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Off-site impacts of soil erosion and runoff: why connectivity is more important than erosion rates

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Abstract

Off-site impacts of soil erosion are of greater social and economic concern in western Europe than on-site impacts. They fall into two related categories: muddy flooding of properties and ecological impacts on watercourses due to excessive sedimentation and associated pollutants. Critical to these impacts is the connectedness of the runoff and sediment system between agricultural fields and the river system. We argue that well-connected systems causing off-site damage are not necessarily related to areas of high erosion rates; emphasis should therefore be on the way in which connections occur. In temperate, arable systems, important elements of connectivity are anthropogenic in origin: roads, tracks, sunken lanes, field drains, ditches, culverts and permeable field boundaries. Mapping these features allows us to understand how they affect runoff and modify its impacts, to design appropriate mitigation measures, and to better validate model predictions. Published maps (digital and paper) do not, by themselves, give sufficient information. Field mapping and observation aided by remote sensing, is also necessary.

Keywords: connectivity, field mapping, runoff and sediment flux, soil erosion, off-site impacts

Introduction

In western Europe soil erosion is recognised as a problem both for farmers and for those affected beyond the farm by flows of runoff, sediment and associated pollutants (Boardman & Poesen, 2006; Evans, 2009 & 2017). In general, off-site impacts are the main environmental and social concern and are of considerable economic significance (e.g. 80 % of soil degradation costs in England and Wales are from off-site impacts (Graves *et al.*, 2015). Except in specific areas of thin soils (e.g. the South Downs, UK) the on-site impact of erosion will not be a threat to crop productivity for many decades (Bakker *et al.*, 2007; Evans, 1996, 2012, 2017).

Off-site impacts have been reported from northern France (Le Bissonnais *et al*., 2001), Belgium (Evrard *et al*., 2007), southern and eastern England (Boardman, 1995; Evans, 2017). Recent reports have detailed similar muddy flooding in Saxony, Germany (Arevalo *et al*., 2012) and in the Swiss midlands (Ledermann *et al*., 2010; Prasuhn, 2011; Bernet *et al*., 2017) (Figure 1). Concern about flooding by runoff from agricultural land was highlighted many years ago by Boardman *et al*. (1994) and Evans (1996) and a short review of what was, by then referred to as 'muddy flooding', was published by Boardman *et al*. (2006) (Figures 2 & 3).

In recent years the emphasis has shifted to the impact of runoff, sediment and associated agricultural chemicals on watercourses. This shift has been largely driven by the EU Water Framework Directive requiring nation states to improve waterways to 'good ecological status' by certain target dates (European Parliament, 2000) and also by a growing awareness of the costs of providing clean water, for example the cost of removal of pollutants, especially pesticides, present in the water at, or above, statutory levels (Evans, 1995).

The emphasis on freshwater pollution (including eutrophication) has tended to be in areas of intensive arable farming, often where soils are not freely draining e.g. East Anglia, UK (Evans, 2012), whereas the emphasis on muddy flooding is associated with a mix of agriculture and rural/urban land uses and often with silty or loamy soils tending to crust e.g. Flanders and northern France. In many areas there is a strong possibility that pollution issues have been overlooked, particularly those associated with frequent, low magnitude runoff events.

Conventional risk analysis of soil erosion has focused on individual fields (Defra, 2005), or even larger areas, aggregating land uses and topography to produce average values, for example for 1 km^2 cells (e.g. Panagos *et al*., 2015). It is assumed that erosion is a problem because it will reduce the productivity of the soil, and other aspects of erosion such as off-field impacts, are not generally considered when making these risk assessments. As noted above, the impacts of erosion of arable land on soil productivity over the short term are small. However, because rates of soil erosion were considered the key factor that needed to be assessed/modelled there has been little consideration until recently (McGonigle *et al*., 2014) of the off-field impacts of runoff and erosion.

Hence, we argue that conventional approaches, including risk-based and model-driven approaches, fail to adequately address the issue of off-site damage or pollution risk. We suggest a different approach. This approach considers both past and current observations of patterns of erosion and sediment transport that show the importance of connectivity; here defined as routes of flow across the landscape from eroded fields to households and watercourses. The findings of such an approach will help design appropriate mitigation measures and will also be useful in validating catchment-scale erosion models (Gascuel-Odoux *et al*., 2011).

Connected and disconnected systems

Ecologists and hydrologists have tended to argue for the benefits of restoring connectivity to often degraded or heavily managed systems such as the removal of dams or weirs (Lespez *et al*., 2015). Others have pointed out the disadvantages of having well connected systems particularly with respect to invasive species. Ponds and dams may have value in sequestering sediments and pollutants: 'creating or maintaining reduced hydrologic connectivity can create ecological benefits' (Jackson & Pringle, 2010). Similarly, Fuller & Death (2017) point out that simply restoring connectivity will not necessarily lead to healthy river ecosystems; well-connected catchments with inappropriate land management can also transmit excessive sediment loads. There seems, therefore, to be a need within river catchments to reach an appropriate balance (with many competing factors) between connectivity and disconnectivity. This will apply especially when we consider the relationship between runoff and sediment generated on hillslopes. This is referred to as 'lateral connectivity' by Fuller and Death (2017).

The connectivity debate has focused largely around non-arable systems. These studies have included urban environments (e.g. Graf, 1977), 'natural' or grazed environments (e.g. Harvey, 2002), alpine environments with debris flow activity (e.g. Berger *et al.,* 2011), forests and the role of roads (e.g. Galia *et al.,* 2017), channels and floodplains (e.g. Sandcock & Hooke, 2011) and semi-arid environments (e.g. Lesschen *et al*., 2009). This emphasis has meant that the issue of connectivity in a major global landscape, that of arable temperate regions, has largely been ignored. There are notable exceptions. For example, the work around the Belton catchment in Northumberland, UK, has shown that interruption of connectivity can protect communities from flooding (Wilkinson *et al*., 2014). In a case study of the Ingbirchworth catchment, Yorkshire, UK, Wainwright *et al*. (2011) show that connectivity may change from storm to storm depending on land use and storm characteristics. Biddulph *et al*. (2017) explored mitigation measures, including the construction of ponds, in a well-connected dairy farming landscape in Hampshire, UK. In England, perhaps the best example of the disruption of connectivity to curtail muddy floods reaching houses is in the Sompting catchment, West Sussex, where vulnerable slopes and linking valley floors were allowed to revert to grassland (Evans & Boardman, 2003).

The concept of the Sediment Delivery Ratio has been discussed at length in many papers e.g. Walling (1983). It is a simple attempt to establish the percentage or proportion of eroded soil reaching the stream and is often expressed as a ratio of sediment yield to soil erosion rates. The connectivity concept is an attempt to refine this measure by describing and quantifying linkages that apply at the landscape scale (e.g. hillslope to channel connectivity) as well as connections between the stream channel, its banks and floodplain. Here we have focused on hillslope to channel connectivity and have not considered other elements of connectivity as hillslope channel connectivity identifies links between agricultural land and the river.

Off-site impacts, erosion rates and connectivity

Figure 4 shows that in northern France, both relatively low rates of soil erosion (<2 t ha^{-1} yr^{-1}) and high densities of muddy flooding occur in the same areas. In Flanders, areas that are predicted to have high rates of erosion are not solely responsible for damage to the village of Riemst. Flowlines superimposed on the image show wide areas of potential runoff and sediment generation (Figure 5). In the Rother valley, West Sussex, UK, runoff and sediment from eroding fields reaches the river by means of ditches and roads (Figure 6). Thus, connectivity appears to be at least as important as high erosion rates on fields in causing off-site damage.

The case is even clearer in areas of low erosion rates where pollution damage to streams is recorded. this catchment water is taken from the river downstream of the monitored locality for public water supply. When pesticides in the river are at concentrations above the legal limit (0.1 µg l^{-1}), the abstraction has to stop and water is pumped from a nearby borehole in chalk bedrock. Metaldehyde, a molluscicide, is a particular problem in this catchment (River Wissey Partnership, 2014). There are also localised problems where there is too much sediment on the river bed, impacting on fish stocks (River Wissey Partnership, 2014). Runoff from fields can flood roads and property (Figure 7). Hence, even in a locality where erosion is not considered to be a significant problem by farmers, diffuse pollution and muddy floods due to runoff are a problem.

The value of observational evidence in mapping connectivity

In the Rother valley, West Sussex, UK, excessive sediment loads in the river are perceived as a problem. In particular, damage to the local trout fishery is related to fine sediment accumulation in a historically gravel-bedded river (Sear, 1996). This is in line with research in many other salmonid-rich rivers in the UK (Evans, 1996; Theurer *et al*., 1998; Collins & Walling, 2007; Collins & Davison, 2009; Kemp *et al*., 2011). Excessive sediment also affects invertebrates (Bond & Downes, 2003; Yeakley *et al*., 2016; *Conroy et al*., 2018).

Mapping in the wet winter of 2006-07 clearly showed transfer of sediment from fields under cultivation to the River Rother. Points at which sediment entered the river are shown in Figure 6. Nationally, Collins *et al*. (2009) suggest that 76 % of suspended sediment in rivers is from agricultural sources.

A database of 180 fields in the Rother valley which have recorded erosion since 1987 has been assembled. This is based on two theses, several *ad hoc* partial surveys, and six-monthly monitoring in the last three years (Guerra, 1991; Shepheard, 2003; Boardman *et al*., 2009). Air photographs and Google Earth images have added to the database (Boardman, 2016). Of the 180 fields, runoff from 103 fields has been shown to connect to the River Rother at various times. Thus, maps of potential or aggregate connectivity can be assembled. As an example, Figure 8 indicates connectivity between arable fields and the river under 'ideal' conditions. In this mapping of potential connectivity, we emphasise the importance of anthropogenic elements in the landscape, such as roads, tracks, ditches, culverts, tractor wheelings and field drains, although the latter are absent from the Rother valley exemplar area (but see below). We have previously highlighted the important role of sunken lanes in hydrological connectivity in the Rother valley which is also the case in Flanders and northern France and many other parts of the UK (Boardman, 2013).

In the Rother valley, of the 103 fields potentially connected to the river, 40 % are connected directly to the river, generally via other fields, and in some cases the runoff crosses roads. Twenty-nine percent are connected via culverts under roads; 16 % via roads and sunken lanes and 15 % via open ditches. Similar analysis in central Belgium in relation to sites of muddy flood damage, shows that in 36 % of cases runoff was directly from rills and gullies; 33 % was via watercourses, ditches and culverts; and 31 % involved flows along roads and sunken lanes (Evrard *et al*., 2007). The importance of elements in the agricultural landscape of anthropogenic origin is clear in both these areas.

Gascuel-Odoux et al. (2011) present a heroic attempt to model connectivity for a small (4.4 km^2) catchment in Normandy. Here, unlike the Rother catchment, arable fields tend to be far from watercourses and therefore not well connected. They acknowledge the role of hedges, roads, sunken lanes and ditches in the movement of water and sediment but accept that they are not easy to incorporate into a model especially taking into account the varying character of rainfall events. They also note that knowledge of flow paths, whilst not easy to obtain by field survey, would be invaluable for validating computed flow pathways.

Mapping of runoff and sediment flux reveals the ambiguous role of field boundaries. In many instances, hedges are not impermeable to flows (Figure 9). Their effectiveness varies with crop type and management of upslope fields, rainfall and runoff amount and the condition of the hedge (thickness, permeability etc.). Under extreme runoff conditions, hedges play a very limited role in detaining runoff. In parts of western Europe with open-field systems and few or no hedges, the hydrological role of field or parcel boundaries is even more problematic. Their role is not predictable from published maps or remotely sensed images unless the latter are available for the period after significant runoff has occurred (Figure 8). In general, field mapping and observations are needed to make valid assessments of connectivity.

In the Wissey catchment, north Norfolk, runoff, erosion (Evans, 2017), stream turbidity, field drain and stream flow were monitored for ten years. Much of the catchment is under-drained to increase the number of days in a year the land can be worked mechanically. Turbid runoff from the land into a stream was seen during the latter end of an *c.*11 mm storm falling onto saturated soil. Mean daily streamflow rarely rose when daily rainfalls of 2.0 mm were recorded, usually as a part of a sequence of rain days. However, more than half of the daily 4-5 mm rainfalls, and most (> 80 %) rainfalls greater than 6.0 mm generated stream flow, as did all storms larger than 12 mm. This rise in flow comprised a number of sources once rainfall thresholds were surpassed (Table 1) – runoff from roads, tracks, compact tractor wheelings, surface wash and field drain flow. Turbid runoff down roads and tracks occurred frequently, on average 47 days per year when rainfall was ≥ *c.* 5 mm, whereas surface wash transported fine particles and pollutants (nutrients and pesticides) from farm land (Evans, 2017) on average 14 days per year. Storms ≥ *c.*10 mm falling onto saturated top-soils could initiate runoff (Evans, unpublished). Once drains started flowing responses to rainfall were rapid, drain flow rose quickly after rainfall and fell rapidly during dry periods. Drains flowed for long periods, on average starting 47 days before soils were at field capacity (Potential Soil Moisture Deficit = 0 mm) and continued to flow for 45 days after the soils started to dry out. Drains flowed for large parts of every year, even for a short period in July of the wet year 2007 and were dry for only *c.*75 days in the wet summer of 2012. The longest period over which drains did not flow (*c.*257 days) was 2011 when the summer was very dry; drains did not flow until about 31st December. On average drains started to flow *c.* 47 days before soils became fully saturated (excess precipitation) and continued to flow for *c.* 45 days after soils began to dry out (in deficit). Drains were dry on average *c.*139 days a year, and over the monitoring period flowed for 62 % of the time. In this catchment, connectivity of flow from the land to watercourses is high but temporally variable.

Mitigation

Agricultural systems dominated by arable land uses are typically well connected in terms of transfers of water and sediment to watercourses: see for example the evolution of a Flemish agricultural landscape as depicted in Figure 2 (Boardman & Vandaele, 2015). As we have already shown, the connectivity is frequently a function of anthropogenic elements particularly roads, tracks, sunken lanes, ditches, field drains, culverts, gates and permeable field boundaries. The condition of soils and field surfaces with low organic matter content, an increasing tendency to compaction and crusting, and the presence of tramlines and wheelings, all contribute to the risk of high levels of lateral connectivity. This is especially true in the areas that we have focused on. A further complication is that field boundaries (fences, grass banks, hedges etc.), may not impede water flow but may trap sediments, thus functioning differently for water and sediment movement. Two approaches are commonly pursued in relation to mitigation. First, the focus could be on fields with predicted or actual high rates of erosion (see Figures 5 & 6). In this case, measures such as minimum or no-till, the planting of winter cover crops or, *in extremis*, a change in land use to crops with a lower risk of erosion provide alternative solutions. Secondly, because off-site damage is not necessarily related to areas of high rates of soil erosion, the focus should be on interrupting the flow of runoff, encouraging infiltration, and diverting flows from sensitive potential receiving sites. A long-term farm study in north Norfolk, UK, shows interruptions in connectivity being effective in reducing erosion risk (Evans, 2006). Similarly, a serious muddy flooding problem at Sompting, West Sussex, UK, was solved by returning some steep slopes and a valley bottom to grass (Evans & Boardman, 2003).

Mitigation measures may be characterised as being either emergency measures or those of longer-term significance (Boardman *et al*., 2003). Emergency measures are necessary where muddy flooding occurs and is likely to be repeated such as that in Flanders in May/June 2018. Figures 10 & 11 show long-term and effective protection for threatened communities by means of retention ponds and emergency measures using straw bales. A range of other mitigation measures are proposed for the Rother valley, but few are in place at present. These include buffer strips, grass waterways, retention ponds, cover crops and the breaking up of large blocks of similar land use to form 'patchwork landscapes' (Boardman *et al*., submitted). Recent work in northern France, suggests that vegetation barriers ('fascines') effectively interrupt flow along depressions in the arable landscape and encourage sediment deposition. These are particularly relevant where field boundaries allow through-flow (Frankl *et al*., 2018), as in the Rother catchment (Figure 9). Where connectivity is high, as in the catchment monitored in Norfolk, the problems of reducing flow either over the surface or through field drains are significant. The Norfolk catchment had many field grass margins before the monitoring project was initiated. It will not be practical to allow field drains to deteriorate, and it will need a change in land management to improve currently compacted soils: for example, more cover crops, more short-term grass leys, better timeliness of cultivation, drilling and harvesting, coupled with growing crops less damaging to the land at harvest time (sugar beet, potatoes). Sediment traps did not work well, either on the Wissey (Evans, personal observation) or in Sussex (Evans & Boardman, 2003) because the volumes of flow to be trapped were significantly underestimated. Better designed silt traps are being trialled in the Wensum Demonstration Catchment, adjacent and to the north of the Wissey catchment, in Norfolk. These are designed to avoid runoff flooding roads and carrying sediment from fields, damaged roadside verges and other sources into watercourses (River Wensum DTC, 2017).

Demonstration Test Catchments (DTCs) were established by the UK Department for Food and Rural Affairs (Defra) to explore the effectiveness of options to mitigate diffuse agricultural pollution in a range of farmed landscapes in the UK. Numerous papers are emerging from the four regions in which these issues have been explored e.g. Perks *et al*. (2015), Ockenden *et al.* (2017) and Biddulph *et al*. (2017). A summary of the achievements of phase 1 of this long-term project, including a list of publications arising from the work, is available from Defra (2016). Several important messages are emerging in relation to the effectiveness of mitigation options at the catchment and landscape scale. Of significance is the observation that in catchments such as the Wissey, piecemeal mitigation is unlikely to influence major river systems and that most farmers in any catchment or landscape need to sign up to a range of targeted options in order to effectively reduce the sediment and / or diffuse pollution pressures. This means that solutions to the muddy flooding issue, as mainly addressed here, are not necessarily the same as those that would be appropriate for whole river improvement. While managing connectivity may be an appropriate option for improving river water quality in some cases, solutions to the muddy flooding issue could be spatially targeted to protect key settlements and infrastructure under threat from extreme soil loss. In Flanders, connectivity is a key component of local muddy flood management but the spatial targeting of measures to control muddy floods may not be effective at the catchment scale to mitigate against fine sediment delivery to rivers. Understanding and managing connectivity will help in many cases but isolated mitigations will be unlikely to result in effective river management where a whole catchment solution is likely to be required.

Conclusion

Govers *et al*. (2017 p. 47) suggest that, 'Investing in the application of soil conservation measures is only meaningful when erosion rates are higher than acceptable.' However, we believe that this is not universally true. In north west Europe in particular, we have shown that connectivity is more important than absolute rates of erosion in relation to off-site impacts which are of primary societal concern. The related point is that we are discussing flood prevention rather than soil conservation measures which may be construed as being about on-farm issues.

We have tried to show that in areas where off-site impacts are of concern the emphasis must be on how runoff and sediment transfer systems are connected rather than on rates of erosion alone. Similarly, recent emphasis on low magnitude but frequent runoff to watercourses suggests it is impacts, rather than absolute rates, that are important. With regard to mitigation measures, the emphasis should shift from individual fields to the connected systems that are the cause of off-site damage and pollution (Biddulph *et al*., 2017). We argue strongly that field observation and monitoring are crucial to understanding the connectivity in arable landscapes.

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Table 1. Rainfall thresholds and sources stream flow (after Evans, unpublished)

THRESHOLD	IMPACT ON STREAM FLOW	COMMENT
c. 5 mm rainfall.	Initiation runoff and rise in stream flow.	Runoff from roads and tracks, and occasionally bare, compact tractor wheelings in fields.
c. 10 mm rainfall, usually low intensity, occasionally as storm.	Initiation runoff and more marked rise in stream flow.	Runoff from roads, tracks and bare, compact tractor wheelings in fields; from land when topsoils are saturated or when in a storm infiltration rate into soil is exceeded.
c. 20 mm rainfall, usually more intense storm.	Initiation runoff and marked rise in stream flow.	Runoff from roads, tracks and bare, compact tractor wheelings in fields; from land when topsoils are saturated and in summer months when soils are drier when infiltration rate into soil is exceeded.
c. 50 mm Potential Soil Moisture Deficit.	Field drains flow.	Drain flow starts and ceases when PSMD *c*.50 mm.

Figure captions

Figure 1. Areas with frequent muddy floods and important off-site damage 1. Armannac-Languedoc 2. Rhone valley 3. Alsace 4. Picadie 5. Flanders 6. Swiss midlands 7. Saxony 8. South Downs and Rother valley 9. Norfolk. Base map from EUROSTAT, 2010.

Figure 2: Riemst, Flanders, muddy flooding in the summer of 2016

Figure 3. Muddy flood, Flanders, May 2018

Figure 4: Erosion rates in France (left) compared to frequency of muddy flooding (right)

Figure 5: Predicted risk of erosion on fields south of Riemst, Flanders; purple and red are highest risk. Runoff flow lines are superimposed onto the map.

Figure 6: Rother valley, West Sussex, UK. Risk of soil erosion assessment (Defra, 2005) and routes of sediment to the River Rother, winter 2006-07.

Figure 7: Wissey catchment, Norfolk: runoff from outdoor pig field via road to flood property (August 2012). This flow reached the River Wissey.

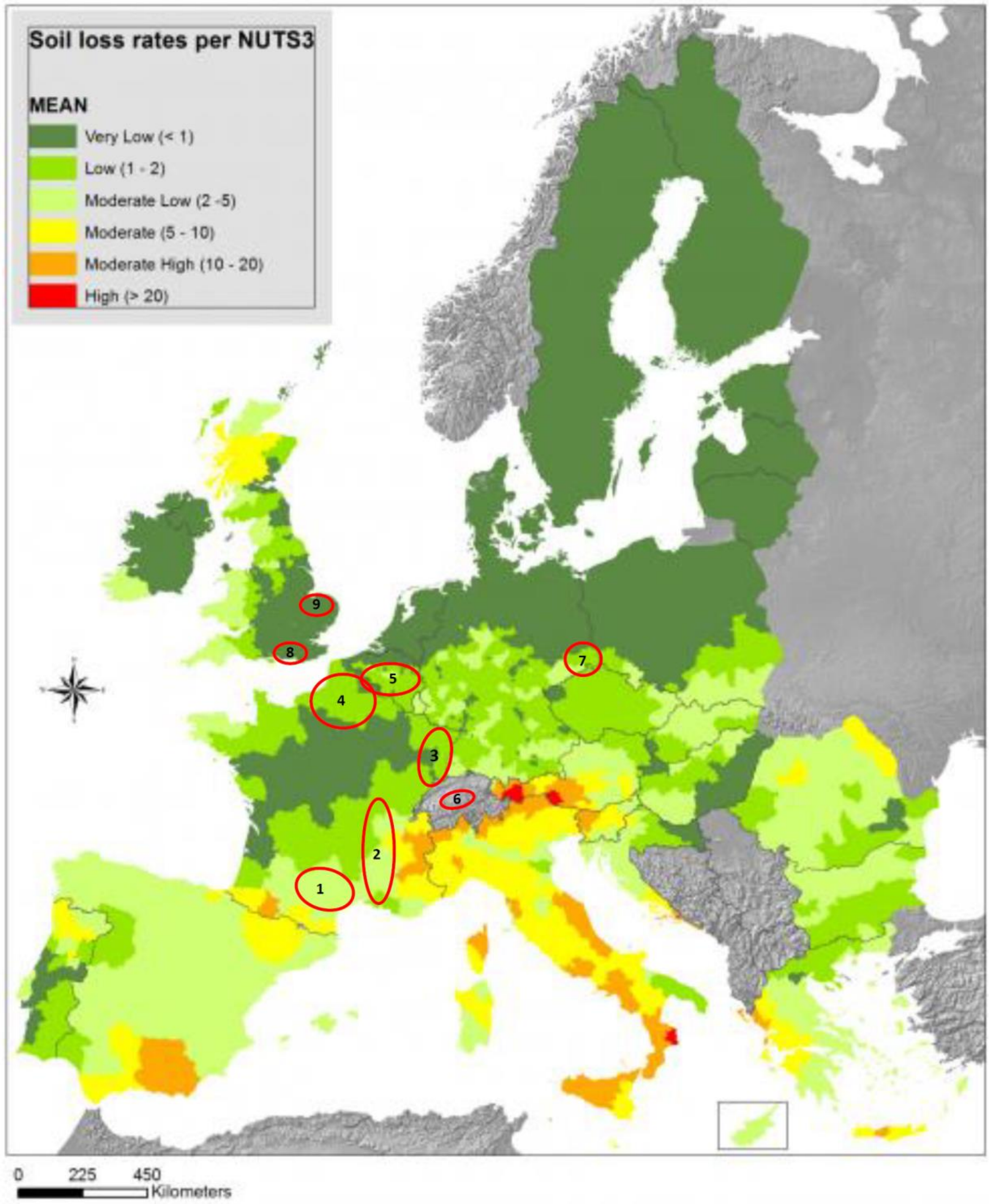
Figure 8: Example of aggregate connectivity map for Rother valley, West Sussex, UK

Figure 9: Connected flow from fields through permeable hedge lines (January 2001), Rother valley, West Sussex, UK (from Google Earth)

Figure 10: Retention ponds, 1 June 2018, Flanders

Figure 11: Straw bales forming temporary dam, June 2018, Flanders

Figure 1

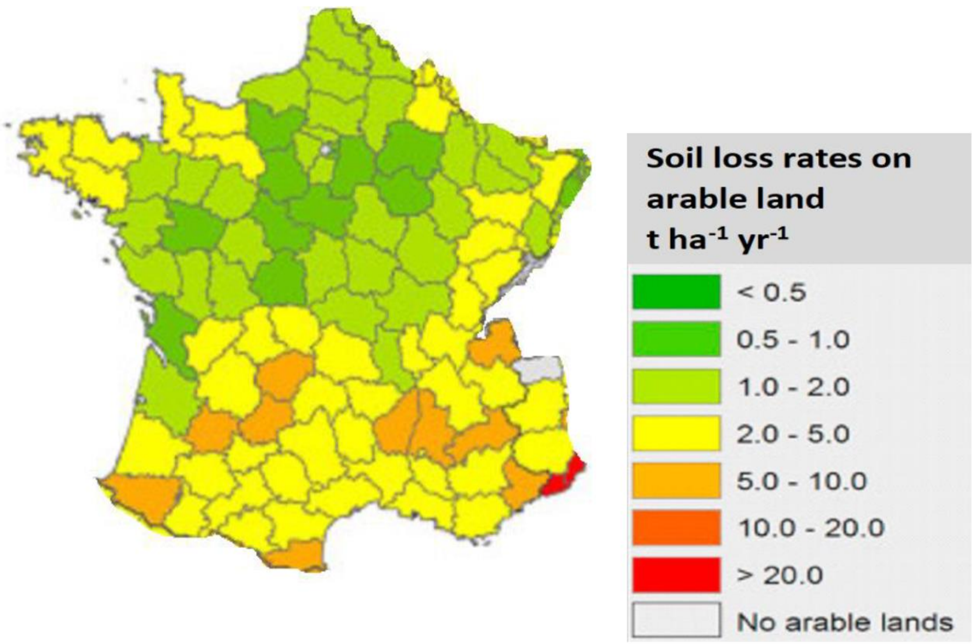


Soil loss rates per NUTS3
MEAN
Very Low (< 1)
Low (1 - 2)
Moderate Low (2 -5)
Moderate (5 - 10)
Moderate High (10 - 20)
High (> 20)
1
2
3
4
5
6
7
8
9
0
225
450
Kilometers

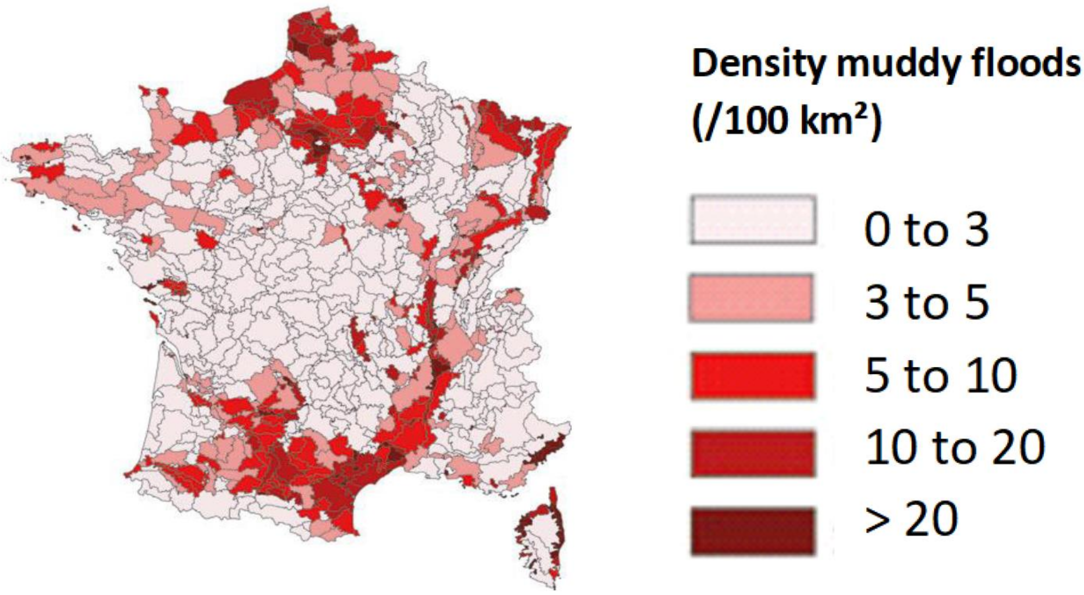
Figure 2

Figure 3

Figure 4



Soil loss rates on arable land
t ha^{-1} yr^{-1}
< 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 5.0
5.0 - 10.0
10.0 - 20.0
> 20.0
No arable lands



Density muddy floods
(/100 km²)
0 to 3
3 to 5
5 to 10
10 to 20
> 20

Figure 5

Figure 6

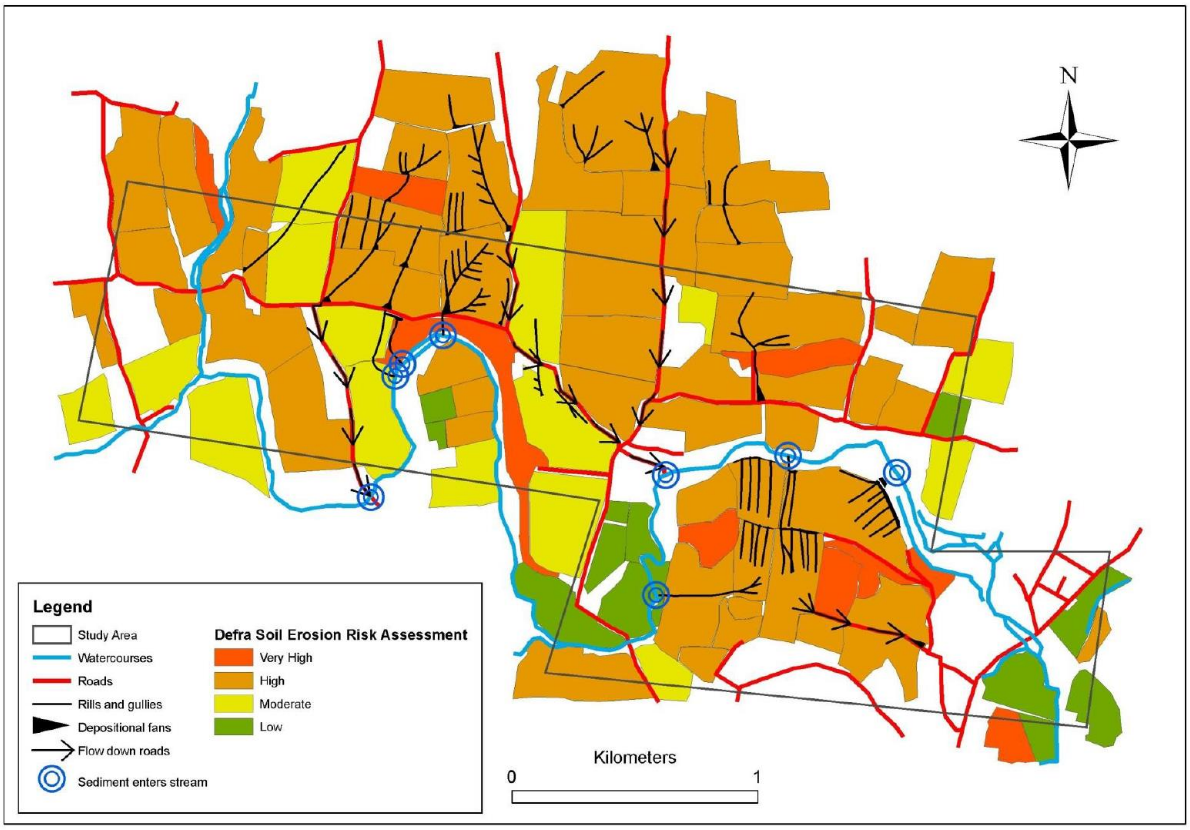


Figure 7

Figure 8

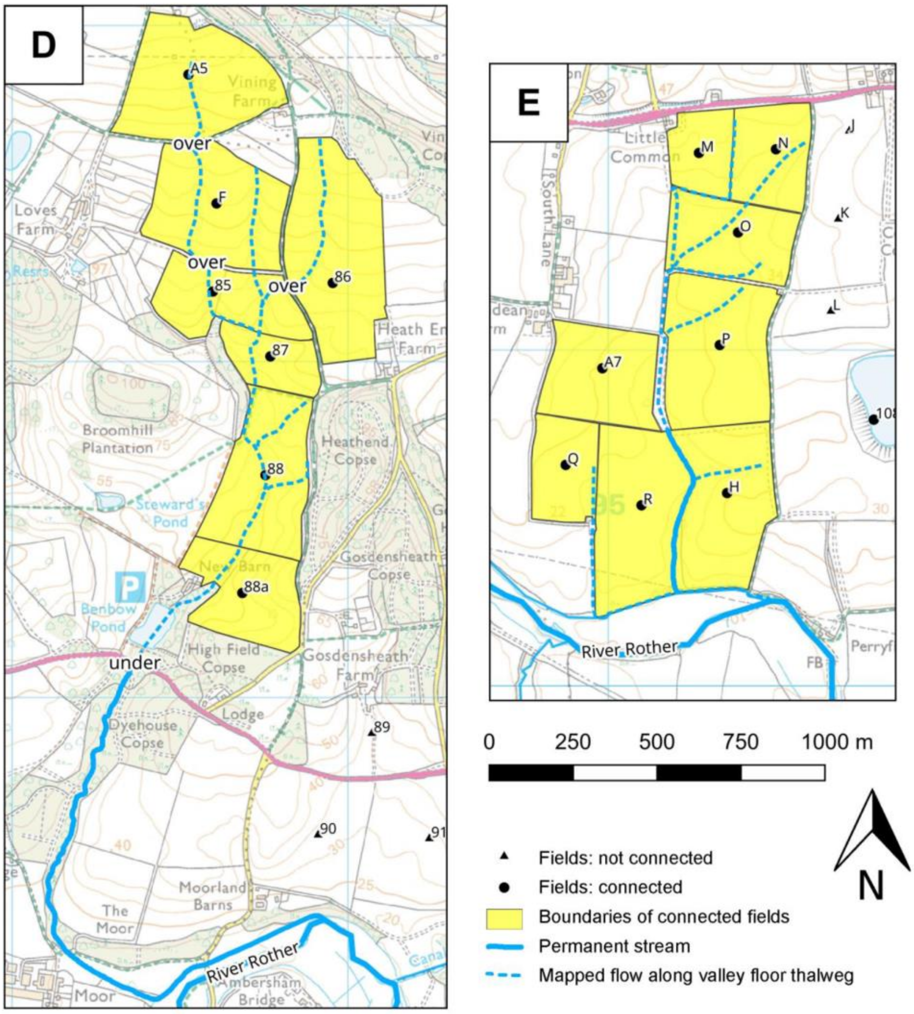


Figure 9

Figure 10

Figure 11