017). In the UK, agricultural land, which covers 25% of the total UK area (Department for Environment Food and Rural Affairs, 2018), is the primary source of contaminants affecting river water quality (Bilotta *et al.*, 2012; Arnell *et al.*, 2015), including fine sediments (Gruszowski *et al.*, 2003; Quinton *et al.*, 2010). Soil erosion rates on cultivated land range from 0.001 – to 10.5 t ha^{-1} yr^{-1} (Brazier, 2004), indicating that rates may exceed acceptable thresholds of around 1 t ha^{-1} yr^{-1} (Boardman *et al.*, 2009; Verheijen *et al.*, 2009).

Agricultural policies have been one of the main drivers for agricultural land use change in the UK. The aim of European food self-sufficiency resulted in the Common Agricultural Policy (CAP) in 1962 and led to increases in agricultural production (Parris, 2005) that contributed to increases in arable field size (Westmacott and Worthington, 2006) and intensified agricultural practices (Robinson and Sutherland, 2002). In the early 1990s, the addition of compensation payments to farmers in the purchase of modern heavy machinery (Lowe *et al.*, 2002) exacerbated soil compaction problems on arable fields (Richard *et al.*, 2001). The increase in arable field sizes and use of heavy machinery led to a range of field and catchment-scale impacts on soil erosion (Boardman, 2013) and water quality (Bilotta and Brazier, 2008; Withers and Jarvie, 2008). Subsequent CAP reforms promoted the development of environmental protection practices by farmers, but do not always have the expected positive impact (Winter, 2000). These issues emphasize the importance of scientific approaches for agricultural land use decision-making in the UK (McGonigle *et al.*, 2012).

Increases in runoff, soil erosion and sediment generation have been linked to varying farming practices (Boardman *et al.*, 2009; Deasy *et al.*, 2014). Land under arable crops often generates higher levels of soil erosion as a larger proportion of the soil is bare, especially during the period when the crop is still not well established, compared with other vegetation cover (e.g. grass and woodland), with exposed surface soil susceptible to detachment by raindrop or leaf drop impact (Department for Environment Food and Rural Affairs, 2013). The Demonstration Test Catchment (DTC) initiative in England (McGonigle *et al.*, 2014), where several catchments were monitored to provide evidence of the impacts of agricultural practices on water quality, identified arable land as one of the main sources of suspended sediment (Collins *et al.*, 2010; Cooper *et al.*, 2015). In addition, the DTC project helped identify the main mitigation practices used by farmers and stakeholders to reduce sediment and nutrient delivery; the use of cover crops was reported as one of the most popular strategies for sediment yield reduction (Collins *et al.*, 2018). This approach is considered as a primary erosion mitigation practice (Dabney *et al.*, 2001; Cooper *et al.*, 2017) offering multiple benefits to ecosystems (Novara *et al.*, 2020).

The impact of farming practices and the effectiveness of mitigation strategies are closely related to rainfall seasonality. At the present time, strategies to reduce soil erosion recommend ploughing, harvesting and rolling operations for particular seasons depending on the crop type (Department for Environment Food and Rural Affairs, 2005). A flow response analysis on the River Axe (southwest England, 1996-2002) related autumn-sowing and late crop harvesting to increases in flow peaks and duration (Climent-Soler *et al.*, 2009). Furthermore, late-drill practices (late October) can produce higher runoff and soil losses than early drilling (end of September, Withers *et al.*, 2006). The effects on soil erosion from delayed agricultural operations (e.g. drilling operations in early November instead of mid-September) have shown increases in soil losses in years characterised by wet autumns in areas with winter cereal cover (Boardman, 2003). Evans (2005) also reported larger erosion events in autumn than spring in fields predominately cultivated with winter cereals. Likewise, spring cereals and maize have been associated with increases in runoff and erosion, though the impacts are highly related to climatic variability (Boardman and Favis-Mortlock, 2014; Evans, 2017).

Runoff and sediment load reductions may be achieved by appropriate mitigation strategies where their success largely depends on temporal applicability. However, widespread and long-term implementation of these strategies is not always feasible due to time demands and negative impacts on production (McGonigle *et al.*, 2012). Therefore, buffer strips have emerged as alternative, aiming to trap and store eroded sediment on field margins rather than reducing the rate of soil detachment within fields. Internationally, buffer strip studies (field- contour and riparian) have shown effectiveness in reducing runoff, sediment yield and river pollutants (Dabney *et al.*, 2006; Duchemin and Hogue, 2009; Stevens and Quinton, 2009; Puntenney-Desmond *et al.*, 2020). This practice can alter runoff and sediment generation areas and the way they connect to the stream network (Deasy *et al.*, 2009; Lexartza-Artza and Wainwright, 2011). However, there is a limited understanding of how this mitigation affects flow and sediment delivery at a catchment scale (O'Connell *et al.*, 2007).

The impacts of agricultural land use changes have been widely investigated using hydrological models. Applications using a physically based approach, especially to evaluate land management practices, can provide a better representation of soil and catchment hydrology compared with empirical and conceptual models (Bathurst, 2011). Empirical models are generally based on catchment data (e.g., flow and sediment load), while conceptual models involve a general description of catchment processes but their parameters tend to have limited physical interpretability (Merritt *et al.*, 2003), whereas physically-based models use fundamental physical equations that can provide a better basis for representing future change through adjustments to parameters that have physical meaning (Bathurst, 2011). Physically based models have been used to show the effect of reforestation in reducing runoff and sediment yields (Lukey *et al.*, 2000; Birkinshaw *et al.*, 2011). At catchment scale, land cover changes have been related to variations in water and sediment yield (Fohrer *et al.*, 2001; Schob *et al.*, 2006; Bathurst *et al.*, 2007), where land management practices were shown to be main drivers of flow and sediment generation (Takken *et al.*, 2001; Lagacherie *et al.*, 2010; Taylor *et al.*, 2016; Özcan *et al.*, 2017). Simulations of mitigation strategies have shown these to be highly effective in reducing flow and sediment loads (Gumiere *et al.*, 2011; Ricci *et al.*, 2020). While modelling has predicted increased sediment loads in UK rivers under climate change (Whitehead *et al.*, 2009), land cover change and agricultural practices are considered more important drivers of soil erosion (Bussi *et al.*, 2016).

Models representing annual or even monthly variability in runoff and sediment output are ideal for longer-term simulations spanning decades to centuries (Smith *et al.*, 2018), but do not capture event-scale variability in runoff, and sediment generation. Therefore, when seeking to represent the effects of agricultural land use at an event scale, physically based spatially distributed models are useful tools to capture intra- and inter-event variability in runoff and sediment loads, with the advantage over lumped conceptual models of representing the effects of spatial changes in catchments with physics-based parameters. The intensity and duration of a precipitation event can largely influence surface runoff and sediment generation (Parsons and Stone, 2006). Sequential storm events and isolated extreme events can account for a large proportion of annual soil losses (Smith *et al.*, 2003) and nutrient transport (Perks *et al.*, 2015). Furthermore, extreme precipitation events on agricultural catchments can alter natural hydro-morphological river responses (Boardman, 2015) and disrupt ecological processes (Krometis *et al.*, 2007). In the UK, the magnitude of rainfall events (1-2 days duration) is predicted to increase by 10% due to climate change (Ekström *et al.*, 2005), and depending on the region and season, to vary between 5 and 30% (Fowler and Ekström, 2009). This climatic variability may increase flow and sediment yield at a catchment scale (Coulthard *et al.*, 2012). Planning strategies for water quality and its management require predictions that address the response of flow and sediment generation to precipitation events (Falloon and Betts, 2010).This raises the questions; how do these strategies affect flow and sediment generation on a catchment-event scale? And can these mitigation strategies contribute to reductions in event flow and sediment loads? A physically based model can help us better understand flow and sediment flux responses at the event-scale which is fundamental for mitigating the impacts of agricultural land use and mitigation practices.

This contribution aims to assess the event scale response of flow and sediment generation using the SHETRAN model representing three common scenarios of agricultural land cover change: a) changes in land cover (cropland extent and spatial arrangement), b) changes in crop type, and c) the use of riparian buffer strips. The main novelty of this contribution is the application of systematic methods such as synthetically generated land cover maps and the representation of vegetation cover change over time with a physically-based spatially-distributed hydrological model to examine event-scale flow and sediment yield responses to agricultural land cover change. The study provides knowledge of event scale flow and sediment load behaviour generally less available in the literature. Studies modelling catchment erosion and sediment load responses to agricultural change tend to focus on annual or longer-term average timescales that fail to capture shorter-term variations in vegetation growth or antecedent conditions that can drive wide variations in the response to rainfall events of otherwise similar magnitude-intensity. In the present study, the use of two agricultural catchments with similar characteristics provides a larger sample of events for analysis than a single catchment and enables an assessment of the general consistency in modelled catchment responses to scenarios for a range of rainfall events. Furthermore, the events selected from continuous simulations in both catchments allow us to statistically assess the effectiveness of mitigation measures at an event scale, while at the same time representing those factors that vary on a seasonal and annual basis. Practical implications and recommendations are discussed based on the results of this study.

2. MATERIALS AND METHODS

2.1 Study area and catchment data

Blackwater (18 km^2) and Kit Brook (22 km^2) are sub-catchments that form part of the River Axe hydrological network located in southwest England (Figure 1). These two small catchments were selected for the study as they have high resolution flow and suspended sediment load data available based on measurements of pressure and turbidity (FNU) at 15-minute time-steps. Pressure data were converted to flow (m^3 s^{-1}) using a stage-discharge rating curve with measurements collected for each catchment.

Digital elevation models (DEMs) of the catchments (5 m resolution) were obtained from the Ordnance Survey (OS) through EDINA Digimap. The Blackwater elevation rises from 49 m at the outlet to 250 m in the southeast with slopes between 0 and 36° (μ = 5.5°). The neighbouring Kit Brook catchment has elevations ranging from 42 m (outlet) to 251 m (northeast) with similar slope angles (0 - 36°, μ = 5.5°).

The Met Office Raymond's Hill station was the nearest rainfall station (~5 km) with the same measurement resolution as the catchment flow data. Daily potential evapotranspiration (PE, mm) was calculated using a temperature-based formula (Oudin *et al.*, 2005) and mean daily temperature data were obtained from the Seavington station (~16 km).

The land cover for Blackwater was obtained from a 2010 ground-based field survey from the Westcountry Rivers Trust and for Kit Brook by digitising 2010 imagery from Google Earth. Land cover was classified into four groups: 1) urban, 2) deciduous woodland, 3) arable crops, and 4) grass. At Blackwater, 60% of the area was covered by grass, followed by arable crops (27%), deciduous woodland (12%), and urban land (1%); with comparable land cover in the Kit Brook catchment (57%, 29% 13% and 1%, respectively). Winter cereals were selected as the arable crop used for model calibration in both catchments, given that winter cereals are the most common crop type in south-west England (Department for Environment Food and Rural Affairs, 2020a).

Soil data acquired from Cranfield University's National Soil Resources Institute (NSRI) identifies five soil types in the Blackwater catchment. The dominant soil type is WICKHAM (40%) with a composition of 21% sand, 41% silt and 30% clay, and corresponds to the ‘Eutric Luvic Planosols’ under the international standard soil classification (Baxter, 2007). The soil profile comprises five layers between 0 and 1.5 m; the properties of each soil type and layer vary according to land use. The NSRI identify six soil classifications and five depth layers (0 – 1.5 m) in Kit Brook catchment. The soils covering the largest catchment area are BATCOMBE (37%) and CHARITY (31%); the first with soil texture of 18% sand, 58% silt and 24% clay, and the second with 16%, 58% and 26% respectively. Under the international standard soil classification BATCOMBE and CHARITY soil corresponds to ‘Profundic Chromic Endostagnic Luvisols’ and ‘Chromic Luvisols’, respectively.

2.2 SHETRAN model: Calibration, evaluation, and sensitivity

SHETRAN is a physically based, spatially distributed model capable of simulating flow, erosion, and sediment transport at both continuous- and event-based scales. The catchment is modelled as a set of grids with a limit in number of 300 x 300, with each cell containing soil and vegetation information (Ewen *et al.*, 2000).

Escobar-Ruiz *et al.*, (2019) calibrated the SHETRAN model on the Blackwater catchment and evaluated sediment and flow parameters on the nearby Kit Brook catchment. Model performance was evaluated for continuous discharge using the Nash-Sutcliffe efficiency coefficient (NSE), which presented values of 0.78 in Blackwater and 0.60 in Kit Brook. Event prediction was assessed using the coefficient of determination (R^2) between measured and simulated values for flow volume (Qv), peak discharge (Qp), sediment yield (Sy) and peak sediment flux (Sp). In addition, event prediction errors for these variables were estimated by the mean of the absolute percentage of difference (Pct_{diff}). Results showed similar model performance in both catchments (Blackwater R^2 = 0.8 [Qv], 0.6 [Qp]) 0.4 [Sy] 0.2 [Sp]) and Kit Brook R^2 = 0.8 [Qv], 0.6 [Qp]) 0.4 [Sy] 0.3 [Sp]); which corresponded to larger differences (Pct_{diff}) in Kit Brook (48% [Qv], 66% [Qp], 298% [Sy] and 438% [Sp]) than Blackwater catchment (30% [Qv], 41% [Qp], 106% [Sy] and 86% [Sp]). Kit Brook exhibited higher permeability than Blackwater based on measured flow duration curves (Escobar-Ruiz *et al.*, 2019), supporting the adjustment of the K_{sat} for the 6th soil layer and resulting in considerable improvement in model performance for Kit Brook (i.e. 0.69 [NSE], 44% [Qv], 58% [Qp], 202% [Sy], 319% [Sp]) with no variations in the coefficient of determination.

The reported parameters to which the water flow component of SHETRAN is most sensitive are: Actual evaporation to potential evaporation ratio (AE/PE), Strickler coefficient (Stk) and saturated hydraulic conductivity (K_{sat},(Bathurst, 1986; Anderton *et al.*, 2002; Op de Hipt *et al.*, 2017; Escobar-Ruiz *et al.*, 2019)). In terms of the sediment transport components, the most sensitive parameters include: raindrop soil erodibility coefficient (D_r), and overland flow erodibility coefficient (D_f, (Adams and Elliott, 2006; Op de Hipt *et al.*, 2017; Escobar-Ruiz *et al.*, 2019)). Model sensitivity to multiple different combinations of values for the above parameters was assessed (Escobar-Ruiz *et al.*, 2019); and showed that an equifinality problem (Beven and Binley, 1992) may arise for flow volume as K_{sat} decreases and Stk increases, and vice versa. Modelled sediment yield showed similar responses with large Dr changes combined with small Df changes, and vice versa.

2.3 Agricultural land cover change scenarios

2.3.1 Land cover changes

Recent land cover maps

The use of recent land cover maps provides information on the spatial patterns in cropped fields, reflecting farmer decision-making on plantings, influenced by socio-economic and climatic factors (Angus *et al.*, 2009; Burgess and Morris, 2009). In the south-west region of England, 20% of the land is used for growing cereal crops (Department for Environment Food and Rural Affairs, 2020a). This region has undergone important changes in recent decades (2003 - 2016), where wheat has decreased 12% and barley increased by 15% (Department for Environment Food and Rural Affairs, 2019).

The historic and contemporary land cover maps for each catchment (Figures A1 & A2) were obtained from three sources: (1) UK land cover maps (LCMs) produced from satellite imagery (Morton *et al.*, 2011) for 1990, 2000, 2007 and 2015; (2) digitising Google Earth imagery for 2002, 2005 and 2006; and (3) Westcountry Rivers Trust survey of the Blackwater catchment for the year 2010. The Kit Brook land cover map for 2010 was also digitised from Google Earth. In the 2010 Blackwater field survey, four land covers were characterised: urban (Ur), deciduous woodland (Wd), arable crops (Ar) and grass (Gr). The LCMs and digitised Google Earth maps for both catchments were reclassified according to these four land cover categories. The calibrated parameter values were used in model simulations for each land cover map. Specific soil parameter values were selected with reference to the land cover in each map using the NSRI soils data.

In both catchments, the land cover from 1990 to 2015 has undergone changes related to the extent and spatial distribution in cropland and grassland. In contrast, the spatial extent and pattern of urban areas and deciduous woodland exhibit negligible change. A Mann Kendall test showed that the crop area data does not present a monotonic trend in either catchment ($p > 0.05$). Nonetheless, the difference between the land cover maps with the lowest crop area (1990) and the highest (2007) was 25% and 24% in Blackwater and Kit Brook catchments, respectively.

Synthetically generated land cover maps

The use of synthetic maps provides insight into the impact of land cover changes not captured by the limited historical maps. In terms of cropland extent, three land cover end-member scenarios were modelled to identify flow and sediment load limits. The end-member scenarios assume complete catchment coverage by deciduous woodland (Wd), grass (Gr) and winter cereals (Ar). These scenarios also provide a basis for contextualising land cover changes relative to minimum and maximum effects. The use of a single vegetation cover scenario is useful for comparing how hydrological processes respond and their impact on flow and sediment export at the catchment outlet.

The simulations in this section were run under the climatic conditions from September 2010 to October 2014 to observe the effects on flow and sediment generation associated with changes in crop extent and patterns present in the land cover maps (1990 - 2015). This period represents the time frame for which land cover data is available for the region.

In terms of spatial arrangement of cropped fields, a set of synthetic land cover maps were created to assess variability in flow and sediment flux under different crop spatial patterns. Crop spatial arrangement depends on farmer decisions which can be influenced by crop rotation stage on individual farms, levels of food demand (Angus *et al.*, 2009), agricultural technology (Burgess and Morris, 2009) and policy changes for environmental protection (Dwyer, 2011). The location of cropped fields is not static and field rotation results in changes to sediment contributing areas and transport pathways between slopes and the stream network. The changing spatial distribution of arable fields is difficult to predict on a catchment scale in the absence of map data (e.g., when performing future climate change simulations or historic simulations in the absence of spatial data).

For each synthetic map, the land cover (arable crops and grass), extent and shape (polygons), were obtained from the 2010 land cover map of each catchment. Fields that are not urban or woodland according to the recent land cover maps were randomly assigned as cereal crops using a Monte Carlo method until the total crop area was reached (Peñuela *et al.*, 2018). The total crop area is based on the 2010 land cover (27% [Blackwater] and 29% [Kit Brook]). Two sets of synthetic maps, one comprising 5 maps and the other 10 maps, were generated to examine the effect of the number of replicates on variability in the predicted flow and sediment yields. Each map contained a set of fields randomly assigned a cereal crop. Areas lower than 1 ha were excluded as these were unlikely to represent arable fields. The 15 simulated scenarios used the same calibrated parameter values and were run under the same climatic conditions (September 2010 – October 2014).

2.3.2 Crop type

Cereals are the most common type of crop in southwest England (Department for Environment Food and Rural Affairs, 2020a). Climent-Soler, Holman and Archer (2009) associated cereal crops with increases in runoff in the River Axe (Blackwater and Kit Brook tributaries of this river network, Figure 1). In other UK regions, cropping changes have been identified as possible causes of increased sediment exports (Davidson and Harrison, 1995; Boardman, 2003). Observed sediment load responses to different crop plantings are highly dependent on climatic variability (Chambers *et al.*, 1992; Evans, 2017). Hence, it is important to identify periods of vulnerability to erosion for each type of crop under varying seasonal patterns of precipitation, which can help in determining optimum soil erosion control practices.

The use of cover crops (e.g. rye grass) for soil erosion protection in cultivated land after harvesting crops, such as winter cereals (WC), spring cereals (SC) or maize (Mz), is strongly recommended (Department for Environment Food and Rural Affairs, 2005). Scenarios with (WC-Cc, SC-Cc and Mz-Cc) and without (WC, SC and Mz) cover crops were simulated to observe the effect on runoff, erosion, and catchment sediment exports. The 2010 land cover map and contemporary climatic data (2010-2014) provide a base scenario, with 27% and 29% of arable land in the Blackwater and Kit Brook catchments, respectively.

Within SHETRAN, the representation of the different crop types required temporal changes to specific parameters. For example, in the water flow component, the leaf area index ratio (CLAI) and ground cover by vegetation (PLAI) parameters were modified through the hydrological years; in the sediment transport component, the altered parameters corresponded to proportion of ground shielded by near ground cover (FCG), canopy height (XDRIP), rain drop erodibility coefficient (Dr) and overland flow erosion coefficient (Df). The CLAI and PLAI daily changes were calculated based on the Heat Unit theory (Boswell, 1926) used within the Soil and Water Assessment Tool (Arnold *et al.*, 2012). This plant growth model requires inputs for daily temperature (obtained from the Seavington station) and vegetation information for each crop type (Table A1), such as planting date, the number of days to reach maturity, and the minimum temperature below which plant growth will cease, which were obtained from different sources (Gallagher and Biscoe, 1978; Kiniry *et al.*, 1995; Morgan and Duzant, 2008; Sheikh *et al.*, 2009; Arnold *et al.*, 2012). For the cover crop scenarios (i.e., WC-CC, Mz-CC and SC-CC), the erodibility coefficients (Dr and Df) of the arable land cover were set to permanent grass values only during the rye grass growth period (Table 1).

2.3.3 Riparian buffers

The use of riparian buffers is a common mitigation practice to reduce sediment entering streams and reaching the catchment outlet (Fullen *et al.*, 2006). The effect of a riparian corridor was examined using two buffer scenarios, namely grass and mature deciduous woodland, for both catchments. Riparian buffer widths in UK typically range between 10 – 24 m (Department for Environment Food and Rural Affairs, 2020b), whereas the simulated buffer in this contribution was a 50 m wide strip on each side of the stream, reflecting the limitations of the model (minimum grid size 50 m) which does not allow the use of a thinner strip. The 2010 maps were used for land cover representation. Overall, the riparian buffer covered an area of 1.7 km^2 in Blackwater and 2.2 km^2 in Kit Brook.

2.4 Event flow and sediment load analysis

Event selection from a continuous dataset can reduce errors related to initial conditions (Bussi *et al.*, 2014), providing improvement in the reliability of both water and sediment yield estimation. The SHETRAN model has previously been tested on an event basis (De Figueiredo and Bathurst, 2002; Adams *et al.*, 2005; Adams and Elliott, 2006; Bovolo and Bathurst, 2012; Elliott *et al.*, 2012). Event-scale performance using SHETRAN has been reported for the studied catchments based on analysis of 53 events in Blackwater and 46 in Kit Brook during the study period (Escobar-Ruiz *et al.*, 2019). Events were selected based on data quality (e.g., by avoiding those events affected by a) sensor fouling or burial, leading to periods of persistent high turbidity values until cleaning or b) occasional large rapid variations in measured turbidity unrelated to any change in flow)

In the present contribution, storm events that occurred simultaneously in both catchments were extracted from the continuous base run simulations, resulting in a total of 84 events. The start of an event was defined when discharge exceeded the base flow (Gustard *et al.*, 1992). An event was considered when base flow was exceeded by 20% for at least 6 hours (Blaen *et al.*, 2017; Khamis *et al.*, 2020). The end of an event was determined when flow fell to the pre-event level or to a new base level. Multi-peak storms were separated if events lasted more than 48-hours (Robson and Reed, 2008). This method allows for a selection of storm event lasting between 6 and 48 hrs. For each simulated scenario, event flow volume (m^3, Equation 1) and event sediment yield (tons ha^{-1}, Equation 2) were obtained. The scenario simulation ran from October 2010 to September 2014 with a ‘spin up’ hydrological year (October 2009 - September 2010), but only the events occurring in the last 4-year period were used for analysis.

$$Qv = \Sigma\,(Q_i * 900) \qquad \text{Equation 1}$$

$$Sy = \Sigma\,(Sed_i * 900 * ton) / (ha) \qquad \text{Equation 2}$$

Where, Q = discharge ($m\ s^{-1}$), Sed = sediment flux ($kg\ s^{-1}$), i = number of time steps (15 min) in an event, ton = 0.00110231, and ha = catchment area (ha)

The effect on event flow and sediment yield was assessed using the Kruskal-Wallis test for (a) recent land cover change scenarios, (b) crop spatial arrangement scenarios, and (c) crop type scenarios with no cover crop. The end-member scenarios were used for extrapolation purposes when relating flow and sediment yield to changes in crop area and analysed using a linear regression model. A Wilcoxon test (one tail) was performed between each no cover crop scenario against its respective cover crop. Additionally, the test was conducted on the riparian buffer scenarios, between base run and grass and woodland, respectively. The Wilcoxon analysis of crop type scenarios included seasonal and event magnitude classifications. Two seasonal periods were selected, autumn-winter and spring-summer, whereas for event magnitude categories were defined as (i) very low (total rainfall of the event in the lowermost 20% of the ranked rainfall events), (ii) low (total rainfall of the event higher or equal to 20% but lower than 40% of ranked events), (iii) medium (total rainfall of the event higher or equal than 40% but lower than 60% of ranked events), and (iv) high (total rainfall of the event higher or equal to 60% but lower than 80% of ranked events), and (iv) very high (total rainfall of the event equal to or higher than the uppermost 80% of ranked events). All tests assumed a critical value of 0.05.

3. RESULTS

3.1 Land cover changes

Recent land cover maps

Model simulations based on the land cover maps (1990-2015, Figure 2) presented significant differences in event sediment yield for Blackwater ($p < 0.05$, Table 2) but not for Kit Brook ($p > 0.05$, Table 2). Neither catchment exhibited significant differences in event flow volume. The linear regression analysis showed flow and sediment yield increases associated with expansions in crop area (Figure 3). However, changes in crop area did not always lead to linear alterations in sediment yield. Furthermore, land cover maps with similar cropland extent presented slightly different sediment export during events. This suggests that crop spatial arrangement may have some effect on sediment delivery to the stream network.

Synthetically generated land cover maps

The effect of spatial arrangement in cropped fields did not present significant changes in event flow volume (Qv) or sediment yield (Sy) in either catchment ($p > 0.05$, Table A2). However, the results showed small absolute differences between the base run among the spatial crop arrangement scenarios (Figure 4). For event flow volume, average differences of 1% and 2% were observed in Blackwater and Kit Brook, respectively. In terms of sediment yield, particular events showed differences up to 15% (Blackwater) and 14% (Kit Brook), representing a mean absolute difference of 4% in Blackwater and 5% in Kit Brook. Since the extent of arable land was constant (27% Blackwater and 29% Kit Brook) in all the randomized scenarios, the differences in sediment yield may be attributed to the change in spatial patterns of cropped land.

The absolute percentage of difference in flow ($|Qv_{diff}|$) and sediment yield ($|Sy_{diff}|$) between the base run and the 5 and 10 replicate crop spatial field arrangement scenarios were similar in both catchments. This suggests that further random spatial replicates are not required to represent the effect of crop spatial variability on flow and sediment yield.

3.2 Crop type

The crop type scenarios illustrate how differences in catchment flow and sediment yield at event scale can be attributed to varying farming practices using common UK crops under contemporary climatic variability. In both catchments, no significant differences were observed between crop types excluding the use of cover crops (WC vs Mz vs SC) in either flow or sediment loads ($p > 0.05$, Table A2). Similarly, comparison of crop type with its respective post-harvest cover crop did not show significant differences, except for SC vs SC-CC in Kit Brook catchment (Table 2). Despite the statistical results, these differences correspond to moderate average reductions in event sediment yields (Figure 5). For example, comparing winter cereals (WC vs WC-CC), event sediment loads were reduced by 10% and 11% on average in Blackwater and Kit Brook, respectively. For maize, sediment loads between non-cover crop (Mz) and cover crop (Mz-CC) simulations represented an average difference of 18% (Blackwater) and 19% (Kit Brook). In terms of spring cereals (i.e., SC vs SC-CC), slightly larger average sediment reductions of 19% in Blackwater and 22% in Kit Brook were observed.

Temporal analysis of modelled flow events (Figures 6 & 7) highlights how differences in the timing of cover crop protection practices can influence flow and sediment loads. In the Blackwater catchment (Figure 6), comparing the winter cereal non-cover crop scenario (WC) with its respective rye grass cover crop scenario (WC-CC), single events showed reductions of up to 59% in sediment load (Sy_{diff}). Similarly, between spring cereal scenarios (Figure 6, SC vs SC-CC) specific events presented differences of up to 74% in sediment yield. Maize (Figure 6) showed the lowest event reduction for sediment loads (Sed_{diff}, 53%). However, sediment load differences between the two winter cereals scenarios (WC vs WC-CC) exhibited the largest number of events without changes, which explains its lower average reduction (i.e., 10%). This can be related to the phase of lower plant growth coinciding with the wetter period (October – February) during which most storm events occurred. Additionally, the atypical wet summer period (June – August 2012) presented high-consecutive sediment load differences between the winter cereals scenarios. However, seasonal analysis (i.e., autumn-winter and spring-summer) did not present statistical differences (Table A2). Similar behaviour was observed in the Kit Brook scenarios, with event-scale sediment load reductions of up to 45%, 46% and 73%, for winter cereals, maize, and spring cereals, respectively (Figure 7).

The analysis of rainfall event magnitude in the Blackwater catchment revealed that the use of rye grass as cover crop with maize can achieve sediment yield reductions for medium, high, and very high magnitude events ($p < 0.05$, Table 2). This pattern was also evident in the Kit Brook catchment, with significant differences for very low instead of medium magnitude rainfall events. Spring cereals showed similar behaviour with significant differences for very low, medium, and high rainfall events in the Blackwater catchment, and for all four rainfall event categories in Kit Brook ($p < 0.05$, Table 2). Consistently, in both catchments, high magnitude rainfall events showed significant sediment load differences between use of rye grass as cover crop and the absence of this, for maize and spring cereal. Non-significant differences occurred across all categories for winter cereals in both catchments.

3.3 Riparian buffers

The event flow and sediment exports (Qv and Sy) for each riparian buffer scenario did not present significant differences ($p > 0.05$, Table A2). The simulation of both the riparian buffers (grass and mature deciduous woodland) showed small flow volume reductions compared with the base run (Figure 8a-b). The small difference between buffer types (i.e. BF-Gr vs BF-Wd) may be expected given soil properties and ground-level cover were similar (Escobar-Ruiz et al., 2019). Riparian buffers in Blackwater presented event sediment yield reductions on average of 3% for grass strips and 5% for woodland strips (Figure 8c), whereas in Kit Brook reductions were higher, 6% for grass strips and 10% for woodland strips (Figure 8d). However, sediment yield in particular events showed reductions of up to 6% for the grass buffer in Blackwater and 15% in Kit Brook, and for woodland buffers 15% and 18%, respectively.

4. DISCUSSION

The expansion of cropland in recent years has been reported as an important driver of global soil erosion (Borrelli *et al.*, 2017). In UK, the regional (southwest) land use survey suggests a monotonic trend ($p < 0.05$) with an increase of 10% in crop area during the period 2000 – 2018 (Department for Environment Food and Rural Affairs, 2019) with this likely to increase in the future due to a predicted intensification in crop production (Ewert *et al.*, 2005; Rounsevell *et al.*, 2005). The results for recent land cover maps in both catchments showed that this cropland extension over past years has a significant impact on event sediment yields, and minor effects on flow volume (Table 2).

The linear relationship between increasing crop area and event flow and sediment yield (Figure 3) could be used to set the optimal crop extent to balance agricultural production while limiting sediment delivery to streams. Land cover has been found to be a key factor for sediment generation and transport (Bracken and Croke, 2007). The non-linearity observed between crop area and sediment yield for some simulated land cover maps suggests that the spatial arrangement of cropped fields can influence sediment exports. Moreover, some differences between maps with similar crop extents (e.g., 2002 vs 2015 in Blackwater, 2006 vs 2015 in Kit Brook) may be related to the variation in field size rather than location. However, the different spatial arrangements of cropped fields did not present a significant effect on flow and sediment exports at event-scale in either catchment ($p > 0.05$ in Table A2 [Randomized cropped field arrangement]). Nonetheless, minor variations in sediment yield among scenarios were observed (Figure 4c-d). It is possible that these small event variations gradually contribute to annual differences in load, as differences between spatial arrangements of cropped fields have been quantified elsewhere at an annual scale (Peñuela, Sellami and Smith, 2018). The method applied provides a viable approach to investigate event-scale impacts of crop arrangement using a PBSD model. Future application of the approach could enable improved spatial targeting of fields for erosion mitigation (e.g., crop rotation) to reduce catchment sediment yields where cropped field spatial arrangement is shown to significantly impact sediment delivery to streams.

In the UK, field monitoring has previously identified relationships between increased erosion, crop type and growing season, as well as rainfall variability (Boardman, 2003; Evans, 2005; Watson and Evans, 2007). Winter cereals have been related to higher soil erosion rates than other cereal crops (Boardman *et al.*, 2009; Evans, 2017), where studies emphasise the importance of erosive rainfall coinciding with periods of low crop cover (e.g. during wet autumns). However, in the present study, significant differences in catchment-scale event sediment yields between crop types (WC vs Mz vs SC) were not observed (Table A2). Furthermore, the planting of cover crops regardless of crop type appears to have an insignificant event scale effect (both Qv and Sy). Despite the overall insignificant impacts, when comparing scenarios that involve planting of cover crops (WC-CC, SC-CC and Mz-CC) versus no cover crop practices (WC, SC and Mz), reductions in sediment loads were observed. This planting strategy may play an important role in controlling the impacts of high-magnitude precipitation events, especially with the predicted increase in the frequency of these events due to climate change (Ekström *et al.*, 2005; Fowler and Ekström, 2009). This was highlighted in the analysis of rainfall magnitude, revealing that the use of cover crops for maize and spring cereals for high magnitude events represented an important factor in reducing sediment yields on both catchments (Table 2).

A seasonal effect in flow and sediment yield was not observed with the statistical analysis. However, the temporal analysis (Figure 5-6) highlights the importance of crop cover in relation to seasonal rainfall patterns and sediment generation. The effectiveness of planting rye grass cover crops after harvesting of any cereal crop is related to reducing the 'window of opportunity' for erosion (Boardman, 2003) – i.e. periods of low crop cover that are vulnerable to raindrop impact and overland flow erosion. Maize and spring cereals showed soil raindrop detachment vulnerability in the periods August-February and July-January, respectively. This vulnerability to soil raindrop detachment during these periods is apparent given the load reductions that were achieved for some events by using rye grass in the Mz-Cc and SC-Cc scenarios (Figures 6 & 7). In contrast, soils under winter cereals benefited less from use of a cover crop because the growing period of winter cereals takes place in the months that are typically the wettest in the UK (October - February). Winter cereals have been reported as the most vulnerable crops for soil erosion (Boardman and Favis-Mortlock, 2014) and are the most common crop in the region (Department for Environment Food and Rural Affairs, 2020a). Our findings on event rainfall magnitude support this statement, showing that minimal event sediment yield reductions were achieved using post-harvest cover crops with winter cereals as an erosion mitigation practice.

The crop scenarios were useful for recognising the importance of cover in flow and sediment generation and the importance of reducing the extent and duration of exposed bare soil through changes in agricultural practice. In general, winter cereals are more prone to soil erosion despite the use of cover crops (Figures 6 & 7), potentially making them a less suitable crop for the region. Climate projections (medium-low emissions) for 2080 in southwest England estimate a 10% increase in winter and up to 40% decrease in summer rainfall (Hulme *et al.*, 2002). Hence, further investigation is required to ascertain if planting of spring cereals with rye grass as cover crop is preferred over winter cereals for reducing erosion at event scale under future climate conditions.

The riparian buffers (grass and woodland) showed no significant differences in flow volume and sediment loads at the event-scale in both catchments, compared with their respective base run (Figure 8). However, on average riparian buffers produced larger reductions for sediment (6%) than flow (1%) when compared with the base run for both catchments. Nonetheless, some events presented sediment load reductions of up to 15% (Blackwater) and 25% (Kit Brook). Similar sediment load reductions (15 - 41%) have been quantified at an annual scale for a 10 m mature deciduous woodland buffer with varied levels of understorey cover (Smith *et al.*, 2018). Additionally, the efficiency of riparian buffers has been associated with vegetation cover maturity (Fullen *et al.*, 2006).

In the UK, riparian buffer width typically ranges between 4 and 24 m (Natural England, 2013). Standard buffers have been reported to be effective in trapping sediment, but increases in buffer width have proven to have a greater impact in reducing dissolved contaminants (Dabney *et al.*, 2006). The buffer width in the present study was set to 50 m, as result of the constraint imposed by the minimum grid size for catchment scale simulations. This modelled width exceeds the width of buffers generally used in practice. Hence, the modelled reductions in flow and sediment load are likely to be in the upper range of what may be achieved. Higher sediment trap efficiency was achieved by the simulated riparian buffer (grass and woodland) in the Kit Brook catchment compared with Blackwater. This is probably a function of the differences in topography between the studied catchments. Kit Brook is an elongated catchment with high slopes (> 18º) closer to main stream channel, compared with the oblique-shape Blackwater catchment with high slopes (> 18º) at the southeast of the catchment outlet (Figure A3).

Statistical tests were applied as the main method to assess the impact of land cover changes on event flow and sediment yields. Relative differences were used to provide a quantitative basis to assess impacts. Time series plots were used to compare the effects of different crop types and show the variability in event sediment yields throughout the four hydrological years (Figures 6 & 7). At the scale of individual events, hydrograph and sedigraph plots show similar shapes (e.g., Figures A4 & A5), largely reflecting changes in magnitude (i.e., flow volume and sediment yield) associated with the different scenario simulations. Limited changes in event timing or duration were observed between scenarios based on these plots.

The non-consistent significant differences between scenarios in the catchments (i.e., significant differences in Blackwater, but non-significant in Kit Brook and vice versa) may be related to the sample size. Events occurring simultaneously in both catchment over the 4-year simulation resulted in 84 events for analysis. The p-values in majority of the non-significantly cases were lower than 0.1, but higher than the critical value (0.05). Generally, increases in sample size cause a decrease in the standard error, and consequently the p-value decreases. Therefore, the larger the sample size, the greater likelihood of detecting a significant difference (if present in the data). The 84 events over the 4-year simulation were selected to obtain a systematic error in the simulated scenarios and used in the previous model calibration and evaluation (Escobar-Ruiz *et al.*, 2019).

Despite the use of calibration and validation processes, a certain degree of uncertainty should be considered in modelling (Batista *et al.*, 2019). For SHETRAN, this might be associated with model representation of physical processes (e.g., dimensional formulation, Bathurst, 2011), the choice of grid scale (Escobar-Ruiz *et al.*, 2019) and basis for estimating parameter values (Ewen and Parkin, 1996; Bathurst *et al.*, 2004). Therefore, it is important to recognise this uncertainty when interpreting model results. Differences related to the range of errors associated with input values for parameters can be significant, and also similar catchment responses may be achieved with a combination of different parameter values (i.e., equifinality; Beven and Binley, 1992). It is possible that the model uncertainty is greater than predicted changes in catchment response between scenarios. Therefore, caution is required when considering model predictions, particularly in terms of absolute values. However, regardless of the uncertainty associated with the~~to~~ modelling, the relative magnitude and direction of change between scenarios can be informative. ~~Furthermore, ~~T~~t~~he ~~simulated events~~model simulations ~~are ~~provide an indication~~ors~~ of event-scale catchment flow and sediment load ~~catchment ~~responses to agricultural land cover changes, an unanswered problem that has been highlighted before (Smith *et al.*, 2003; Boardman, 2006, 2015). Furthermore, t~~T~~he use of physically-based models at an event scale ~~can ~~may ~~be use as ~~provide a basis for developing ~~guidelines to develop ~~strategies to mitigate the impact of extreme rainfall events.

5. CONCLUSION

The present study focuses on quantitatively demonstrating the effects of change in agricultural land cover on sediment exports on an event basis, in contrast to most studies considering longer timescales (e.g., annual) that mask variation in event flow and sediment load responses to land cover change. Moreover, the combination of a physically-based model with representation of the daily variation in vegetation cover provides added insight into the factors driving differing event and seasonal scale behaviour in flow and sediment load. The results of this contribution can inform agricultural practices for reducing sediment load, as well as the circumstances under which mitigation measures may be less effective at an event scale.

The simulated changes in the extent of arable crops produced a significant effect in catchment sediment yields at the event scale, but not flow volume. Results of the simulated arrangement of cropped fields, presented a slight influence on the extent of slope-to-stream sediment delivery, demonstrating that selection of fields for growing arable crops may contribute to event-scale variability in catchment sediment exports. In terms of crop type, the findings showed that cover crops such as rye grass can reduce erosion and sediment delivery to steams during certain events, which may also result in differences at the annual scale. Furthermore, the use of cover crops with maize and spring cereals significantly reduced sediment yields for high magnitude rainfall events. However, this response was not detected for winter cereals, the most common crop type planted in the study catchments. The use of riparian buffers may be a plausible long-term strategy for mitigating event sediment delivery by overland flow to channels, while the deciduous woodland buffers demonstrated slightly higher trap efficiency than grass only.

The study illustrates the adaptability of the SHETRAN model to simulate agricultural land cover and mitigation scenarios. The capacity of SHETRAN to simulate daily variation in leaf area index allows representation of the effects of different crop types. The integration of the model software with GIS for catchment spatial information, enables the representation of spatial controls on sediment generation, such as field arrangement. Collectively, this study shows the SHETRAN model to be a viable framework for representing the effects of changes in agricultural land cover and for quantifying at event-scale the effectiveness and design of mitigation strategies to reduce overland flow and sediment delivery.

ACKNOWLEDGEMENTS

We appreciate the guidance of Dr Stephen Birkinshaw in the use of SHETRAN model. This work was supported by the Mexican National Council on Science and Technology (CONACYT) through the funding of a PhD studentship to Veronica Escobar-Ruiz at the University of Liverpool. Hugh Smith received support from the Strategic Science Investment Fund (SSIF) allocated to Landcare Research by the New Zealand Ministry of Business, Innovation and Employment (MBIE).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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