Department for Environment, Food and Rural Affairs Research project final report

Project title	To review the overall costs and benefits of soil erosion measures and to identify cost-effective mitigation measures Sub-Project C of Defra Project SP1601: Soil Functions, Quality and Degradation – Studies in Support of the Implementation of Soil Policy
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Understanding the costs and benefits of mitigation measures used to reduce or prevent soil erosion.

Sub Project C of Defra Project SP1601: Soil Functions, Quality and Degradation – Studies in Support of the Implementation of Soil Policy

C.1. Review of current understanding of the types, causes, extent, magnitude and impact of soil erosion in England and Wales.

This review considers soil erosion (types, causes, extent, magnitude and impacts) and the costs and benefits of mitigation methods specifically associated with agricultural land. This includes arable, pasture and horticultural land and, where appropriate, will clearly distinguish between upland and lowland systems. The review does not consider soil erosion caused by construction, infrastructure, industry (other than agriculture), recreation or tourism.

Soil erosion is a key threat to soil resources. An estimated 2.2 million tonnes or megagrams (Mg) of arable top soil are eroded annually in the UK by water. These erosion rates vary between <1 - 20 Mg ha^{-1} yr^{-1} (Defra, 2009b; NE draft position on soil) compared with soil formation rates which are estimated to be in the range of ca. 0.1 – 1.0 Mg ha^{-1} yr^{-1} for most of Europe (Verheijen *et al*., 2009). The costs of soil erosion in the UK are estimated at £45 million per annum (Defra, 2009). Soil provides a wide range of environmental and socioeconomic services to society. The functions of soil, as defined in the Soil Strategy for England (Defra, 2009), include: food, timber and fibre production; environmental interaction (between soils, air and water); storage of water, nutrients and carbon; support of ecological habitats and biodiversity; protection of cultural heritage (including landscape); providing a platform for construction and infrastructure; and providing raw materials. Soil erosion can reduce the ability of the soil to provide these goods and services.

Soil erosion can be linked to a range of anthropogenic activities and natural phenomenon, and is associated with a variety of land management sectors including agriculture, forestry, the built environment, and recreation, amenity and tourism. Agriculture has the greatest spatial influence on soil systems in England and Wales.

Concerns over soil erosion are presently motivated by a combination of environmental awareness, health concerns and social-economic impacts. However, concerns in respect to soil erosion are also growing in response to future food security issues, requirements for sustainable agricultural production, diminishing fossil fuel resources, and the consequences of predicted climate change. The main policy drivers for soil protection currently include: government policy responses to European Union policies such as the Water Framework Directive, the Nitrates Directive, the Urban Waste Water Treatment Directive and the Landfill Directive, and GAEC cross-compliance. None of these policies are soil specific, but they do consider soil indirectly as part of the wider environment. In response to EU policy the UK government published a Soil Action Plan for England 2004-2006 and more recently the Soil Strategy for England. Policies in the future will need to focus on the demands of a growing national as well as world population, balancing conflicting demands for food supply, growing infrastructure for housing, transport and business, and environmental protection. The shift from focussing on agricultural production towards environmental protection is currently under scrutiny, given the pressing issues of food security on a global, national and local scale (AEBC, 2005).

Definitions of soil erosion: causes, extent, magnitude and impact

As an essentially non-renewable resource, soil requires careful management in order to maintain its functionality and subsequent economic and environmental benefits that society gains from it. It is therefore essential that appropriate mitigation measures are put in place, which are both effective and sustainable. In order to achieve this it is important to understand the soil erosion process, the factors that increase the likelihood of soil erosion, what can be done to modify these factors (and so reduce rates of erosion) and the impact of soil erosion in terms of economic and environmental costs.

Soil erosion processes

In the UK the most widely studied forms of erosion are wind and water. The spatial distribution of these forms of erosion in the UK have been presented by Morgan (1985; see Figure 1) and by Boardman and Evans (2006; see Figure 2). However, other forms of erosion also potentially threaten soil resources. The types of erosion considered in this report include water, wind, tillage and co-extraction with root vegetables and machinery, as these are the main erosive agents acting on agricultural soils in England and Wales. A comprehensive review of erosion by wind, tillage and co-extracted with root vegetables and machinery, in England and Wales, was under taken by Owens *et al*. (2006*a*).

Soil erosion is often described as a two-phase process consisting of the detachment and transport of soil particles or small aggregates (Morgan, 2005). The detachment process relates to the breakdown of the soil mass into smaller, and therefore lighter, particles by agents of soil detachment, such as rainsplash, wetting and drying phases, freezing and thawing, frost heave, biochemical processes and tillage operations. In the erosion process, detachment is followed by entrainment and then transport of particles by an erosive agent, such as water. The final stage of the erosion process is the deposition of particles/small aggregates, which is caused by a loss or reduction in erosive energy. The distance over which soil particles are transported before deposition, is a function of the erosive force and the size of the eroded particle/aggregate. This distance can range from a few millimetres (in the case of rainsplash) up to several kilometres (if transported by wind or overland flow). However, while transport distance may only be limited, re-detachment of deposited sediment means the erosion cycle can repeat over and over again, so that cumulative transport distance may be much greater. In order to reduce soil erosion, mitigation measures are needed that act on one or more of the detachment, entrainment, transport and deposition phases of soil erosion. The philosophy of 'control at source' is common in soil conservation design – this usually means control of the first phase of soil erosion – detachment of particles/aggregates.

Factors that increase the rate of soil detachment

From a mitigation perspective, erosion can be limited by reducing the availability of detached particles. Detachment of soil can occur through raindrop impact or surface water flow. Factors that contribute to detachment by rainfall include the size (mass) and velocity of raindrops. These two characteristics are related: for example a 1 mm diameter raindrop has a terminal velocity of 4 m s^{-1} while a 5 mm diameter raindrop falls at 9 m s^{-1} (Morgan, 2005). Raindrop erosivity (ability to cause erosion) is largely determined by the kinetic energy of the drop which is increased as a function of mass and velocity. Surface cover (e.g. vegetation, crop residues, erosion blankets) can act to reduce raindrop mass (by shattering raindrops on impact) and velocity (through raindrop interception in the cover). Thus the soil is most vulnerable when soil surface cover is sparse, especially at times of the year when intensive rainfall events are expected. Other factors that contribute to particle detachment include soil texture, soil shear strength, moisture content of the soil and the mechanical break up of the soil either by climatic conditions (e.g. wetting and drying of soil, freeze and thaw cycles or frost heave) or tillage. The use of conventional tillage practices, especially those used to produce fine seed beds for valuable crops such as winter wheat, potatoes and carrots, produce an abundant source of small, lighter, particles that are vulnerable to erosive forces.

Silt sized particles are the most vulnerable to detachment by raindrops (Poesen, 1985). Smaller particles (clays) are more resistant to detachment because of cohesion, and larger particles (sands) are resistant because of mass/weight. As soil shear strength increases, detachment decreases exponentially. Although rainsplash is the most important detachment process, it is only capable of transporting particles over short distances because most of the erosive energy is used up in the impact and detachment process.

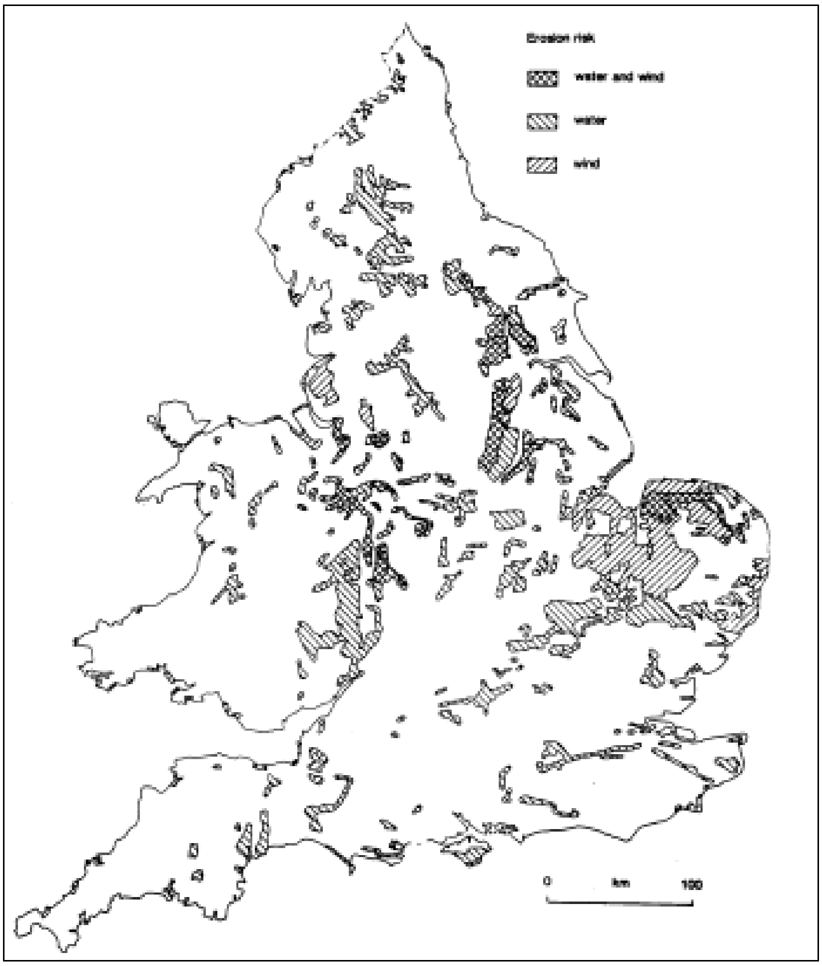

Figure 1: Areas of soil erosion risk in England and Wales (from Morgan, 1985)

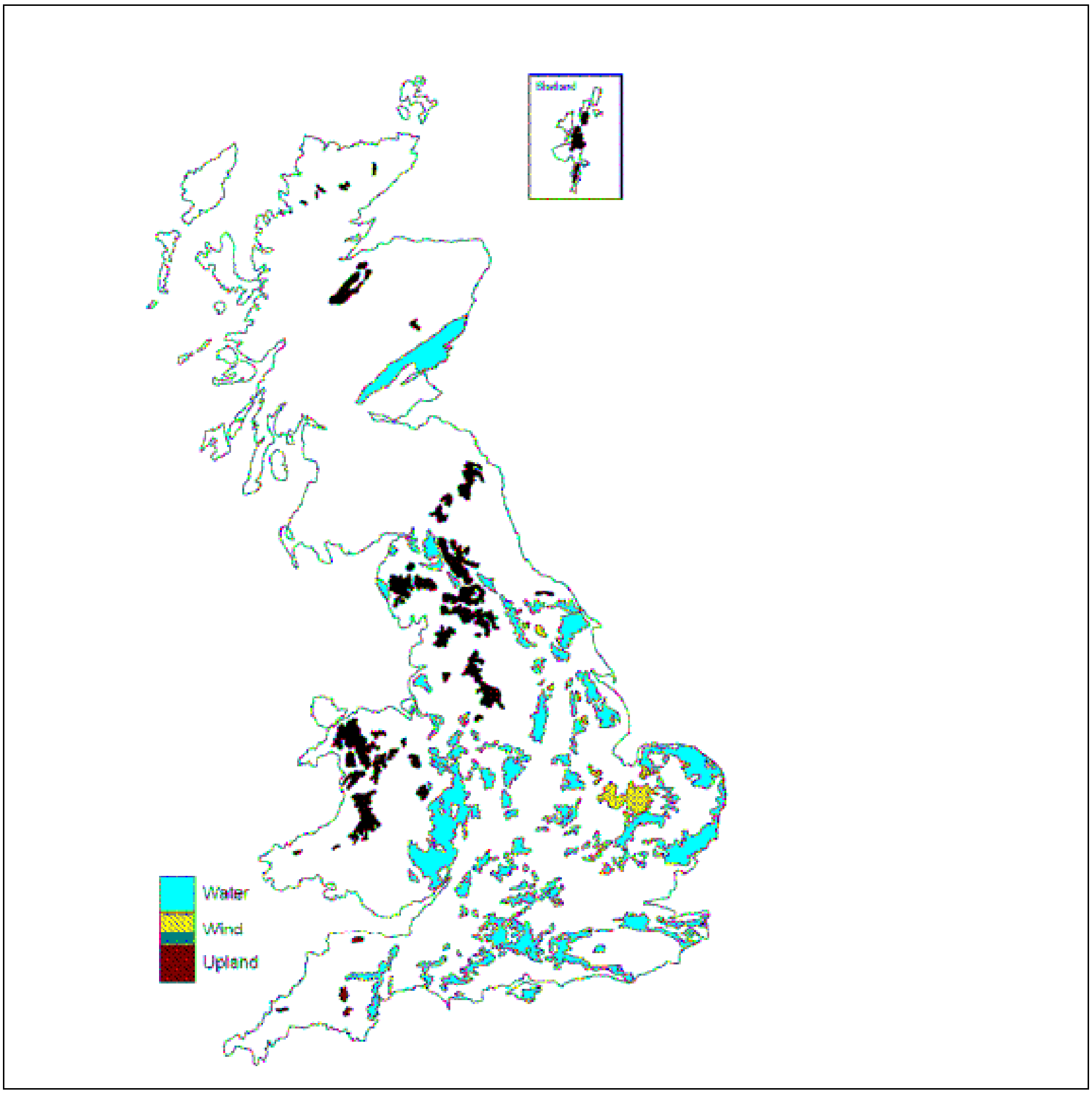

Figure 2: Areas of soil erosion risk in England, Wales and Scotland (from Boardman and Evans, 2006).

Detachment of soil particles can also take place by overland flow. However, the critical shear velocities required to detach soil particles are unlikely to be reached by unconcentrated overland flow, due to high levels of friction imparting roughness to the flow (expressed in coefficients such as Mannings ‘n’). The resulting turbulence reduces the energy available to detach soil. Some erosion models (e.g. the original Morgan, Morgan and Finney erosion prediction model; Morgan *et al*., 1984) assume that all soil detachment is due to raindrop impact and even ignore any detachment due to overland flow. The rate of detachment by rainfall, runoff or wind is therefore influenced by prevailing climatic and inherent site conditions, as well as the timing of land management practices and the intensity of land management.

Entrainment and transportation of detached soil
Soil erosion can also be limited by the capacity of the eroding agent to transport detached particles, once detached. The first stage of the transport process is the entrainment of detached soil particles into the transporting agent.

Factors that increase the likelihood of overland flow generation include the infiltration capacity of the soil and the intensity and duration of rainfall. The infiltration capacity of a soil is primarily determined by the soil texture, with more coarse textured soils (i.e. sand) tending to having greater infiltration rates than finer textured ones (clays), unless macropore features exist, which can increase the hydraulic conductivity of the soil. Land management can also act to increase overland flow. Land management practices can lead to the development of surface sealing and capping, and structural compaction, all of which reduce the infiltration capacity of a soil and increase the risk of surface runoff. Surface sealing is caused by rainsplash erosion and slaking on a vulnerable soil. Slaking occurs when rapid ingress of water compresses air trapped in soil pores, leading to a sudden pressure release, so destabilising aggregate structure, which can lead to aggregate breakdown and surface sealing by the resulting soil fragments. When surface seals dry out, a soil crust or cap may form. The sealing and capping process reduces the porosity of a thin layer of surface soil. Although the layer may only be thin it can significantly restrict infiltration from either rainfall or irrigation, leading to runoff generation, even on soils thought to have high infiltration rates.

Compaction, depending on where it occurs in the soil profile, will allow some infiltration. However, compaction will restrict percolation rates and the soil profile above may quickly become saturated preventing further infiltration and this may lead to the generation of surface ponding and/or runoff. Drainage is also an important factor. Soils that drain quickly, either naturally or through artificial drainage systems are less likely to be affected by erosion from overland flow. However, rainfall intensity will determine the generation of overland flow as rainfall intensity in excess of infiltration capacity will generate overland flow, even on gentle slope gradients.

It is the velocity, rather than volume of overland flow that dictates the rate of entrainment and transport. This increases as a function of numerous factors including rainfall intensity, slope length, slope angle and surface roughness. As with rainsplash, silt sized particle are entrained and transported more readily than either clay (because of cohesion) or sand particles (because of mass/weight). As flow is channellised, its capacity to erode increases as less energy is lost to frictional drag at the soil/water interface. The entrainment and transport of soil particles by water can lead to surface (e.g. sheet erosion, rills and gullies) and sub-surface erosion (e.g. piping and tunnel formation).

Entrainment and transport of soil particles by wind requires a much greater shear velocity than water. The process of detachment and entrainment occurs as a combination of wind velocity and the momentum imparted to *in-situ* soil from soil particles already entrained in the air flow. Soil moisture determines the resistance of the soil to wind erosion with wet soils being less erodible than dry soils, due to cohesive forces between particles. A protective cover of vegetation, crop residues, stones, erosion blankets etc. can reduce velocity at the ground surface, so reducing wind velocities and erosivity.

Erosion relating to mechanical movement
Tillage translocation of soil particles is a redistribution process that results from gravity and the disturbance of soil by farm implements. It generally results in soil loss in a down slope direction. Soils on convex slopes are often transferred to either a concave slope position or to the field boundary. Factors that control tillage erosion are shown in Figure 3 and include slope gradient and variations in

slope curvature, tillage operation (including plough depth, direction and speed) and tillage implementation type (Owens *et al*., 2006a). The process of ploughing lifts and breaks up the soil mass. Downslope tillage displaces soil in a downslope direction by the drag of the plough and gravity. Upslope tillage drags the soil upslope but gravity draws some of it back downslope, so the net movement is less than for downslope tillage. Tillage along the contour can cause both up- and down-slope soil translocation, depending on the alignment of the tool in relation to the slope direction. However, unless the field boundary is removed, it is unlikely that net export of soil from the field occurs due to tillage erosion.

Soil can also be lost from a field due to its co-extraction on crops during harvest, principally root vegetables such as potatoes, carrots, sugar beet and onions. Soil can also be removed when attached to agricultural farm vehicles and implements. Ruysschaert *et al*. (2004) provides an overview of factors that contribute to soil loss through co-extraction and on machinery (as reviewed in Owens *et al*., 2006a). The most notable of these factors includes soil wetness and high clay content which increase the adhesion of soil to crops and farm equipment. Harvesting techniques and weather conditions also play a role in the amount of soil extracted with the crop.

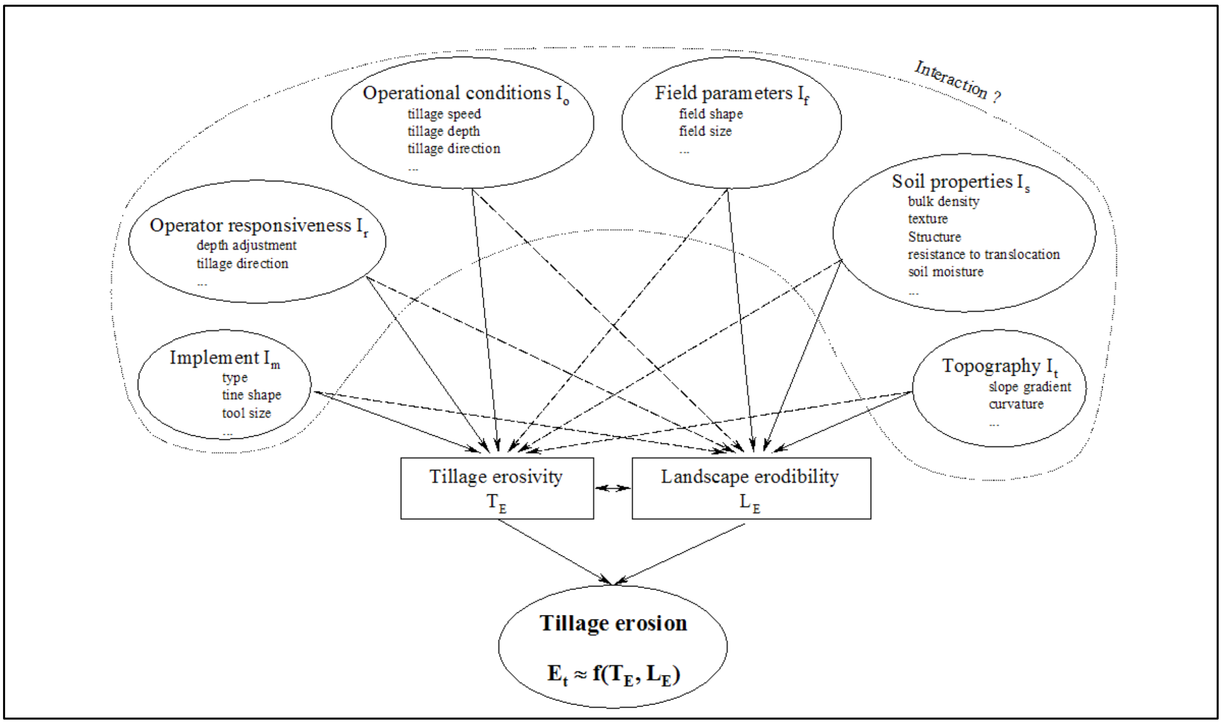

Figure 3. Factors affecting tillage erosion processes (from Van Oost et al., 2006)

Deposition
Deposition of eroded soil (sediment) represents the end point of an erosion cycle. However, the overall erosion process may consist of several erosion cycles, each moving the soil particles further and further away from their point of origin. Deposition occurs as erosive energy diminishes. Frictional resistance encountered by flow acts to diminish the transport energy until a point is reached at which it can no longer support the load it is carrying. The rougher the surface over which water or wind flows, the quicker the demise in transport energy. Also, the larger the calibre of the transported material, the sooner the material is deposited once energy decreases. Some small particles (notably clay) may never be deposited, as they are in suspension even at zero flow velocity. This has serious implications for water quality, especially as these particles are able to absorb agrochemicals and other contaminants associated with eroded sediment, due to their high specific surface area. It should be noted that deposited material is easily re-detached as it lacks the cohesion, structure or shear strength of *in-situ* soil.

The final deposition phase by tillage erosion is either on a concave slope or at the field boundary. At these points transport of soil particles downslope ceases due to a reduction in slope steepness (gravity effect is less) or because the edge of the field is not cultivated. The deposited material will remain here until the slope is modified, the field boundary is removed or an extreme weather event re-detaches the deposited material. However, deposition of soil particles from farm vehicles can occur at any point from field to farm shed, and has been associated with the deposition of mud on roads. Soil particles co-extracted on harvested crops can be removed as far away as processing plants where it is washed from the crop (Owens *et al*., 2006a).

Extent, magnitude and impact of soil erosion in England and Wales

Extent of erosion by water
Brazier (2004) provides a summary of available data describing rates of erosion by water from the hillslope scale to the large catchment scale. Measurements are reported from erosion plots, overflight and field surveys, Cs137 data, reservoir sedimentation and suspended sediments monitoring. Evidence suggests that soil erosion rates in excess of acceptable thresholds occur on a wide range of soils and under a wide range of land uses throughout the country. The soils in England and Wales most susceptible to water erosion are sandy soils in south west and south east England, East Anglia, the Midlands and South Wales; chalky soils on the South Downs, Wolds and in East Anglia (Defra, 2005). Wood *et al*. (2006) conclude that brown earths were the major soil group with the highest soil erosion vulnerability overall.

In upland areas, peat soils and podzols (particularly the wetter stagnoposzols) were at the highest risk of erosion. Factors affecting erosion in these areas include wind splash erosion of blanket peat (Foulds and Warburton, 2007). Vegetation removal and exposure of soil is also important. McHugh *et al*. (2007) found that sheep and cattle significantly contributed to upland soil erosion in England and Wales. CAP reform (Defra, 2004) that switched to farm area-based payments removed the incentive to maintain large flocks and so reduced numbers.

It has been estimated that the annual soil erosion rate for the UK is 2.2 million tonnes of topsoil (SSLRC, 2000; Environment Agency, 2007). Considering that the agricultural area in the UK is 18.7 million hectares (Agristats, 2009), this erosion rate does not seem very high. Indeed, the 'State of the Environment' (Environment Agency, 2005), estimated that only 17 per cent of the land in England and Wales is affected by erosion. This would result in an average soil loss of 0.7 Mg ha^{-1} yr^{-1} on land affected by erosion.

However, Evans (2002) estimated that 29% of the farmland was affected by erosion at an average rate of 1.9 Mg ha^{-1} yr^{-1} during the period 1982-1986 (Table 1). He noted that soil loss may be considerably higher on individual fields causing considerable on- and off-site damage. Other studies have estimated typical erosion rates at 1 to 20 Mg ha^{-1} yr^{-1}, but erosion rates are thought to be less than 1 Mg ha^{-1} yr^{-1} for most fields (Defra, 2009a).

Other estimates of erosion rates include work by Wood *et al*. (2006; Figure 4), using a GIS based model prediction, at a 1 x1 km pixel resolution, comprising slope class (50 m PANORAMA digital elevation model), soil (NSRI NatMap), land cover (Landcover Map of Great Britain) and erosion model (total channelled erosion). They estimated that annual erosion rates across England and Wales were extremely low for a rain event with a 1 in 1 year return probability. However, for the 1 in10 year return period, annual erosion rates were estimated to be 0.52 Mg ha^{-1} (≤12^{o} slope) and 1.56 Mg ha^{-1} (>12^{o} slope) in some parts of England and Wales (Figure 4). The results of Wood *et al*. (2006) correspond well with observations made by Evans (1998) and Boardman (1998). A similar method to Wood et al., (2006) was used to estimate the annual sediment delivery rates to watercourses in England and Wales (McHugh et al., 2002; Figure 5). These estimates assuming no mitigation measures where used.

These predictions and estimates should be verified by actual measurements of soil erosion, but these have been *ad hoc* in the UK. Based on field experiments, Morgan (1980) measured low rates of annual soil loss (0.23 to 0.98 Mg ha^{-1} yr^{-1}) on agricultural fields under natural rainfall. The rate of soil loss on bare soils, however, was very high at 11 Mg ha^{-1} yr^{-1}. More severe rates of soil erosion have been measured during storm rainfall events, resulting in soil loss between 2 and 8.6 Mg ha^{-1} yr^{-1}. Morgan (1980) thus concluded that soil erosion is typically associated with rainfall events of moderate magnitude. For the majority of rainfall events rates of soil loss are thus negligible. Soil loss rather takes place during moderate to high magnitude rainfall events, and local conditions (soil conditions, land cover, slope) determine whether any particular field is susceptible to erosion processes.

Table 1: Occurrence of soil erosion caused by water, measured in 1982-1986 (Evans 2002)

Crop	% national crop area	% occurrence erosion	total % occurrence erosion	Mean erosion rate (Mg ha^{-1} yr^{-1})	Median erosion rate (Mg ha^{-1} yr^{-1})
Winter cereals	62%	43%	26%	1.85	0.68
Spring cereals	14%	12%	2%	1.75	0.71
Oilseed rape	5%	2%	0%	1.92	0.30
Temporary grass	5%	0%	0%	4.09	1.14
Sugar beet	5%	18%	1%	3.04	0.92
Potatoes	3%	11%	0%	2.53	1.01
Market garden	3%	6%	0%	5.08	1.47
Peas	1%	1%	0%	1.21	0.91
Fallow	1%	2%	0%	1.61	0.27
Field beans	1%	0%	0%	0.47	0.22
Kale	1%	1%	0%	2.10	1.41
Maize	0%	2%	0%	4.48	1.00
Hops	0%	1%	0%	3.92	1.01
Other	1%	3%	0%		
Total			29%	1.91	

In a recent Farm Practices Survey (2007), 50 per cent of farmers said they observed at least some soil erosion on their land. Boardman *et al*. (2003) measured average erosion rates between 0.65 to 6.5 Mg ha^{-1} yr^{-1} in South East England during the 1980s. However, rates on individual fields reached over 260 Mg ha^{-1} yr^{-1} in occasional years. In a more recent study, erosion rates of 31 to 234 Mg ha^{-1} were measured on fields prone to erosion in South East England during the 2006 – 2007 winter season (Boardman *et al*., 2009). Walling *et al*. (2005) assessed net erosion rates from arable and pasture fields in South West England and calculated that the median net rates of soil loss were 4.1 Mg ha^{-1} yr^{-1} and 0.6 Mg ha^{-1} yr^{-1}, respectively. The net erosion rates were about half of the gross erosion rates. Within-field storage of sediments is thus significant in the gentle rolling terrain that characterizes most arable fields in this region. This has implications for soil protection as it implies that a significant amount of soil erosion is 'invisible' – i.e. soil and its functions are being lost at source, but with no visible evidence (e.g. turbid runoff, muddy floods and sedimentation in streams).

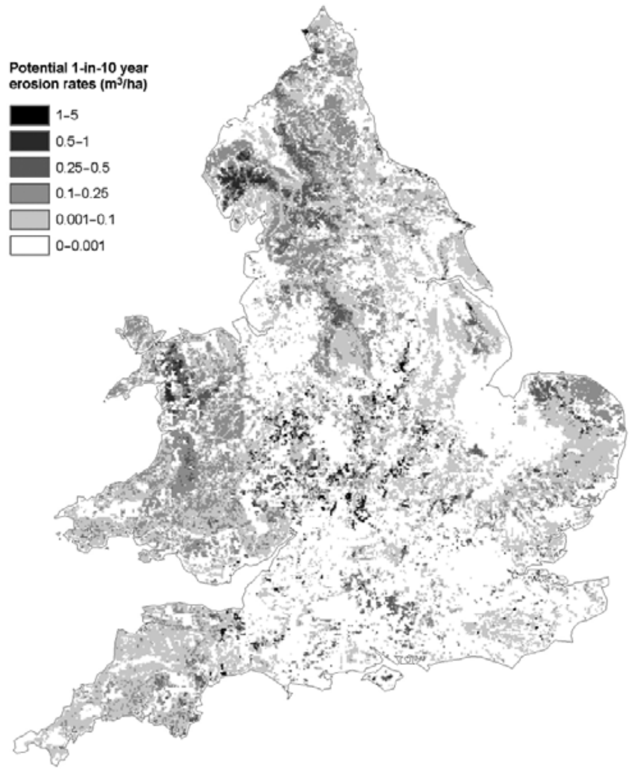

Figure 4: Potential 1-in-10 year soil erosion rates in England and Wales (Wood *et al*., 2006)

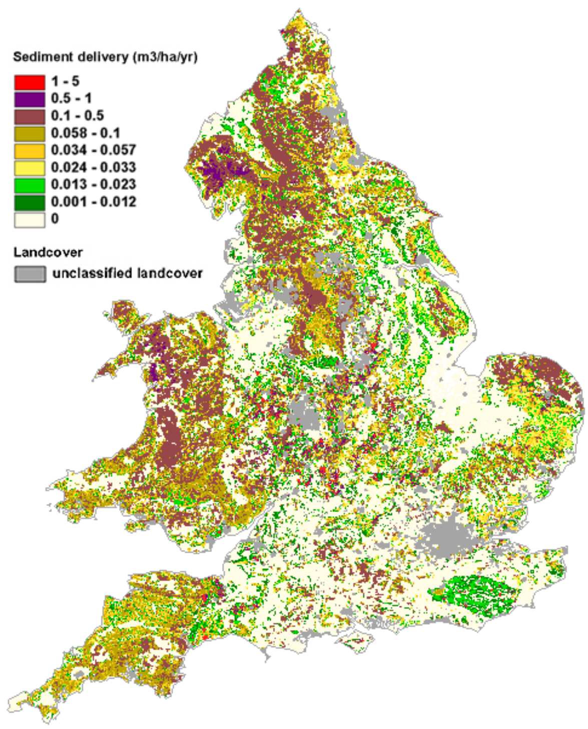

Figure 5: Distribution of estimated 1-in-10 year sediment delivery to watercourses in England and Wales expected to occur annually (from McHugh *et al*., 2002b)

Extent of wind erosion
Wind erosion has mainly been recorded on sandy and peaty soils in the eastern and middle counties of England e.g. East Midlands and East Anglia, and parts of the uplands of England and Wales (Figure 6). In comparison to water erosion, the area of England affected by wind erosion is small (Chappell and Warren, 2003). However, the rate of erosion can be greater by wind than by water. This is partly due to the fact that wind erosion is likely to impact on a whole field area while erosion by water is limited to where the water flow is concentrated (Evans, 1996; Owens *et al.*, 2006a).

Uplands are at risk of wind erosion, especially on exposed bare soils and peat, where overgrazing can expose soil and peat (McHugh *et al*, 2002). Drier summers may increase the risk from wind erosion as soils dry out and become friable. Peat soils in particular will become more vulnerable to wind and water erosion, both through drier conditions (leading to vegetation loss and increased susceptibility to wind erosion), and from extreme rainfall events in the winter. Critically, erosion of peat will lead to a loss of carbon back into the atmosphere.

Wind erosion can be a problem in England, especially on arable farms in East Anglia. Farmers in this area expect moderate damage to crops from wind erosion once every three or four years and severe damage once in 10 years (Chappell and Thomas, 2002). The mean rate of wind erosion has been estimated at the order of 0.1 to 2 Mg ha^{-1} yr^{-1}, although maximum values for fields can be one or two orders of magnitude higher. Evans (1996) reported that the value of the crop in wind eroded fields is often higher than that affected by water erosion, so the on-site cost of wind erosion is often greater (five times or more) than when fields suffer from water erosion. The national annual cost of agricultural inputs lost because of wind erosion in the mid-1980s was estimated at £210,000 and the loss of crop at £705,000: equivalent values for water erosion were £285,000 and £940,000 respectively, due to the larger area affected by water erosion (Quine *et al*. 2006).

Extent of tillage erosion
The extent and magnitude of soil loss by tillage erosion in England and Wales is poorly understood (Owens *et al.,* 2006a). There are almost no easily available (i.e. published) data on the magnitude of tillage erosion in England and Wales. Exceptions include field data from Dalicott Farm in Shropshire (Govers *et al*., 1993; Quine and Walling, 1993; Quine *et al*., 1994, 1996) and Coombe Barton Farm in Devon (Quine and Zhang, 2004a, b). These limited studies suggest that within-field movement by tillage operations can be similar or greater than that due to water and wind erosion, and tentatively within the range 0.1 to 10 Mg ha^{-1} $year^{-1}$.

Van Oost and Quine (2006) produced a map of simulated tillage erosion rates (Figure 7). The extent of tillage erosion will be limited to arable land that is conventionally tilled.

Extent of erosion by co-extraction with root vegetables and machinery
According to Owens *et al.* (2006a), there have been almost no scientific studies of soil loss due to co-extraction with root crops and associated farm machinery in England and Wales. One explanation for the paucity of data for England and Wales may be that measures have been taken by the industry in the UK, so that the amount of soil removed at harvest has reduced significantly since 1987, and less soil is removed here during harvest than in other European countries. The UK now has the lowest dirt tare (percentage of soil and waste material lifted with a crop) in the EU (http://www.defra.gov.uk/corporate/consult/eisugar/responses.htm). These losses are, however, still substantial and of the order of 350,000 t $year^{-1}$. Specifically, it is estimated that 2 Mg ha^{-1} $year^{-1}$ is eroded during the harvesting of sugar beets and potatoes (Figure 8). It has been estimated that this represents the loss of about 1% of the topsoil of beet fields per century.

Annually British Sugar receives around 450,000 t of soil with the 9×10^6 t of sugar beet it purchases from UK farmers. The available information suggests that for sugar beet of the order of 1-3 Mg ha^{-1} $year^{-1}$ may be lost from the field on crop roots, depending on its occurrence within crop rotations. However, sugar beet only occupies about 4% of the total crop land of England and Wales at present. Values of soil loss associated with other root vegetables are likely to be less. Figure 7 shows the distribution of sugar beet and potato production and soil erosion risk.

Owens et al. (2006a) found no literature on the magnitude of soil co-extracted on farm machinery. However, a first attempt based on typical information on farm machinery, for example tyre dimensions, suggest that the maximum likely loss of soil associated with a tractor and trailer for sugar beet harvesting is ca. 1-2 Mg ha^{-1} per harvest.

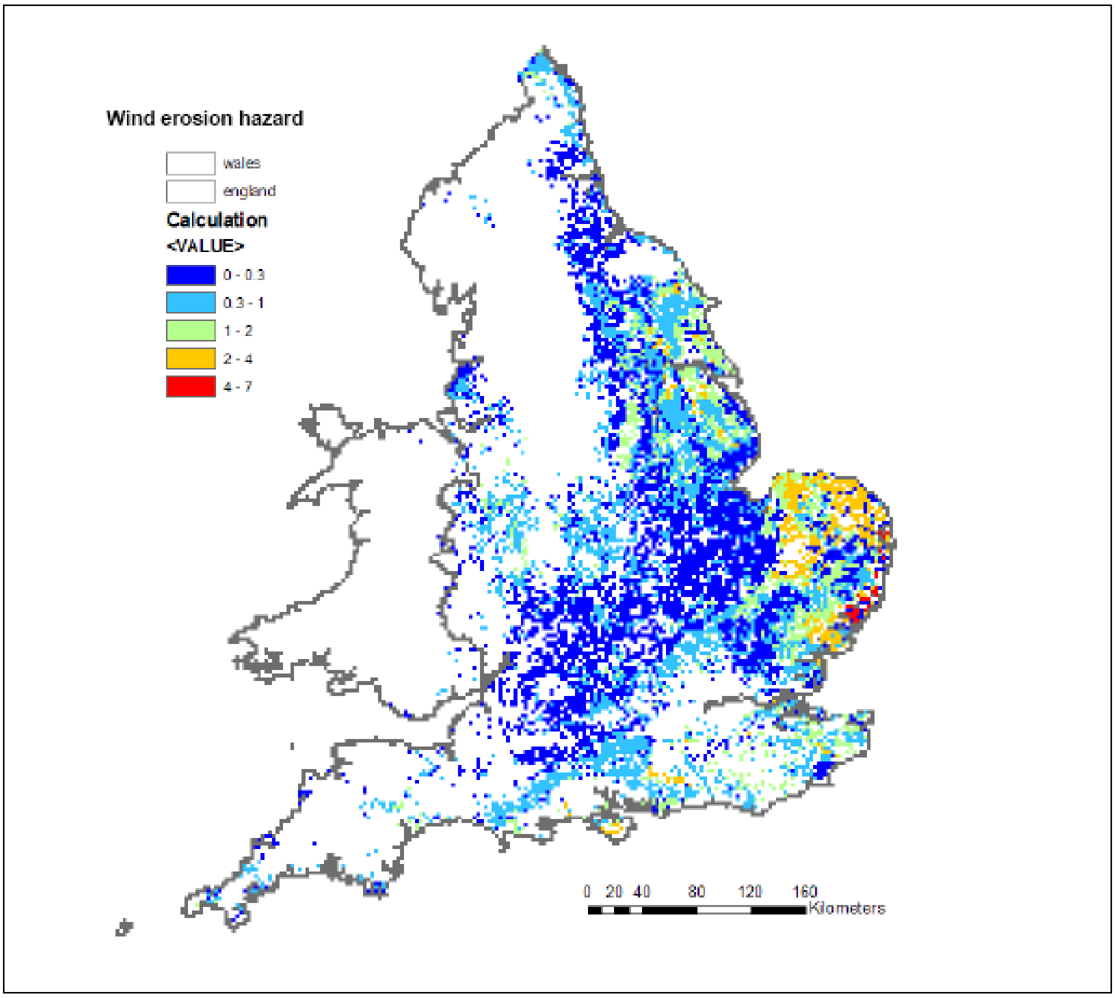

Figure 6: Annual wind erosion hazard for mineral soils (SOM<5%) derived by summation of monthly wind erosion potential based on the RWEQ Qmx parameter. The scale is a quantitative relative scale. Source data: UKCIP 1961-1990 scenario (simulated by HadRM3 with SRES A2 Medium –High emissions scenario); MetOffice 5 km gridded data; and Digital Soil Information from NSRI: NATMAP, SOILSERIES and HORIZON © Cranfield University (NSRI) 2006. (Taken from Quine *et al*., 2006)

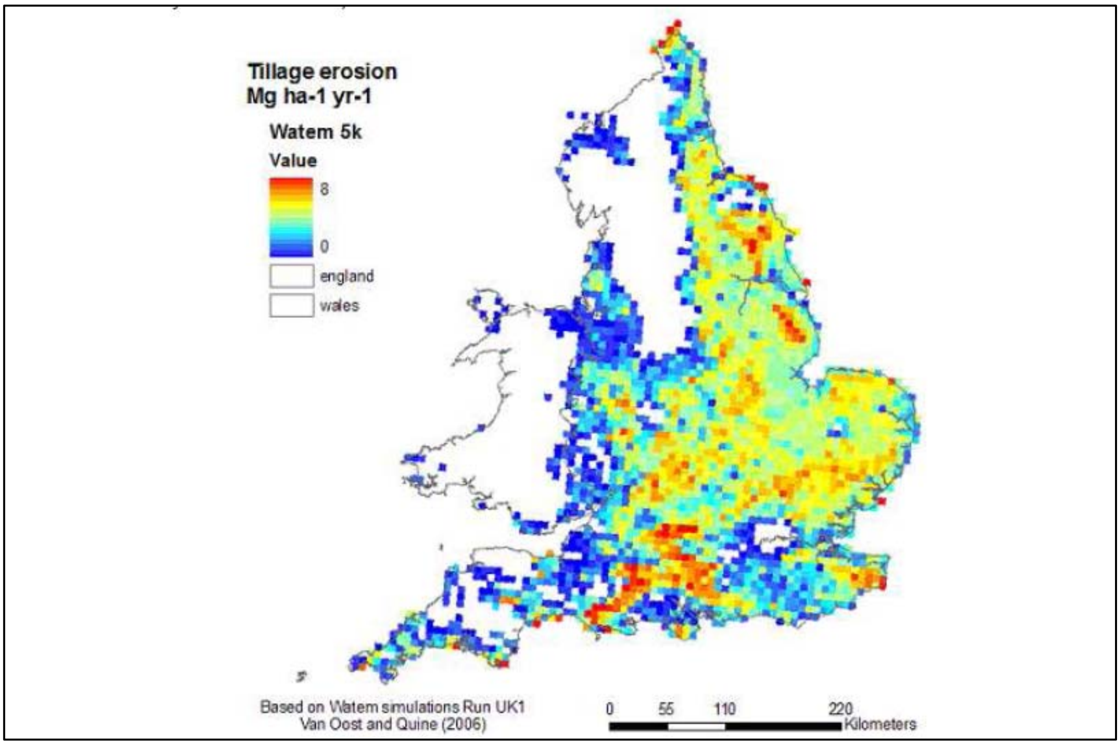

Figure 7: Simulated tillage erosion rates aggregated at 5km, derived using the WATEM model, assuming a tillage transport coefficient of 600 kg m^{-1} yr^{-1}. Curvature is derived from SRTM 90m topography and is corrected for underestimation based on comparison with high resolution data for 3 test sites in the UK. RRMSE of map is c. 22%. Based on Van Oost and Quine (2006). CORINE land over 200 (CLC2000) 100m- version 8/2005 version 2 © EEA, Copenhagen, 2005. Land-form PROFILER-contours and Digital Terrain Mapping © Crown Copyright/database right 2006. An Ordnance Survey (data centre) supplied service, Hole-filled seamless SRTM data v1, 2004. International Centre for Tropical Agriculture (CIAT).

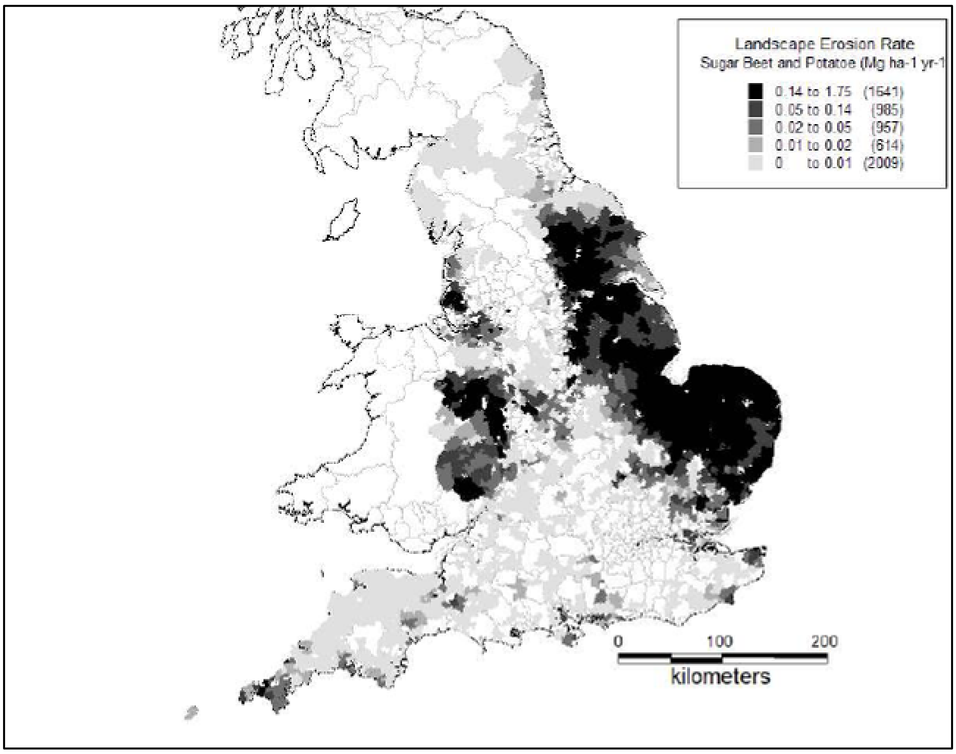

Figure 8: Simulated landscape scale rates of soil erosion with sugar beet and potato harvest. Rainfall data from UKCIP 1961-1990 scenario (simulated by HadRM3 with SRES A2 Medium-High emissions scenario). Sugar beet distribution data: ©:© Crown Copyright, 2004. Defra, Foss House, Kings Pool, 1-2 Peasholme Green, York YO1 7PX.

Comparison between erosion forms (from Owens et al., 2006a; Table 2)
The likely range of annual soil loss rates may be similar for all forms of erosion. There will, however, clearly be temporal and spatial variations in the relative magnitude and extent of the different processes, with arable land being susceptible to all forms of erosion, and uncultivated land only at risk of water and, to some extent (i.e. exposed sandy and peaty soils), wind erosion.

Table 2: Comparison of the magnitude of soil loss for different erosion processes in England and Wales.

	Wind	**Tillage**	**Co-extraction with root crops and farm machinery**	**Water**
Typical erosion rate range (Mg ha^{-1} $year^{-1}$)	0.1 – 2.0	0.1 – 10.0	0.1 – 5.0	0.1 – 15.0
Land use affected	Arable, upland, some pasture	Arable	Arable	Arable, pasture, upland
Exported off field	Yes	No	Yes	Yes

Climate change predictions and significance for soil erosion
Recent climate change predictions suggest that the UK is likely to experience hotter drier summers, warmer wetter winters and an increased frequency of extreme weather conditions (e.g. heat waves, dry spells and more intensive rainfall events (Defra, 2009a)). Climate change is also causing changes to the intensity, amount, frequency and type of rainfall, with an increasing trend for 'heavy' (greater than 10 mm d^{-1}) and 'extreme' (> 95^{th} quartile) rainfall events (Simmons and Rickson, 2008). The Hadley Centre for Climate Prediction and Research (HCCPR) in the UK reported that over the last 40 year some parts of the UK have seen a two-fold increase in the magnitude of extreme rainfall events. In the future, the extremes of heavy precipitation are very likely to increase in both magnitude and frequency. However, the frequency of localised summer storms is difficult to predict at present.

Predicted changes in climate are likely to have a range of affects on soil erosion rates in England and Wales. Increasing frequency of extreme rainfall events will increase the risk of soil erosion by water, as erosivity increases. The potential for soil erosion will also increase as rainfall intensities increase because rainfall intensity and erosivity are linked. Rainfall intensity affects drop size distribution of a rainstorm event with median raindrop size increasing with intensity up to 76 mm hr^{-1} (Simmons and Rickson, 2008). The size of the raindrop affects the velocity with which it falls and therefore affects the kinetic energy of the raindrop to detach soil material (see above). Hence, the more intensive the storm, the greater the erosivity of the rainfall event and the greater the potential for erosion. Short duration, high intensity rainfall events may become the dominant mechanism of soil erosion in the future.

Wetter soils are more likely to promote runoff and increase the risk of erosion by overland flow. Greater wind speeds driven by higher atmospheric temperatures, combined with drier, more friable, soils in summer months will increase the potential for wind erosion. Increasing temperatures will also affect vegetation. Some natural vegetation may be lost which, if not replaced, will expose soils to wind and rainfall related erosion. However, it is also possible that higher temperatures will promote more vigorous grow (if not limited by other factors such as water availability), which would offer greater protection from wind and rainfall. Agricultural crop production may also have to change and adapt to warmer, more drought-prone conditions which may require different mitigation measures to reduce soil loss than present day crop production scenarios. Warmer winters may change the temporal patterns of crop production by extending growing periods, but the risk of increased soil degradation may rise because higher predicted winter precipitation rates will increase risk of working the land when wet, thus increasing the risk of loss of soil and soil structure through compaction and smearing. Later harvest may also increase the risk of loss of soil co-extracted on root vegetables and farm equipment if the soil moisture is high.

Changing temperature and rainfall regimes may also affect cropping patterns, in terms of varieties or even introduction of new crops. These crops may have more or less ability to control the processes of erosion through interception of rainfall, runoff and air flow.

The impacts of climate change on soil processes, functions and its relevance to England and Wales are further discussed in Sub Project D.

The impacts of soil erosion

Soil erosion has both ‘on-site’ (where the erosion process takes place) and ‘off-site’ (the downslope/downstream destination(s), either temporary or permanent, of the eroded material) impacts (Table 3; Boardman *et al*., 2009). Previously soil has been managed to increase crop production by intensification of farming practices enabled by the availability of inorganic fertiliser that have masked the impact that such intensification has had on soil degradation. It is now recognised that such practices are not sustainable in the long term. In order to determine how sustainability may be threatened or achieved it is important to identify the costs and benefits of soil erosion and its mitigation from the perspective of both on-site and off-site impacts.

Table 3: On-site and off-site impacts of soil erosion from agricultural fields.

Erosion type	On-site impacts	Off-site impacts
Water	• Rills and gullies • Damage to crops • Removal of nutrients and top soil	• Muddy roads • Blocked drains • Damage to property • Pollution of receiving bodies
Wind	• Damage to crop • Loss of soil nutrients and top soil	• Public health issues • Pollution of receiving bodies
Tillage	• Soil redistribution down slope • Redistribution of nutrients in a field • Loss of top soil	
Co-extraction on root vegetables	• Loss of soil through removal • Loss of nutrients through removal • Loss of top soil through removal	• Disposal of soil washed from vegetables
Co-extraction on farm machinery	• Loss of soil through removal • Loss of nutrients through removal • Loss of top soil through removal	• Mud on roads • Pollution of receiving bodies

On-site impacts of soil erosion (Table 4)
On-site impacts of soil erosion affect the ability of the soil to provide essential services by reducing the soils capacity to perform environmental, economic, social and cultural functions, as identified in the Soil Strategy for England (Defra, 2009).

Table 4: On-site impacts of soil erosion on agricultural land.

Service / Function	**Impact**
Environmental	• Loss of carbon store • Loss of soil water storage • Loss of biodiversity (e.g. microbiological communities)
Economic	• Loss of a resource • Loss of nutrients • Increased use of inorganic fertiliser • Potential need for irrigation • Reduction in yields • Damage to crops
Society	• Loss of ecological service
Cultural	• Exposure of historic artefacts • Change to valued landscape

Off-site impacts of soil erosion (Table 5)
Off-site impacts of soil erosion also have consequences for environmental, economic, social and cultural services. These impacts are felt by individuals (consumer and non-consumer), Local Authorities, businesses or society. Table 5 outlines the off-site impacts of soil erosion.

Table 5: Off-site impacts of soil erosion on agricultural land

Service / function	Impact
Environmental	• Contamination of water courses by sediment and associated contaminants • Contamination of low input soil habitats with sediment borne nutrients • Loss of biodiversity • Loss of water storage, increasing risk of downstream flooding
Economic	• Blockage of drains by eroded sediment, so increasing risk of flooding • Siltation of navigation channels • Closure of roads • Increased accident risk • Increased need for water treatment • Loss of recreational income • Loss of amenity value • Damage to property • Siltation of reservoirs • Increased flood risk
Society	• Health problems associated with water pollution and flooding • Loss of ecological service
Cultural	• Loss of amenity value • Loss of landscape aesthetic

The on- and off-site impacts (and associated costs) of erosion are further discussed in Section C3.

Mitigation measures

In the context of this report the term 'mitigation measures' is used to describe actions that can be taken to reduce soil erosion. The severity of erosion depends on the availability of particles to be transported and the ability of the eroding agents to transport it. Erosion can therefore be described as detachment-limited and/or transport-limited (Morgan, 2005). The erosion processes driven by water, wind, tillage and co-extracted with root vegetables and machinery, have been outlined above. In order to reduce the impact of these erosive processes, steps need to be taken to reduce the availability of transportable material, increase frictional resistance to reduce erosive force, prevent the concentration of flow and reduce any mechanical disturbance. The most appropriate actions that can be taken to reduce or mitigate soil erosion by the erosive agents are described below.

Factors that limit erosion by rainsplash

Soils are most vulnerable to rainsplash erosion when they have limited surface cover. In an agricultural system this can occur due to the timing of sowing, harvesting and fallow periods. Row crop production can leave large areas of a field unprotected. Overgrazing can denude the soil of plant cover. Therefore, the best protection from rainsplash erosion is often to ensure that a plant canopy is present at the most vulnerable time. If this is not possible in the current management system, then alternative methods that will shield the soil surface must be applied, such as applying mulches or leaving residual crop material which protect the soil surface from the direct impact of raindrops. This cover will also trap mobilised soil particles.

Factors that limit erosion by overland flow

Erosion by overland flow can be limited by protecting the soil surface so that soil particle detachment is limited. This can be achieved by providing protective cover in the form of crop canopy mulches, crop residue or geotextiles (see C.2) at times of the year when rainfall rates are at their most erosive. Such surface protection also increases the surface roughness of a field which increases the frictional resistance of overland flow and reduces its erosive force. Increasing surface roughness can therefore limit the amount of particles entrained and transported and it can also act to reduce the transport capability of flow and promote deposition (e.g. vegetated buffer strips, see C.2).

The way in which soil is managed is also an important factor when it comes to reducing the erosivity of overland flow. In particular practices that prevent soil compaction (e.g. restricting access of vehicles and animals on wet fields promoting infiltration with rough surfaces that enhance surface storage and effective drainage)) will help limit the generation of overland flow. Practices that prevent the convergence of flow to a single point e.g. contour ploughing can also be effective in reducing flow erosivity.

Factors that limit erosion by wind
The impact of soil erosion by wind can be limited in a similar way to that caused by water. Protection can be provided through vegetation cover, mulches, crop residuals or geotextiles which also act to increase surface roughness and frictional resistance. Wind fetch also plays a critical role in rate of erosion, therefore, by reducing or breaking up the fetch, wind velocities are reduced so the transport capacity of the air flow can be controlled.

Factors that limit erosion by tillage
Most conventional tillage methods impose a risk of translocation of soil particles in a downslope direction. However, decreasing tillage depth and ploughing along the contour lines can reduce tillage erosion rates. Translocation of soil also reduces with slope steepness. Reduced tillage (including conservation tillage) techniques can limit translocation of soil particles due to less disturbance of the soil during cultivations. Tillage erosion only redistributes soil particles within the confines of field boundaries. Therefore, as long as field boundaries are protected, it is unlikely that tillage erosion will result in a net export of soil from the field.

Factors that limit erosion by co-extraction with vegetables and farm machinery
Studies of land trafficability take into account soil type and wetness class in determining when machinery can be put on land without causing damage. See SSLRC work, Owens *et al.* (2006b). The shape of the crop can affect the amount of co-extracted soil material that is harvested with smoother surfaces helping to reduce the amount of soil lost. Improved harvesting techniques can reduce the soil take with crop. Use of better machinery, avoiding heavier soils (e.g. clay soils) and high soil moisture content at time of harvest can help to reduce the amount of soil co-extracted with vegetable. Soil harvested with root crops such as sugar beet is collected during processing and sold back as 'topsoil' for agricultural land improvement (SDC report, 2003). Approximately 50% of co-extracted soil is then returned to agricultural land.

C.2. Current and potential mitigation measures used to control erosion in England and Wales.

"Soil erosion occurs with sufficient frequency and severity on arable land in the UK to warrant erosion control measures" (Morgan, 1992). In the following section, current soil erosion mitigation measures used in England and Wales are reviewed and their suitability for future requirements is assessed. Other mitigation measures, not currently used in the UK, but are found internationally are also reviewed and assessed regarding their suitability to present or future needs in England and Wales. The information is a synthesis of that reported in the public domain (as cited in the reference list). A number of methods have been developed to prevent or reduce soil erosion caused by water, wind, tillage or co-extraction of soil on root vegetables (Owens *et al*., 2006). Rather than explicitly controlling soil erosion *per se*, some measures are designed to control diffuse pollution, referring to off-site losses of soils and nutrients, especially P and N (Table 6). Following the approach of Cuttle *et al*. (2007), erosion mitigation methods are summarised (Table 9) and discussed in terms of:

- **Description:** A description of the actions to be taken to implement the method.
- **Rationale:** The broad reason for adopting the method as a means of reducing erosion.
- **Mechanism of action:** A more detailed description of the erosion processes involved and how the method may achieve a reduction in erosion.
- **Potential for applying the method:** An assessment of the farming systems, regions, soils and crops to which the method is most applicable.
- **Practicability:** An assessment of how easy the method is to adopt, how it may impact on other farming practices, problems with maximising effectiveness and possible resistance to uptake.

Mitigation methods fall under three main sub-headings: agronomic, field engineering and soil management.

Agronomic mitigation measures

Agronomic measures of erosion control are defined as vegetation and/or simulated vegetation (e.g. geotextiles, erosion control blankets) used to reduce erosion rates by changing the energy of rainfall, runoff and wind through canopy, stem and root effects. As erosion risk is greatest on arable land (due to exposure of bare soil, low canopy cover, row cropping, soil disturbance during cultivations, presence of wheelings and tramlines, etc.), emphasis is placed on the measures used on cultivated land rather than pasture / grassland.

Measures used specifically for erosion control in England and Wales

a. Land use change

Soil erosion is a natural process therefore it would be inappropriate and potentially damaging to the wider environment to prevent all erosion. Hence, under appropriate land use some erosion would be expected to occur at a tolerable rate (Verheijen et al., 2009). However, unacceptable levels of soil erosion have been interpreted as a consequence of inappropriate land use, i.e. when land is 'used' beyond its capability (Figure 9). An example would be the cultivation of steep slopes or the removal of natural surface cover from friable, peat soils, both of which can result in soil erosion. As well as erosion by water, experimental studies have shown that slope gradient has a dominant influence on soil translocation during tillage operations as it is a gravity-driven process (Lindstrom *et al*., 1992; Lobb *et al*., 1995; Van Muysen *et al*., 1999). The concept of 'land capability' implies that all land resources have an inherent ability to support any given land use sustainably (i.e. without any degradation of that land resource).

Figure 9: Soil erosion leading to gully formation.

According to Klingbiel and Montgomery (1961), land capability is primarily based on spatial units defined by the physical characteristics of:

$$\text{Land capability} = \frac{\text{Soil texture / Permeability / Soil depth}}{\text{Slope gradient / Erosion status}}$$

Units with high capability are able to sustain/support any land use; areas with low capability are limited in the land use they can sustain/support. Matching appropriate crops to land capability is mentioned in the Defra/EA Protecting our Water, Air and Soils - Codes of Good Agricultural Practice, (Defra/EA, 2009).

Land uses with a high incidence of soil erosion such as arable (especially row crops), turf production or outdoor pig production can be reverted to land uses with low erosion risk, such as permanent grass, perennial crops such as miscanthus or woodland (Defra, 2005). Moving from an arable to a non-arable agricultural system will also reduce the incidence of tillage erosion as soils are no longer tilled, as well as preventing any soil loss through co-extraction on root crops.

Choice of crop variety (e.g. early-maturing maize varieties) may allow more flexibility in maximising crop cover and minimising erosion risk. Defra/EA (2009) also advise against ploughing up permanent grass for arable production in places where the risk of erosion is high, such as on sandy, peaty or silty soils, on sloping sites, in high rainfall areas, where wind fetch, duration and velocity are significant or in river valleys that flood. Management of specific crops for erosion control are summarised in ‘Controlling soil erosion: a manual for the assessment and management of agricultural land at risk of water erosion in lowland England’ (Defra, 2005).

Table 6: Methods to control diffuse water pollution from agriculture (from Cuttle *et al*., 2007). Measures targeted specifically at soil erosion control are underlined.

Category	No.	Method
Land use	1	Convert arable land to extensive grassland
Soil management	2	Establish cover crops in the autumn
	3	Cultivate land for crop establishment in spring rather than autumn
	4	Adopt minimal cultivation systems
	5	Cultivate compacted tillage soils
	6	Cultivate and drill across the slope
	7	Leave autumn seedbeds rough
	8	Avoid tramlines over winter
	9	Establish in-field grass buffer strips
	10	Loosen compacted soil layers in grassland fields
	11	Maintain and enhance soil organic matter levels
	12	Allow field drainage systems to deteriorate
Livestock management	13	Reduce overall stocking rates on livestock farms
	14	Reduce the length of the grazing day or grazing season
	15	Reduce field stocking rates when soils are wet
	16	Move feed and water troughs at regular intervals
	17	Reduce dietary N and P intakes
	18	Adopt phase feeding of livestock
Fertiliser management	19	Use a fertiliser recommendation system
	20	Integrate fertiliser and manure nutrient supply
	21	Reduce fertiliser application rates
	22	Do not apply P fertilisers to high P index soils
	23	Do not apply fertiliser to high-risk areas
	24	Avoid spreading fertiliser to fields at high-risk times
Manure management	25	Increase the capacity of farm manure (slurry) stores
	26	Minimise the volume of dirty water produced
	27	Adopt batch storage of slurry
	28	Adopt batch storage of solid manure
	29	Compost solid manure
	30	Change from slurry to a solid manure handling system
	31	Site solid manure heaps away from watercourses and field drains
	32	Site solid manure heaps on concrete and collect the effluent
	33	Do not apply manure to high-risk areas
	34	Do not spread farmyard manure to fields at high-risk times
	35	Do not spread slurry or poultry manure to fields at high-risk times
	36	Incorporate manure into the soil
	37	Transport manure to neighbouring farms
	38	Incinerate poultry litter
Farm infrastructure	39	Fence off rivers and streams from livestock
	40	Construct bridges for livestock crossing rivers and streams
	41	Re-site gateways away from high-risk areas
	42	Establish new hedges
	43	Establish riparian buffer strips
	44	Establish and maintain artificial (constructed) wetlands

b. Cover / nurse / catch cropping

Maintaining soil cover at all times is fundamental for erosion control, especially as erosive rainstorms or wind speeds can occur at any time during the year in England and Wales. To minimise run-off and erosion between main crops (especially before spring sown crops), it is good agricultural practice to establish a temporary cover or catch crop (Figure 10) to provide green cover over winter (Defra/EA, 2009; Morgan, 1992). Complying with this will ensure current cross compliance requirements are met. As well as erosion control, this practice results in uptake of N by the cover crop which may reduce nitrate leaching and contamination of ground water.

Figure 10: Cover crop in a field.

Even during main crop cultivation, farmers 'under sow' high risk crops such as maize (Inman, 2006) whilst the main crop canopy establishes sufficient cover to protect the soil from erosion. For perennial row crops (e.g. hops, vines), where erosion risk is high (due to concentration of overland flow between the rows, especially in up/down slope orientations), natural regeneration of vegetation or grass establishment is practiced to prevent erosion.

Plastic covers (used increasingly in horticultural systems) increase rainfall/runoff ratios, generating large volumes of runoff, with associated soil erosion. Wherever possible, surface cover should be placed to intercept the runoff. Grass and surface applied natural geotextiles have been used to minimise damage from runoff from polytunnels (Simmons, pers. comm.)

c. Mulching

Defra/EA (2009) recommends that crop residues / stubble should be left in the field post harvest to minimise run-off and erosion over winter before crops are sown in the spring (Figure 11). The effectiveness of this practice is discussed in Quinton and Catt (2004; Table 7), Cooper (2007) and Deasy *et al*. (2008). Mulching can also be used to control wind velocities close to the ground surface, so reducing erosion and protecting establishing crops from the scouring effect of sediment transported by air currents. The crop residue is either left on the soil surface or can be slot planted in rows. This technique has been used in the East Anglian Fens (e.g. trialled at the Arthur Rickwood Experimental Station) in high value crops such as carrots and onions.

Figure 11: straw mulching in a field.

Crop residues have also been used to control tramline erosion (Deasy *et al*., 2008; Tatham, 1989). Residues of late harvested crops, such as root crops, can be left undisturbed until the following spring, unless the soil is compacted and there is a risk of run-off or soil erosion

.

Table 7: Effect of retaining crop residues, tillage type and cultivation direction on soil loss (Quinton & Catt, 2004).

Treatment[b]	Event soil loss (kg ha^{-1})	No. of plot events	Event runoff (mm)	No. of plot events
U	262 ± 566	252	$1.32 \pm 1.35_{cc}$	248
A	148 ± 774	252	$0.82 \pm 1.26_{cc}$	248
M	156 ± 437	252	0.99 ± 1.31	248
S	253 ± 855	252	1.15 ± 1.35	248
UM	$245 \pm 571_{a}$	126	$1.41 \pm 1.50_{ddg}$	124
US	$278 \pm 563_{b}$	126	$.24 \pm 1.19_{ee}$	124
AM	$67 \pm 202_{ab}$	126	$0.58 \pm 0.92_{ddeeff}$	124
AS	229 ± 1072	126	$1.07 \pm 1.49_{ffg}$	124

[a]Data marked with one and two letters the same are significantly different at P<0.05 and P<0.01, respectively.
[b]Treatment key: U, cultivations up-and –downslope; A, cultivations across-slope; M, minimal tillage with crop residues retained; S, standard tillage with residues removed.

d. Geotextiles

Geotextiles are "permeable textiles used in conjunction with soil, foundation, rock, earth or any geotechnical engineering related material, as an integral part of a man made project" (John, 1987). Whilst they are used in numerous applications (filtration, separation, slope stabilization and drainage) in agriculture they are mainly used for erosion control and vegetation management. Geotextiles mimic vegetation in controlling erosion: the canopy, stem and root components of vegetation are all evident in erosion control geotextiles. These products can be classed into natural and synthetic products, and come in the form of 2d and 3d mats, sheets, grids or webs (see for example Figure 12). Although of limited use in agriculture at present, these products have been used to protect establishing vegetation from cold temperatures and wind erosion, and to line swales and waterways carrying erosive runoff from fields prone to high rates of erosion, such as asparagus production on erodible soils near Ross on Wye (Simmons, *pers. comm.*).

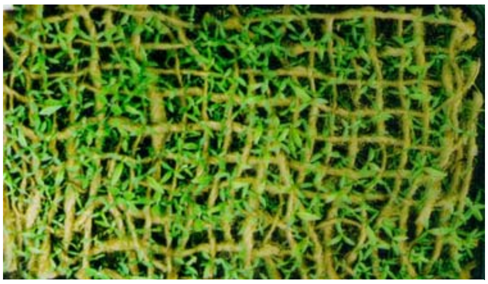

Figure 12: Seeded geotextile material.

Many researchers have tested the effectiveness of different geotextiles in controlling erosion (e.g. Armstrong and Wall, 1992; Cancelli et al., 1990; Fifield and Malnor, 1990; Godfrey and McFalls, 1992; Rickson, 2000a; 2000b). This extensive work has shown that geotextile performance is highly variable, depending on the product used. Even for the same product performance is affected by the erosion processes operating on the site, rainfall intensity, soil type and slope. This makes it very difficult to prescribe any one product as being the "best" available, as this depends on site specific conditions.

e. Timeliness of operations

Erosion risk is greatest when the soil is bare (or with little protective cover) and rainfall (intensity and volume) is highest. Timing farming operations so that these two conditions do not correspond can reduce erosion risk considerably. A significant underlying cause of soil erosion is inappropriate timing of agricultural operations such as ploughing, cultivating and harvesting in wet conditions.

Inman (2006) reports that modern farming systems have increasingly favoured the use of winter sown cereal varieties, due to the high yields these produce. The problem with winter cereals is that unless they are sown early enough in the autumn, there is not time to establish

Figure 13: Establishment of crop prior to intensive rainfall period.

sufficient crop cover to protect the soil from erosion by winter rainfall events (Morgan, 1992). A crop rotation involving spring cereals will usually result in fields being protected by crop stubbles over the autumn and winter months (Figure 13). The problem with spring cereals, from the farmers' perspective, is that they tend to produce lower profit margins and are, therefore, less attractive than the winter varieties.

Good agricultural practice advises to sow autumn-sown crops as early as possible to reduce the risk of capping on susceptible soils, run-off and soil erosion. The land should be cultivated as close as possible to the sowing date of the next crop. For example, Defra/EA (2009) recommend that to minimise the duration of a 'high erosion risk window', farmers should sow a crop within 10 days of having prepared the seedbed.

Autumn harvesting (e.g. of maize, grass turves) often takes place in wet conditions which leads to problems with soil compaction and an associated increase in run-off and soil mobilisation (Inman, 2006). Once maize is harvested, fields of bare soil are often left exposed to autumn and winter rainfall events which can result in extremely high rates of erosion.

f. Field buffer strips

Buffer strips, usually of permanent vegetation (grass, shrubs, perennial crops such as miscanthus or trees) can be located in-field (Figure 14) or at the field edge (Figure 15). Usually used on arable land, they control erosion by breaking up slopes length, so ensuring runoff does not reach critical velocities or volumes where soil detachment and transport take place. They control diffuse pollution by intercepting runoff, reducing its velocity and hence transport capacity so that any sediment (and associated contaminants) are deposited within or just upslope of the buffer strip. Although used primarily to enhance biodiversity, beetle banks can perform the same erosion control function as buffer strips, when oriented across slope.

The effectiveness of buffer strips in the control of sediment and phosphorus from agricultural land is reported in Wood et al. (2007). A decision support system was devised for the design and selection of buffer features (Table 8).

Figure 14: In field buffer strip.

Table 8: A simplified buffer selection table (from Wood et al., 2007). The values (m) in the table represent the required buffer width for preventing less than 2 t/ha of soil from leaving the field each year. Table is based on a 3° field slope (N.B. trapping efficiency is potentially reduced by only 5-6 % for slopes up to 12°).

FIELD CLASSIFICATION		PERCENTAGE COVER (%)				
Class	Soil[a]	<20%	20-40%	40-60%	60-80%[b]	80-100%
HEAVY	C	137 m	63 m	47 m	30 m	24 m
HEAVY	ZC	99 m	53 m	28 m	20 m	14 m
MEDIUM	ZCL	67 m	29 m	18 m	12 m	8 m
MEDIUM	SCL	51 m	24 m	14 m	10 m	6 m
LIGHT	ZL	8 m	4 m	2 m	2 m	2 m
LIGHT	SL	4 m	2 m	2 m	2 m	2 m

[a] Abbreviations: C, clay; ZC, silty clay; ZCL, silty clay loam; SCL, sandy clay loam; ZL, silty loam; SL, sandy loam.
[b] Most common coverage observed by Wood et al., 2007

Good agricultural practice (Defra/EA, 2009) states that where it is not possible to plant row crops such as potatoes and vegetables across the slope, long slopes should be divided by grass strips or unplanted

Figure 15: Edge of field buffer strip.

cultivated headlands within the field. In the Entry Level Scheme (2009 revision) 12-24m wide buffer strips are recommended on cultivated land to protect any adjacent watercourses. Deasy *et al*. ((2008) and Morgan ((1992) report on the effectiveness of grass buffer strips in controlling soil and water losses in England (See Table 12).

It should be noted that buffer strips at the edges of field do not control soil erosion *per se*. Their function is to intercept runoff and any associated sediment before it leaves the field. Good soil management in the rest of the field is needed to control in initial phase of erosion (detachment of soil) rather than controlling the transport of eroded sediment.

g. High density planting

To ensure maximum cover of the soil surface (as well as high yields), farmers increase seeding rates, thereby increasing crop biomass and percentage surface cover to reduce exposure of soil to erosive agents.

h. Crop rotation

Crop rotation, which is the practice of growing different crops on the same parcel of land in sequence, can reduce soil loss by providing a cover crop at vulnerable times of the year. However, intensive rotations can degrade soils – physically, biologically and chemically. In turn, this makes them prone to degradation processes, including erosion by water. Cultivation, or the preparation of the land to grow crops, can lead to loss of both soil structure and organic matter which increase a soils susceptibility to erosion (erodibility). Rotations can be used to mitigate these effects: Ley grasses or green manures can be introduced into arable systems. The build up of organic matter and nutrients increases fertility for enhanced yields and carbon stores for soil biota. This system also allows high erosion risk crops (e.g. potatoes, forage maize and sugar beet) to be compensated with low erosion risk (e.g. cereals, ley grasses, clover) in the rotation.

i. Shelterbelts

Planting rows of trees or hedgerows and wind breaks around fields provides shelter, which protects soil and crops grown on the sheltered side and traps air- borne soil particles. Hedgerows and belts of trees will provide protection downwind for up to 20 times their height. To be most effective they should:

- Permit 30-50% of the wind to pass through.
- Be evenly permeable from top to bottom.
- Run at right angles to the damaging winds.

j. In-field shelter

Using the same principles as large field boundary shelterbelts (see above), in-field shelter reduces wind velocities close to the ground surface, so reducing soil particle detachment, entrainment and transport. This technique is primarily used to control abrasion of young establishing plants by eroded, wind blown soil particles, which can lead to damage to crops and ultimately impacts on crop quality and yield. In-field shelter uses crop residues (e.g. cut straw), slot-planted into rows by specialist machinery such as crimping discs. The strips are oriented perpendicular to the predominant, erosive winds. The main crop is then drilled between the residue rows. There is no agronomic competition between the main crop and planted straw strips. Live strips of fast growing cover crops such as barley are also used. These are drilled in lines perpendicular to the erosive winds, about a month before the main crop is drilled. Once the main crop has established successfully, the planted strips are killed using a selective herbicide. The senescing / dead biomass is still able to impact roughness to air flow, but without competing with the main crop for limited resources such as water on drought-prone peat soils. This technique, demonstrated on the Arthur Rickwood Experimental Station, Chatteris, East Anglia, in the 1980s, has been used successfully in high value crops (e.g. onions, carrots) on peat soils in the Fens.

k. Avoid over-grazing on pasture / grassland

'Overgraze' means grazing land with so many livestock that the growth, quality or diversity of natural or semi-natural vegetation is adversely affected (Defra, 2009, Guide to Cross Compliance). Over stocking of animals on pasture land (i.e. exceeding the carrying capacity of

Figure 16: Poaching around feeding station.

the land) leads to removal of vegetation through grazing and trampling (Figure 16), so exposing soil to potentially erosive rainfall and runoff.

Rotations are used to avoid overgrazing the same piece of land over time. Animals can be confined to sheds, so 'zero' grazing can be practiced. Reducing the head of cattle / sheep has been EU policy, whereby stocking densities have been reduced by switching livestock production subsidies from a 'per head' basis (i.e. number of animals owned) to an area basis in an attempt to reduce the incentive for farmers to concentrate too many animals into too small an area (McHugh *et al.,* 2007). The effectiveness of adjusting stocking rates is shown in Table 12. At the local scale, farmers are encouraged to control stocking rates to avoid serious poaching (removal of vegetation, exposure of soil and soil compaction), especially around supplementary feeders. At such critical points, paving / fencing is recommended. The latter will help vegetation to re-establish and avoids further soil degradation. Fencing off river banks to preclude livestock from grazing and eroding banks is a technique that has been used to good effect.

Additional measures used internationally for erosion control

a) Strip cropping
   i) Field strip cropping (normal to slope)
   ii) Contour strip cropping (follow contours)
   iii) Buffer strip cropping (follow contours, but buffers used on locally steep land in-field)

b) Agroforestry (alley cropping; Figure 17) is used to control soil erosion by reducing slope length and improvement in soil properties, so increasing resistance against erosive forces of rainfall and runoff.

Figure 17: Alley cropping.

Field Engineering Mitigation Measures
The physical modification of land properties (principally slope length and gradient) can reduce the risk of erosion.

Measures used specifically for control of erosion in England and Wales

Figure 18: Potential eroded channel ('thalweg') lined with jute geotextile.

a. Lined waterways or swales

Removing surface and subsurface flow efficiently, but at velocities that do not cause soil detachment and subsequent transport (erosion) reduces erosion risk. In places, overland flow may concentrate especially in valley features ('thalwegs') during storm events, so increasing the risk of rill or even gully erosion in those locations. Combining agronomic control of erosion with designed field engineering features, lined waterways or swales can mitigate erosion on high risk fields (see Figure 18), where steep slopes and/or concentrated surface overland flow may occur (Morgan, 1992). Lined waterways or swales with permanent vegetation (usually grasses) are used to increase resistance against the shearing forces of overland flow. For example, in asparagus fields in Herefordshire, natural depressions have been taken out of production to form a down slope path of preferential flow. As the grass sward establishes in the waterway, a geotextile has been used to protect the bare soil in the short term from direct raindrop impact and any flow generation (Simmons, pers. comm.).

b. Earth banks / physical barriers

Earth banks, other physical barriers or ponding sites may be used to check the flow of water to reduce the off-site impacts of erosion. Their effectiveness is shown in Table 12. Although this is not strictly an erosion control measure (more a sediment control device), breaking up slope lengths with these structures will reduce the likelihood of overland flow velocity becoming critically erosive. These features should be carefully designed and installed to achieve the required effect. Consent is needed from the Environment Agency if, for example, they are within 9 metres of a main river, or if the material used to make them is considered a 'waste' – this could include soil or spoil moved from another part of the holding.

On sloping farm tracks and tramlines, impoundments are recommended to trap runoff and eroded sediment. According to Defra/EN (2009) if run-off is channelled along farm tracks, cross drains should be constructed to reduce and interrupt any runoff that develops.

Tied ridges or dykes in furrow bottoms can be used to reduce runoff generation, decelerate runoff velocities and conserve water through enhanced infiltration. This technique has been used on light but stony soils in potato production.

c. Surface and subsurface drainage

In upland areas, blocking grips and surface drains can also reduce erosion but this must be done in consultation with the Environment Agency to ensure these practices work correctly and do not lead to more serious flooding downstream. Sub-soiling can improve infiltration, so reducing generation of surface runoff. Using a tine between rows with a single-leg subsoiler will remove compaction and prevent channelling of water. The effectiveness of drainage in controlling erosion is indicated in Table 12.

d. Irrigation

Irrigation is not used directly to control soil erosion in England and Wales, although soil moisture does affect the susceptibility of soil to wind erosion. Keeping the soil moist especially during periods of low canopy cover will reduce soil loss by wind blow. Conversely, over-application of irrigation water can lead to surface sealing and capping, especially if the droplet size is large (as affected by the water pressure on discharge) and application rates greater than soil infiltration rates will generate potentially erosive runoff, especially in tramlines and natural depressions.

Additional measures used internationally for soil erosion control on agricultural land

a. Terraces

- Fanya Juu

A ditch dug (usually by hand) on the contour, with the spoil from the ditch thrown uphill. Ditches are usually spaced at 1m vertical interval. This means ditches are closer together on steeper slopes; further apart on gentler slopes, so reflecting the likely risk of erosion.

- Channel terraces

These terraces are recommended on slopes with gradients up to 7^{o} (United States Department of Agriculture recommendations). They consist of an excavated ditch with bund placed downslope. The dimensions of the ditch and bund (cut and fill) are determined by the amount of runoff received from the catchment area above. Channel terraces can be constructed on the contour or at a slight gradient across slope – usually at 1:250.

- Bench terraces

Where slope gradients exceed 7^{o}, the spacing of channel terraces becomes uneconomic. On these steeper slopes, bench terraces (Figure 19) can be constructed, involving considerable land engineering. Level or very gently sloping benches are created from cut and fill procedures which result in a level bench on which cultivation takes place and an over-steepened riser.

Figure 19: Bench terraces.

b. Stone strips are oriented across slope to reduce slope length and intercept runoff, reduce velocity and encourage deposition of any sediment transported in the flow. In principle they act in the same way as vegetative, in-field buffer strips in controlling runoff and soil erosion (see above).

Soil Management Mitigation Measures

Soil management involves the manipulation of soil properties through the use of machinery and/or cultivation techniques in order to increase soil resistance to the destabilising forces (namely detachment and transport) of erosive agents – here rainfall and runoff. The type and timing of cultivations can be designed to minimise the time the soil is left in its most vulnerable condition (Defra, 2005).

Figure 20: Conventional versus conservation tillage.

Measures used specifically for control of erosion in England and Wales

a. Reduced / minimum tillage

Reducing the depth and number of cultivation practices helps maintain soil structure and reduces soil susceptibility to erosion (Table 11; Figure 20). Practices include direct drilling, minimum tillage and reduced tillage. Non-inversion of the soil surfaces also helps keep protective surface cover, soil structure, soil biota and organic matter intact. Poorly structured or low organic matter subsoils are less likely to be exposed through non-inversion tillage. A number of studies have evaluated the use of reduced tillage on runoff and soil losses (e.g. Quinton and Catt, 2004; Table 7, Deasy *et al*., 2008, Cooper, 2007).

According to Van Oost et al., (in press), tillage depth is the most important factor affecting tillage erosivity, which increases exponentially with tillage depth. Therefore reducing this can be considered as an effective soil conservation strategy. Tillage implement shape will also influence erosivity.

b. Contour / across slope cultivation

Operating across the slope can reduce the risk of run-off and erosion as long, up/down slope runs are avoided (Table 9; Table 11). This is only feasible on non-complex, gentle to moderate slopes. Harvesting across slope on steeper gradients can be difficult and even dangerous for the operator. Good agricultural practice suggests that where possible, drilling should be across the slope and any tramlines should be established in the same direction (Defra/NE, 2009). Tillage direction also has an important control on tillage erosivity (see Figure 3).

c. Tramline management

The MOPs (Mitigation Of Phosphorus and Sediment) project (PE0206; Deasy *et al*., 2008; Table 12) demonstrated that tramlines (Figure 21) can be a significant source of runoff, eroded soil and associated contaminants. It is recommended that wheelings (in row crops or bed systems) and tramlines (in combinable crops) should be cultivated (or 'disrupted') to loosen any compaction if it is causing run-off and erosion. To reduce the risk of run-off, tramlines should be established only after the winter, or if possible they should not be used until the spring. Pulling a tine along a compacted tramline can reduce run-off.

Figure 21: Tramlines.

d. Establish coarser seedbeds

A coarse seedbed will reduce the risk of the soil slumping or capping which can reduce emergence and lead to run-off and erosion. Land is left with a rough surface following operations such as ploughing, discing or tine cultivation (Figure 22). The Code of Good Agricultural Practice for farmers, growers and land managers (Defra/NE, 2009) suggests farmers should prepare as coarse a seed bed as possible, but that will still produce good germination and ensure the effectiveness of any pre-emergence herbicides. Where any harvesting takes place or if forage crops (e.g. kale, stubble turnips) are grazed, in winter or under wet conditions, a primary cultivation as soon as conditions are suitable will create a rough surface that will reduce the risk of run-off and erosion.

Figure 22: Tillage effects on seedbed preparation.

e. Increase soil organic matter

Soil organic matter is fundamental in maintaining soil resistance to erosion processes, as it improves soil stability and increases soil biotic processes which contribute to lower erodibility. Various methods are recommended to increase soil organic matter. Cover crops (see above), green manures or mulches of previous crop residues can be incorporated to increase soil organic matter, providing they do not contain much nitrogen, such as cereal straw. If carried out in the autumn, this will help to reduce the amount of nitrate leached and to maintain or increase soil organic matter. Bulky organic manures can also be added to soil to increase organic matter content, although restrictions apply in Nitrate Vulnerable Zones due to potentially excessive nutrient leaching.

Additional measures used internationally for erosion control

a. Zero tillage.

Zero tillage is a form of conservation tillage in which the soil is not disturbed by tilling. Seeds are planted directly into the soil using a specially modified seed drill that penetrates through plant residue from previous crops. Parts of the plant that are not removed at harvest are left on the field and form a surface coverage that protects the soil surface from erosion by water and wind. The plant residue also helps increase the carbon content of the soil. While the bulk density of soils under zero tillage are known to increase, soil structure is expected to be improved as natural processes have time to develop the structure which is not destroyed by subsequent tillage. Improvements to structure can help maintain a satisfactory drainage through the soil while enabling plant available water to be stored for longer periods. The method does however rely on careful management to prevent soil compaction e.g. appropriate crop rotation or restricted trafficking.

Table 9: Summary of soil erosion mitigation measures

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	Land use change (e.g. arable to grassland)	Less soil disturbance and bare soil exposure over time.	Permanent cover protects soil from rainfall, runoff and wind. Soil is not moved downslope by tillage practice. Soil not co-extracted with crops at harvest.	Low, due to economic losses and environmental limitations.	Farmers unlikely to change land use for erosion mitigation due to lower gross margins.	✓	✓	✓	✓	✓	✓
	Cover / nurse / catch cropping	Maintain soil protection through crop cover, especially in vulnerable months	Vegetation (canopy, stems, roots and organic matter) intercepts rainfall, runoff and wind. Species – grass, winter rye, winter barley or mustard. Kill off cover crops before the spring crop is drilled or during early life of main crop, by cultivation or spraying with selective herbicide. Surface soil is protected from wind forces. Can be used in tramlines and wheelings to reduce soil exposure to wind.	Limited due to extra expense involved in planting and then managing cover crop. Perceived competition with main crops for water and nutrients. *Establishment of cover crop - Broadcast* – spread barley seed in time for it to establish ahead of the row crop. This can give good overall protection. *Drilled* – sow barley between each, or between some, of the proposed crop rows. Consider using machines which form beds and drill barley in one pass. Has been used in the Fens effectively for several years. Tried and tested technique. Cover crop may improve soil structure, organic matter content and resistance to detachment by wind.	Specialist machinery required to direct drill into cover crop. Additional costs associated with establishing /managing / removing cover crop. Nurse crop may not establish quickly enough to be effective Competition between cover crop and main crop may deter uptake by farmers. Herbicides may cause pollution concerns – importance of correct dosage rates. Cost of additional seeds, herbicides, specialist drilling equipment etc. Additional farming operations required Where the cover crop is drilled in rows, damaging blows can occasionally cause erosion along the rows. Timing of operations is critical – especially killing of cover crop to avoid competition with main crop.	✓	✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	Mulching	Use of previous crop residues to protect soil surface	Standing stubble or cut residues intercept rainfall, runoff and wind. Mulches provide surface protection, without competing with main crop. Roughness of mulch elements dramatically reduces velocity and thus erosivity of wind flow near soil surface. In the long term, mulches may add organic matter to soil, reducing its erodibility. May increase soil moisture content, due to reduced soil evaporation. The application of mulches to the surface of seedbeds on sandy soils at 5-15 t/ha after drilling is an effective control. E.g. used for sugar beet seedbeds. Can be used in tramlines and wheelings too. Materials applied at 5-15 t/ha include farmyard manure, sugar beet factory lime, organic manures, sewage & paper sludge. Loosened Stubble – remove compaction by under loosening and drill the crop directly into stubble. The system can be designed so that drill units directly follow the subsoiler tines.	Residues are readily available from previous crop. Not commonly used. Database on effectiveness exists (although little specifically for UK conditions).	Issues with pest control (e.g. slugs) and microclimatic effects of mulch (e.g. suppression of temperature). Direct drill equipment needed. Availability of mulch materials may be limited. Pest/ disease/ fire risks. Mulch decay may use up nitrogen – competition with crops. May have negative micro-climatic impacts (cooler temperatures in the day, but warmer at night due to insulation effects). May reduce effective growing season. Mulches are not generally suitable for vegetables. Thin even spreading is necessary to minimise risks of reduced crop emergence or poorer weed control. Risk of applying excess nutrients, lime or contaminants – must comply with the Defra 'Soil Code' and 'Water Code'. Certain industrial wastes (e.g. sewage sludge) may also be suitable but consultation with the Environment Agency is recommended and expert advice is needed before spreading, as these are subject to legal requirements or local water protection restrictions; See the *Codes of Good Agricultural Practice* for further guidance. Avoid disturbing the mulch or effect is lost. May not create suitable seed bed.	✓	✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	Timeliness of operations	Avoid disturbing the soil during rainfall / windy conditions	Early sowing of winter crops. Leaving the soil undisturbed will increase resistance against erosive forces. Less risk of soil exposure, due to faster germination, emergence and establishment of sufficient cover, compared with late sowing.	Difficult to predict the weather conditions. Machinery may be shared, so may limit freedom to choose when to cultivate etc.	Depends on ownership of equipment and labour availability to keep flexibility of timing operations. May not be practical if previous harvest is delayed, or soil is too wet for land operations in late autumn.	✓	✓	✓	✓	✓	✓
	Buffer strips	Reduce slope length and intercept runoff and sediment	Vegetation stems intercept runoff, so slowing velocity. Transport capacity is reduced, so encouraging sediment (and associated contaminants) to be deposited.	Agri-environmental schemes already encourage use of buffer strips (albeit primarily for biodiversity). Increasingly used on farms.	Relatively easy to keep existing headland / field margins down to permanent vegetation. May take 2 seasons or so to establish.	✓			✓	✓	✓
	High density planting	High seeding rates increase crop, stem and root density	Higher canopy, stem and root densities help intercept erosive forces to reduce erosion.	Accepted agricultural practice (to maximize yields rather than control erosion)	Highly practical – common practice already with most farmers.	✓	✓			✓	✓
	Crop rotation	Compensate high erosion risk crops with low risk crops. Improves soil structure, resistance against detachment and surface cover	Row crops are susceptible to erosion. Ley grasses are not. Combining in a rotation reduces the erosion risk overall	Already accepted practice (for economic reason, rather than erosion control)	Highly practical as already practiced by most farmers. Low economic returns for 'conservative' crops may deter uptake	✓	✓	✓	✓	✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	Shelterbelts	Planting rows of trees or hedgerows provides shelter and wind breaks around fields. Grow rows of trees or hedges to provide protection for soil and crops grown on the sheltered side and to trap air-borne soil particles.	Vegetation reduces wind speeds and erosivity to cause wind blow. Hedgerows and belts of trees will provide protection downwind for up to 20 times their height. *To be most effective they should:* ▪ Permit 30-50% of the wind to pass through. ▪ Be evenly permeable from top to bottom. ▪ Run at right angles to the damaging winds. Allow existing hedgerows to grow taller in vulnerable areas but do not allow gaps to develop at the bottom. Provide shelter to crops	Limited potential due to loss of land when implemented. Some woodland planting schemes may apply. Tried and tested technique. The benefit depends on the frequency and direction of any damaging winds. Payments for establishing new hedgerows and belts of trees may be available under the Environmental Stewardship Scheme (from March 2005 onwards) or the England Woodland Grant Scheme (from July 2005 onwards). Ecological benefits – habitats for predators of pests.	May have negative microclimatic effects leading to competition with main crops. May take several years to establish. Protection of the soil reduces with distance from the shelter and does not extend more than 20 times its height. Wind direction may be variable, making site of shelterbelt difficult to ascertain. Long term establishment of trees and shrubs. May restrict field size. Shelterbelts may compete with crops (for water, nutrients etc.) Shelterbelts may harbour pests. Maintenance requirements.		✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	In-field shelter (cover crops, straw planting).	Inter-row strips of residues or live cover crops reduce wind velocities. In-field shelterbelts exert drag on wind flow, reducing velocity and erosivity of wind. On peaty soils, mechanised straw planting in rows may provide shelter for early sown vegetable crops. Straw is planted between the crop rows just before or after drilling.	Roughness imparted by the strips to air flow causes turbulence and reduced velocity of flow. In turn energy to detach, entrain and transport air borne particles is reduced. Establishing crops are protected from abrasion from windblown particles The work by Morgan and Finney in the 1980s was based solely on measuring the effect of in-field shelter systems on wind velocity and the drag exerted by a crop row. Morgan and Finney (1987) tried to develop the results into some design parameters for crop barriers for erosion control and a model for predicting erosion.	Effects are more immediate than field boundary shelter (see above). Specialist machinery may not be available. Probably only cost effective on high value crops (e.g. horticulture) where windblown abrasion is an issue. Quicker to establish than conventional field boundary shelterbelts. Can be traversed with farm machinery. This technique has been used successfully on peaty soils and some light sands. Gives immediate protection. No risk of competition. No requirement for extra herbicide applications so can be used with sensitive crops. Suitable for organic farming systems.	Live cover crops may compete with main crop. Additional operations needed to plant residues / cover crops. Specialist machinery required for slot planting residue strips Additional costs associated with machinery and additional operation. Morgan & Finney's work in the 1980s showed was that there were some conditions under which a crop cover could exacerbate rather than control the potential for erosion. Limited recent data available on effectiveness. The operation is slow. Requires specialist machinery. Availability of straw may be limited.		✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
1. Agronomic measures	Avoid overgrazing (e.g. outdoor pigs in lowland systems; sheep in upland areas)	Overgrazing leads to loss of vegetation, exposure of bare soil and compaction. Maintain vegetation cover.	Animals remove vegetation and increase compaction due to poaching. The latter leads to generation of surface runoff and erosion due to lack of vegetation cover.	Policy mechanisms have changed to assist farmers to reduce stock numbers.	Difficult to apply given economic sensitivity of reducing stock numbers. Economic benefits of production outweigh soil protection issues.	✓				✓	✓
	Avoid excessive burning of upland vegetation	Maintain protective vegetation cover			Undesirable species may persist without burning regime.	✓	✓			✓	✓
	Strip cropping	Broad strips of alternating crops	Variation in above ground architecture creates an in-field shelterbelt/ reduces slope length. Also reduces effective distance over which wind / overland flow accelerates, and interrupts air flow.		Practical difficulties in cultivating different crops in same field. No design procedure for recommended width of strips. Competition between crops may affect yields.	✓	✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*			Use**		
						W	I	C	T	E & W	O
1. Agronomic measures	Simulated vegetation (geotextiles)	Erosion control blankets simulate plant canopy, stem and root effects. Artificial windbreaks such as polyethylene netting or webbing can be appropriate for protecting small areas of high value crops	Protection of soil surface from rainfall, runoff and wind. % cover, water holding capacity and adhesion to soil surface affect performance (Rickson, 2000). Can be used on slopes and in channels.	Highly effective at controlling rainsplash detachment, overland flow and wind velocities	Costly. Synthetic materials are from non-renewable sources. Fencing may interfere with farming operations. Shading effects of fences (may be beneficial, depending on crop)	✓	✓			✓	✓
	Field layouts	Avoid large fields / field consolidation, to minimise fetch (uninterrupted distance over which wind blows) and slope length (water erosion control).	Small field sizes reduce fetch and acceleration of wind flow. Also may reduce soil movement by tillage erosion.		Ergonomic and economic disadvantages associated with relatively small fields.	✓	✓		✓	✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
2.Field engineering	Lined waterways and swales	Protect areas of concentrated flow	Vegetation (or linings) imparts roughness to surface flow, reducing velocity and transport capacity. Less detachment and transport of eroded soil as a result. Physical protection of the soil surface too.	Not a familiar technique on most farms in E&W.	Requires design of waterway dimensions. Land (and yield) lost to waterway. Costs of lining water whilst permanent vegetation establishes. Maintenance required. May interrupt farming operations	✓		✓	✓	✓	✓
	Earth banks/physical barriers	Interrupt slope length and intercept runoff.	Reduces runoff volume and velocity, so reducing detachment and transport of soil by runoff (no effect on rainsplash detachment).	Not a familiar technique on most farms in E&W.	May interrupt farming operations and take land out of production. Require design for any given site and maintenance.	✓				✓	✓
	Drainage (surface & subsurface)	Intercept runoff, so erosion minimised. For wind erosion control, ensure soils are kept moist and cohesive.	Rainfall and runoff are intercepted by surface or subsurface drains, so limiting detachment and transport of soil. Water table is maintained at a level that will keep soil moist, cohesive and resistant to wind erosion. Wetter soil is less susceptible to wind erosion, due to higher cohesion between soil particles and organic matter	Commonly used technique to improve ground conditions for cropping (but not necessarily explicitly used for erosion control). Unsuitable on soils prone to seasonal droughts.	Cost implications for farmers in installation and maintenance. Wetter soils are more susceptible to erosion by water and crop harvesting. Wetter soils may be less favourable for certain crops. Soil trafficability is affected by moisture – access to land may be limited by wetter conditions.	✓				✓	✓
	Terraces	Interrupt slope length and intercept runoff.	Reduces runoff volume and velocity, so reducing detachment and transport of soil by runoff (no effect on rainsplash detachment).	Not a familiar technique in E&W.	May interrupt farming operations and take land out of production. Require design for any given site and maintenance.	✓					✓
	Irrigation	Avoid soils drying out	Increasing soil moisture content will increase cohesion and soil shear strength against wind erosion		Too costly to justify investment for wind erosion control alone – likely to only be an added benefit of existing irrigation system.		✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
3.Soil management	Reduced / minimum tillage	Maintain soil structure to resist erosive forces	Rough, undisturbed soil surfaces intercept rainfall splash and runoff to minimize runoff. Soil aggregation intact to resist shearing forces of rainfall and runoff. These techniques minimise the disturbance to soil, so maintaining soil cohesion and aggregate bonds to resist detachment by air flow. Also, more vegetative material is kept on the surface with non-inversion tillage operations. Anchorage of this material is important, so some incorporation is necessary. Ecological advantages – encourages wildlife. Reduced depth of tillage will help to reduce tillage erosion and translocation. Controls erosion by water too.	Increasing uptake as multi-purpose – reduces fuel costs, labour demands as well as controlling erosion. Only suitable on certain soils due to problems of persistent weed control and compaction.	Specialist machinery may be needed. Increase use of chemical weed control (not cultivations) may have environmental concerns. Specialist equipment may be needed. Bulk densities may increase in the medium term – increasing risk of runoff generation. May need sub soiling to alleviate this. Vegetative material left on surface may act as a mulch (see drawbacks of mulches above) May not create suitable seed bed.	✓	✓		✓	✓	✓
	Contour / across slope cultivation	Reduce slope length	Runoff generation limited, so reducing erosion risk. Soil and water conservation.	Already applied in places where erosion risk considered high. Risk of runoff concentrating in ‘low spots’ which then overtop and cause may erosion.	Difficult to apply on complex / steep slopes, especially for harvesting operations. Small field sizes limit contour operations.	✓			✓	✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
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Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
3.Soil management	Tramline management	Interrupt concentration of runoff in tramlines. Cover cropping can be used in tramlines and wheelings to reduce soil exposure to wind and water.	Intercepting flow with physical barriers (e.g. mulch) or limiting flow generation (e.g. tining) will reduce soil detachment and transport.	Farmers may be unwilling to concentrate efforts on relatively small area of (unproductive) land. Application of mulch and subsoiling represent extra field operations, so increasing production costs.	Mulch materials and subsoiling equipment is readily available on most arable farms.	✓				✓	✓
	Establish coarser seedbeds	Maintain soil structure to resist erosion	Rough, undisturbed soil surfaces intercept rainfall splash and runoff to minimize runoff. Soil aggregation intact to resist shearing forces of rainfall and runoff. Rough, cloddy surfaces are recommended. Rotary implements should be avoided as these disturb the soil surface a great deal.	Suitable for runoff and erosion control but may compromise traditional quality of seedbed for crop establishment (fine, loose tilth). On sandy soils, cultivations which leave a rough or cloddy surface can be the most cost-effective methods of erosion control for sugar beet (Defra, 2005).	Equipment required is readily available on most arable farms. Cloddy surfaces are not suitable as seed beds for many crops, due to poor soil/seed contact for imbibition to take place. Under-researched - the use of tillage practices for wind erosion control was tested at Gleadthorpe Experimental Farm in the 1980s, but this work was not continued.	✓	✓			✓	✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
3.Soil management	Increase soil organic matter	Correlation between SOM and aggregate stability / resistance to erosion (to 10%)	SOM decreases erodibility, encourages water infiltration, increases fertility giving better crop canopy, stem and root density, so controlling erosion.	Tried and tested technique. Farmers familiar with importance of SOM for production and erosion control.	Incorporating resides can be part of seed bed preparation for following crop. Specialist machinery may be needed on heavier, wetter soils, where slow decomposition of residues may be detrimental. Sourcing of organic matter may be difficult. Long term effects – bonds between organic matter and soil particles take a long time for form. Very organic soils (e.g. peats) are highly liable to drying out, when they become susceptible to wind erosion.	✓	✓	✓	✓	✓	✓
	Zero tillage	Maintain soil structure to resist erosive forces	Soil structure undisturbed by cultivations. Maintain cover from previous crop to resist erosive forces of water and wind. No translocation of soil by tillage.	Specialist machinery required (e.g. slot planters, direct drills). Perceived risk of compaction and increased generation of runoff over time. Needs long term view to allow soil structure to stabilize, so improving infiltration and reducing runoff generation.	Limited in E&W due to perceived compaction problems. Increased used of herbicides to control weeds may have environmental consequences, especially if compaction leads to reduced infiltration and greater runoff.	✓	✓		✓		✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
3.Soil management	Bed systems (in potatoes etc.)	Avoid ridge systems which expose more soil surface to wind forces			Comparative soil losses from bed v. ridge systems not trialled to date. Agronomy of crop may be compromised.	✓	✓	?	?	✓	✓
	Furrow press	plough and furrow press the land when moist (to maintain micro-topography created), using a 45° angle press to leave steep ridges (e.g. with a Cambridge roller). Drill as soon after as possible, at an angle to the ridges.	Light pressing/compaction increases soil cohesion and resistance to detachment by wind. Ploughing when the soil is moist will avoid wind blow as soil cohesion is highest. Rougher surface soil results in reduction in wind velocities at the soil surface. Multi-directional roughness intercepts wind from different origins.		Higher bulk densities associated with pressed/ compacted soil may impede infiltration, leading to higher risk of erosion by overland flow. To be effective the soil must contain sufficient clay for the ridges to be stable. Specialist equipment may be needed. Ploughing (and harvesting) when the soil is moist may increase risk of soil loss on farm machinery (and root crops).		✓	✓	✓	✓	

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Mitigation measure	Description	Rationale	Mechanism of action	Potential for applying the method	Practicability	Erosion type*				Use**	
						W	I	C	T	E & W	O
3.Soil management	Addition of clay sized particles	Mixing of clay rich soil with in-situ soil.	Higher clay content improves soil aggregate stability and resistance to detachment by air and water flow.	Increasing the clay content of surface soils is a long-term solution to wind erosion.	Application rates of 400-1000 t/ha are likely to be needed to achieve a suitable increase in clay content. This may be practicable if marl or clay rich waste materials (e.g. lake dredgings) are available locally. Professional advice needed before using waste materials. The EA must be consulted before dredgings or industrial wastes, including waste soil, are spread. Increasing clay content would increase risk of soil loss on root crops and farm machinery	✓	✓				
	Synthetic stabilisers (polyvinyl alcohol).	Proprietary soil stabilisers including PVA (polyvinylacetate) emulsions or PAM (polyacrylamides) can provide protection when sprayed onto sands after drilling.	Applied quickly and easily if a blow is forecast. Useful in protecting small areas of high value crops.		Costs limit this technique to high value horticultural crops. Temporary protection only. Not suitable for peats or organic systems. Often from non-renewable sources. Appropriate professional advice should be obtained before these materials are used. Pollution risks if used inappropriately.	✓	✓	✓	✓		✓

*Types of erosion: W = erosion by water; I = erosion by wind; C = soil co-extraction on root crops; T = tillage erosion
**Use / Current adoption: E&W = England & Wales; O = International

Table 10: Effects of cropping/tillage soil conservation measures on soil degradation processes (from Deeks *et al*., 2008)

	Soil degradation problem									
Measures	soil erosion water	soil erosion wind	decline in organic matter	negative carbon balance	diffuse contami-nation	compaction	salinisation	acidification	decrease of water retention capacity	Off-site damage
intercrops	2		ne		2	0				2
undersown crops	2		2		2	1				2
grass strips	1		1		1	0				1
reduced tillage	2		0	1		ne				1
contour tillage	1		0	0					1	1
restriction of row crops on steep slopes	2		0			0				2
wheel sizes and pressure / restricting excessive heavy machinery use	1					2				
restrictions on the max. amount of (liquid) manure application					2					1
restrictions on the max. amount of N- fertilisation					2					1
restrictions on the max. amount of P-fertilisation					2					2
controlled livestock movement	1		0		1	2			1	1

Legend: The numbers indicate *the general effects of soil conservation measures on soil threats in the case study*, examined in questionnaire 1 with the following units: 2 = farming practice highly mitigates the threat, 1 = farming practice mitigates the threat, 0 = farming practice has no effect on threat and ne indicating that it is dependent on other variables. The grey marked cells are not relevant because this measure has no relationship to the threat.. Source: ZALF

Table 11: Effects of long term soil conservation measures on soil degradation processes (from Deeks *et al*., 2008)

	Soil degradation problem									
Measures	soil erosion water	soil erosion wind	decline in organic matter	negative carbon balance	diffuse contami-nation	compaction	salinisation	acidification	decrease of water retention capacity	Off-site damage
liming					ne			1		0
drainage management to mitigate salinisation and/or compaction	1					ne				
controlled traffic tramlines	1					2				ne
retention ponds	1		0		2	0			1	2
hillside ditches			0		0	0			0	ne
subsoiling						2				
adjusting stocking rates	1				2	1				2
adjusting duration and season of grazing animals	1				1	2				1

Legend: The numbers indicate *the general effects of soil conservation measures on soil threats in the case study*, examined in questionnaire 1 with the following units: 2 = farming practice highly mitigates the threat, 1 = farming practice mitigates the threat, 0 = farming practice has no effect on threat and ne indicating that it is dependent on other variables. The grey marked cells are not relevant because this measure has no relationship to the threat.

Source: ZALF

Table 12: Effectiveness of mitigation options trialled on different soil types for between one and three years, and estimated per-crop costs. Figures are calculated by comparing mean values for treatments and control treatments by year and by site, and represent the results for all treatment combinations. (from Deasy *et al*., 2008).

Treatment	Impact on farm margin (£ ha^{-1})	No. of Site-years trialled	Mitigation effectiveness (Reduction in overwinter loss, with% relative change)								
			Runoff (mm)			SS (kg ha^{-1})			TP (kg ha^{-1})		
			Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Tramline disruption[1]	- 2-5	5	3.5-11.0	5.3-75.4[a]	N/A	49-223	373-4780[a]	N/A	0.19-2.14	0.72-2.89[a]	N/A
			(69-88)	(95-97)		(75-96)	(98-99)		(72-95)	(97-99)	
Crop residues[2]	0	1	0.2-2.0	N/A	N/A	9-200	N/A	N/A	0.03-0.52	N/A	N/A
			(24-50)			(40-43)			(34-50)		
Minimum tillage[3]	+ 44-50	5	2.2-7.8	N/E[a]	0.8-31.6[bc]	107-841	N/E[a]	54-1133[bcf]	0.33-2.28	N/E[a]	0.04-0.86[bcf]
			(66-81)		(4-62)	(94-98)		(37-62)	(92-97)		(29-52)
Contour cultivation[4]	0	2	N/A	N/A	16.5-56.0[d]	N/A	N/A	90-1223[d]	N/A	N/A	0.09-1.00[d]
					(64-76)			(45-79)			(48-79)
Vegetative barrier[5]	- 2-5	2	N/A	N/A	11.9-17.6[e]	N/A	N/A	41-228	N/A	N/A	0.04-0.45
					(45-91)			16-94			(9-97)

N/A = Not applicable. N/E = not effective in this project. [1]Trialled for 2 years on sandy and 3 years on silty soils. [2]Trialled for 1 year on sandy soils. [3]Trialled for 1 year on sandy, 1 year on silty and three years on clay soils. [4]Trialled for 2 years on clay soils. [5] Trialled for 2 years on clay soils. [a]Not effective when trialled in year 3. [b]Not effective when trialled in year 1. [c]Not effective when trialled under contour cultivation in year 3. [d]Not effective when trialled under minimum tillage in year 3. [e]Not effective when trialled under minimum tillage in year 2. [f]Not effective for tramline losses when trialled in year 3. N.B. While these results reflect our findings, the three year duration of the project may not have been long enough to accurately reflect the impact of the treatments on diffuse pollution losses.

C.3. Costs and Benefits of Mitigation Measures (descriptive and analysis).

Introduction: Costing the benefits of soil mitigation

The assessment of costs and benefits of soil erosion and its mitigation is not a simple process. The costs of soil erosion cannot simply be judged by what soil erosion has cost the producer and the consumer as it also incurs costs that are not paid for by either, termed 'externalities' by Pretty *et al*. (2000). Externalities include the cost, for example, of cleaning up roads, polluting the environment or producing water fit for consumption. Pretty *et al*. (2000) defined five features of externalities relating to the agricultural sector that are also relevant to soil erosion: 1) externality costs are often neglected; 2) they often occur with time lags; 3) they often damage groups whose interests are not represented; 4) the identity of the producer of the externality is not always known; and 5) they result in sub-optimal economic and policy solutions.

Because of its diffuse nature, it is difficult to quantify soil erosion induced externalities for a particular field. Not all soil erosion will lead to off-site damage. In addition to the challenges of identifying all cost and benefits that may occur as a result of soil erosion and its mitigation, assigning an economic value to these costs and benefits is also complicated, as these values can be subjective. As Inman (2006) suggests, to assess the true cost of externalities one must know the value of nature's goods and services, and what happens to these when they are impacted, as well as the value of these non-market goods. Because of this it can be easy to underestimate the current and future value of a natural resource. The OECD (2003) report from the expert meeting on agricultural soil erosion and soil biodiversity indicators suggested that:

'*Off-site costs of erosion and sediment redistribution are probably at least an order of magnitude greater than on-site (private costs). It should be noted that there is considerable ambiguity in quantification of off-site costs, and especially in how to quantify the impact of agriculture on soil and other natural resources (air and water). This ambiguity needs to be addressed.*'

The problem is that some cost and benefits, in particular those relating to the environment, may not be valued properly and, as a result, policies may be misdirected or even inappropriate. In an attempt to overcome these shortcomings, Defra introduced 'An introductory guide to valuing ecosystem services' (Defra, 2007). The aim of this approach is to '*ensure that the true value of ecosystems and the services they provide are taken into account in policy decision*-making'. Defra's ecosystem services approach follows the Millennium Ecosystem Assessment framework (MA, 2005), which offers a widely accepted method of categorising ecosystem services. These are defined by Defra (2007) as services provided by the natural environment that benefit people (Defra, 2007). The MA approach defines four broad categories of ecosystem services (see Table 13), and links ecosystems and their services to human wellbeing. This approach attempts to place an economic value on ecosystem services that can then be used in a cost-benefit analysis. By placing value on ecosystem services, a better appraisal of the consequences of policy intervention (here, soil erosion mitigation) that alters an ecosystems condition is possible.

The economic valuation of ecosystem services is based on the values or the utility derived from actual or potential use, as well as value for other reasons (e.g. non-use values based on pleasure of knowing something is there). Ecosystem services contribute to economic welfare in two ways: through contributions to the generation of income and wellbeing, and through the prevention of damages that inflict costs on society (Defra, 2007). In order to understand the value of an ecosystem, it is necessary to characterise and quantify the relationships between ecosystems and the provision of ecosystem services, and to identify the ways in which these impact on human welfare (Defra, 2007).

An economic appraisal of erosion mitigation measures usually consists of an assessment and quantification of the physical effects such as impacts on soil productivity. When evaluating the costs and benefits of mitigation measures, the spatial and temporal characteristics have to be considered: i.e. the on-site and off-site effects as well as the present and future impacts (Seckler, 1987). An individual land user normally only considers the on-site costs and benefits before deciding whether to implement mitigation measures. However, society has an interest in the off-site costs and benefits of the mitigation measures (see C.1. above). An economic appraisal, including the off-site impacts, may show that a mitigation measure is cost-effective, whereas the financial appraisal, excluding the off-site impacts, may conclude the opposite, or vice versa.

In economic and environmental terms it is generally not optimal to reduce erosion to zero as the marginal benefits will be less than the increasing costs. Soil erosion mitigation measures can be implemented at different intensities (Erenstein, 1999), for example:

- Absolute conservation: assuring that soil erosion is reduced to zero.
- Standards-based conservation: on-site standards take the soil formation rate into account, technology based standards take the best available control technology.
- Efficient or optimal soil conservation: soil erosion is prevented only if benefits of doing so are larger than the costs.

Table 13: Millennium Ecosystem Assessment categories of ecosystem services and examples relating to soil (adapted from a table in Defra, 2007)

Category	Examples of ecosystem services provided by soil
Provisioning services i.e. products obtained from ecosystems	• Food • Fibre and fuel • Genetic resources
Regulating services i.e. benefits obtained from the regulation of ecosystem processes	• Climate regulation • Water regulation • Water purification/detoxification • Bioremediation of waste
Cultural services i.e. non-material benefits that people obtain through spiritual enrichment, cognitive development, recreation etc.	• Spiritual and religious value • Inspiration for art, folklore, architecture etc • Social relations • Aesthetic values • Cultural heritage • Recreation and ecotourism
Supporting services, necessary for the production of all other ecosystem services	• Soil formation and retention • Nutrient cycling • Primary production • Water cycling • Provision of habitat

Two approaches are generally applied to assess mitigation options: multi-criteria analysis (MCA) or cost-benefit analysis (CBA). Both approaches consist of impact analysis, but CBA includes the valuation of these impacts in monetary terms. MCA uses weights to assign a relative value to the different types of impact.

An important consideration is the valuation of the off-site costs and benefits of mitigation measures, which in monetary terms is complex as the biophysical environment determines the magnitude of the impacts, and the socio-economic environment determines their value. The following valuation techniques are commonly used to assess the benefits of mitigation measures (Enters; 1998; Gregersen *et al*., 1987; Grohs, 1994):

- Change in productivity (based on market prices) based on comparisons of 'with' and 'without' mitigation.
- Replacement cost (based on market prices), i.e. the cost of replacing the damaged asset (for example, the cost of fertilisers to replace nutrients associated with eroded soil).
- Hedonic pricing and property valuation (using surrogate market prices), comparing prices of land experiencing different levels of erosion.
- Contingent valuation (using hypothetical prices) to value environmental impacts which are non-tradable.

There are many challenges that need to be met in order to provide an absolute appraisal of mitigation measures. These challenges include those identified by Bojö (1992) and Cameron (2007):

- Valuation of impacts, in particular those that are non-tradable.
- Combining information on physical and socio-economic systems.
- Modelling causality and linking concepts and variables.
- Identifying observable and measurable indicators.
- Coping with data gaps and inaccuracy.

- Weighting indicators into composite indices (comparisons for evaluation require aggregation of indicators into a single number index, requiring weighting of indicators – *de facto* a form of relative valuing or pricing).
- Discounting – determining today's value of future impacts.
- Uncertainty, in particular with regard to future impacts.

An additional challenge is double-counting. When comparing cases 'with' and 'without' mitigation, the costs associated with soil erosion are converted into benefits (i.e. costs foregone) for mitigation measures, but this may lead to double-counting. In addition, impacts of soil erosion are often interlinked. Soils provide many ecosystem services (see Sub-project B), including water retention, carbon storage, nutrient recycling and agricultural production. Soil erosion affects these ecosystem services, as nutrients and organic material are lost, affecting the agricultural production and soil's capacity to retain water. Assessing these impacts separately may lead to double-counting as it is difficult to separate these processes.

Defra's ecosystem approach (Defra, 2007) has been taken as a guideline in order to determine the cost-effectiveness of the different mitigation measures identified in C.2. The procedure for determining the cost-effectiveness of mitigation measures is as follows:

1) Establish the environmental baseline.
2) Determine the costs of different mitigation options
3) Determine the effect of mitigation options on soil erosion.
4) Value the impacts of mitigation options on specific ecosystem services.

Step 1: Establish the environmental baseline

The environmental baseline determines the impact of soil erosion (as reported in C.1. above) on ecosystem services at national level (Table 14), namely:

- Support of food, fuel and fibre production
- Environmental interaction functions
    - Regulating the flow of and filtering substances from water
    - Emitting and removing atmospheric gasses
    - Storing carbon
- Support of habitats and biodiversity
- Protection of cultural heritage and archaeology
- Providing raw materials.

Soil erosion can affect the performance of soil functions (see Sub-project B). In addition, soil erosion can impact 'off-site' ecosystems and the services they provide; for example:

- Sedimentation on downstream farmland affecting food, fuel and fibre production
- Siltation of water courses affects
    - Land drainage
    - Flood regulation
- Siltation of aquatic ecosystems affects the following ecosystem services:
    - Tourism: angling and boating
    - Provision of drinking water
    - Hydro-power
- Air pollution by soil particles
- Sedimentation affecting infrastructure
- Degradation of riverine / wetland habitats due to siltation and pollution

Table 14 reviews and summarises existing available information on the estimated impacts of soil erosion on ecosystem services in the UK.

Table 14: Impact of soil erosion on ecosystem services

a)'On-site' ecosystem services (related to soil functions)

Ecosystem services		Soil erosion impact	Baseline
Provision	Support of food, fuel and fibre production	Reduced yields due to crop damage	In 2008, the value of total agricultural output for the UK was £19.8 billion. Evans (1996) estimated that loss of productivity from loss of soils and nutrients amounts to £9 million for England and Wales. Various studies have found that yield reductions are typically between 0.03 and 0.05% per tonne soil lost (e.g. Biot and Lu, 1995; Hodges and Arden-Clarke, 1988; Owens et al., 2006).
Regulation	Regulating the flow of and filtering substances from water	Reduced water holding capacity	A single hectare of soil has the potential to store and filter enough water for 1000 people for 1 year (Defra, 2009a)
	Storing carbon	Reduced soil carbon (organic matter content)	Soil stores carbon (~ 2.8 billion tonnes in England and Wales), in particular peatlands. In 2007, 21.8 million tonnes CO_2 were emitted from, and 11.6 million tonnes CO_2 were added to UK soils. (Dawson and Smith, 2007; Thompson, 2008; Defra, 2009a). Shadow price for carbon is estimated at £25 t^{-1} CO_2-e, or £92 t^{-1} C, at 2006 prices (Anthony *et al.,* 2009: Defra, 2007). Adas (2006) applied the value of £70 t^{-1} C at 2006 prices.
	Soil fertility / quality	Reduced soil productivity	Impact of erosion on soil productivity depends on the quality of remaining soil and is thus location-specific. Bakker *et al*. (2004) showed that the crop productivity response to soil erosion largely depends on the physical variables affected by soil erosion: soil erosion resulting in water deficits and physical root hindrance generally produce convex response curves, whereas nutrient deficits resulted in linear to concave response curves. Furthermore, the effects vary among crops, as demands for soil structure, rooting depth, and water retention differ per crop. The degree of yield loss thus depends upon the soil profile characteristics, the crop grown, soil management, and the microclimate (Lal, 1985; Posthumus and Stroosnijder, 2009)
Supporting	Support of below-ground biodiversity	Loss of soil biota	At present there is no hard evidence to suggest any serious threat to soil biota as a whole or to key organisms (Defra, 2009c).
	Support of above-ground biodiversity	Loss of (above ground) biodiversity	Value of habitat protection services provided by current land use within the agriculture sector is estimated at £229 million at 2004 prices (EFTEC, 2004).
Cultural	Protection of cultural heritage and archaeology	Exposure of archaeological features leading to increased risk of damage	The soil in England preserves a diverse range of archaeological remains which is a vital resource in understanding anthropogenic history. As a matrix the soil holds palaeo-environmental data and anaerobic wetland soils preserve organic remains.
	Cultural landscapes	Reduced landscape value	Value of landscape amenity services by the current provision of landscapes is estimated at £498 million at 2004 prices (EFTEC, 2004). However, there are still many unknowns; there is a lack of valuation studies and not it is not known how much of the landscape value can be apportioned to agriculture - (Spencer *et al.,* 2008)

b) ***'Off-site' ecosystem services***

Ecosystem services		Soil erosion impact	Baseline
Provision	Support of food, fuel and fibre production	Reduced yields due to sedimentation	No information available on yield loss caused by sedimentation.
Regulation	Drainage / discharge of water	Siltation of water courses	Costs of damage to property and dredging stream channels due to erosion were estimated to be £9 million per year for the UK (EA, 2007). On top of this, during 2006/07, a further £5.5 million was spent on managing accumulated sediment in watercourses managed or owned by British Waterways in England (BW, 2008; Defra, 2009a). The costs of sediment removal in urban drainage systems in England and Wales has been estimated at £50 to £60 million per year (Reeves *et al*., 2007; cited by Defra, 2009a). Agriculture contributes an estimated 76% to the total suspended sediment loads delivered to all rivers in England and Wales (Collins et al., 2009)
	Flood regulation	Increased flood risk / damage	Although there are many uncertainties it is thought that agriculture contributes 14% to total flood damage costs in the UK (EA 2002). The annual cost of flooding due to soil structural degradation is estimated to be between £29 million to £128 million for the UK at 2004/2005 prices (Evans, 1996; EA, 2002; EA, 2007; Defra, 2009a) Spencer *et al.* (2008), however, estimated flood damage costs due to agriculture at £234m yr^{-1} for the UK at 2006 prices
	Provision of drinking water	Water treatment costs to remove pollutants & sediments	Spencer *et al.* (2008) estimated annual cost of nitrates and particulates in drinking water in the UK at £48.7 million and £22.8 million respectively. EA (2007) estimated water treatment cost of soil erosion to be £21.17 million per year in the UK. Pretty *et al*. (2000) estimated that 43% of P in water originates from agriculture mainly due to erosion. More recent work suggests that on average agriculture is only responsible for 25% of the phosphorus but 75% of the sediment. (Anthony *et al*., 2006; Hammond *et al*., 2006; EA, 2007; Defra, 2009a)
		Reservoir capacity	Yorkshire Water estimated that the erosion of peat uplands in the Strines catchment has cost £74 m for the construction of new reservoirs to compensated for the loss of storage capacity of the Strines reservoir (White *et al*., 1997)
	Water quality	Eutrophication of lakes	Costs of eutrophication due to agricultural activity (diffuse pollution) is estimated at £20m to £33m per year in England & Wales (EA 2007, in Spencer *et al* 2008). Spencer *et al* (2008) estimated the annual cost of eutrophication of lakes at £27 million for England & Wales, degraded river quality at £45.4 million for England & Wales and degraded estuary quality at £2.5 million for England. Defra commissioned work by NERA to survey the value placed on water quality by households in England & Wales (Baker *et al*. 2007). The willingness to pay for achieving good ecological status, with all benefits arising by 2015, was estimated to be £1,020 million per year. This value required factoring for the contribution made by agriculture to the total pollutant load. The factor may range from 30% for phosphorus to 70% for nitrate. Applying an average value of 50% gave a net value of £500 million (Anthony *et al* 2009)
	Air quality	Air pollution affecting human health	No data are available on the impact of soil particles on human health

Ecosystem services		Soil erosion impact	Baseline
Supporting	Infrastructure	Obstruction of roads due to sedimentation	Evans (1995, 1996; cited by Pretty *et al*., 2000) estimated that the costs of sedimentation in England & Wales was £4 million for damage to roads and property, £0.1 million for traffic accidents, £1.19 for footpath loss and £8.47 for channel degradation. Spencer *et al.* (2008) estimated offsite soil erosion damage at £9 million per year for the UK. It is thought that soil erosion from farmland accounts for 95% of the damage (Spencer *et al.* 2008)
	Wetland habitat	Sediments affecting wetland biodiversity	No data are available on the impact of soil particles on human health
Cultural	Recreation (angling)	Siltation of rivers affecting fish habitat.	Concentrations of suspended solids of less than 25 mg l^{-1} have little effect on fish. Reasonable numbers of fish survive and breed in water containing between 25 and 80 mg l^{-1} of suspended solids. Waters containing between 80 and 400 mg l^{-1} of suspended solids are unlikely to support sustainable populations of freshwater fish (Alabaster and Lloyd, 1982). EU Freshwater Fish Directive stipulates that suspended solid concentrations should not exceed a guideline annual mean of 25 mg l^{-1}. EA (2007) estimated the potential angling benefits in the UK from improvement of water quality (based on WTP) at £71M yr^{-1}. Agriculture contributes 20% to 50% to diffuse pollution thus costing £14 to £35M yr^{-1}.

Soil erosion affects off-site ecosystem services through the following processes: siltation, pollution (in particular phosphorus) and increased runoff due to reduced water holding capacity of the soils. Mitigation measures can be assessed for their likely impact on these processes. The impact of mitigation measures on downstream ecosystem services will depend on the local context and is therefore difficult to assess. However, current knowledge does not enable the allocation of proportionate impact of sediments or runoff to different ecosystem services. Not all sediments lost from farmland due to erosion will impact all ecosystem services listed in the table above. There is therefore a risk of overestimating the impacts of erosion, as well as the benefits of mitigation measures. As Spencer *et al*. (2008) point out, the valuation of erosion impacts is difficult as this is constrained by physical data limitations; that is, it is difficult to separate the potential impacts of soil erosion in water quality and flooding from other drivers. Spencer *et al.* (2008) also claim there is not sufficient evidence available to quantify off-site damages from soil erosion. Nor is there any information on how soil erosion impacts soil functions. Furthermore, it is unlikely that the impact of soil erosion on ecosystem services follows a linear relationship.

Step 2: Determine costs of mitigation measures

The main on-site costs of mitigation measures are: investment costs (materials and implementation costs), maintenance costs, hindrance of farming operations, loss of productive land, and loss of high value land use in case of land use change. These costs, however, may vary from field to field, depending on soil type, land use, and skills of the farmer.

<u>Investment costs</u>
Investment costs typically consist of the costs of materials (if any), and the costs of labour and machinery used for the installation of a mitigation measure. Only the costs that are made 'on-site', that is at field level, are taken into account as these measures are generally implemented by farmers. There may be cases where farmers have to invest in new machinery, but for the purpose of this exercise it was assumed that farmers either have the machinery required, or make use of contractors. Estimates on investment costs are based on secondary data (Cuttle et al. 2007) and generic costs of farming operations as reported in the Farm Management Pocketbook (Nix 2009). Table 15 summarises the investment costs for the identified mitigation measures.

Table 15: Investment costs of mitigation measures

Mitigation measure	**Materials for implementation**	**Labour & machinery costs**	**Total investment costs** (£ ha^{-1})	**Lifetime** (years)	**Annual cost** (£ ha^{-1})	**Comments**
Cover crops (winter cover)	Barley seed: £55 ha^{-1} (Nix 2009)	Cultivation and drilling: £60 ha^{-1} (Nix 2009)	115	1	115	Anthony *et al*. 2009: 'establish cover crops in autumn': £60 per ha
Cover crops (under sown maize)	grass seed: £50 ha^{-1} (Cuttle *et al* 2007)	drilling: £25 ha^{-1} (Nix 2009)	75	1	75	Anthony *et al*. 2009: 'establish cover crops in autumn': £60 per ha
Geo-textiles / grassed waterway	Geojute at £0.50 per m^2 (Simmons pers. comm. 2009), grass seeds at £50 ha^{-1} (Cuttle *et al*. 2007). Total cost to cover 5% of 1ha: £252.50[1]	Cultivation and drilling (based on Nix 2009): £3.	256	5	51	Assumption: 5% (500m^2 per ha) of field is covered with geo-textiles affected by rill erosion (based on Evans 1996)
Mulching	2.5t straw ha^{-1} (Bailey *et al*. 2007) at £40 t^{-1} (based on Nix 2009)	Low	100	2	50	
In-field buffer strips (6m per ha)	£23 ha^{-1} (based on Nix 2009)	£9 ha^{-1} (based on Nix 2009)	32	10	6	Cuttle *et al* 2007: £31.6 ha^{-1} for 10m strip
Riparian buffer strips (6m per ha)	£23 ha^{-1} (based on Nix 2009)	£9 ha^{-1} (based on Nix 2009)	32	10	6	
High density planting	None	None	None	N/A	0	
Crop rotation	None	None	None	N/A	0	
Timeliness	None	None	None	N/A	0	
Land use change (arable to pasture)	May require adaptations in machinery and buildings at farm level because of change in agricultural enterprise		None to very high	N/A	0	
Agro-forestry	Trees, fertilisers, sprays, and materials for protection: £418	Site preparation and planting (incl. saplings): £85	503	20	25	Total establishment costs for planting broadleaved woodland: £2515 ha^{-1} (Nix 2009). Assuming 20% cover for agro-forestry systems. For comparison, establishment costs for apple and pear orchards are £571 ha^{-1}

[1] It is assumed that 5% of 1 ha is covered with geo-textiles and grass. The geo-textile material costs £5,000 per ha, grass seed costs £50 per ha. Multiplied by 5% this gives £252.50. Cultivating and drilling costs £60 per ha; multiplied by 5% this results in £3. The total sum of 256, divided by the lifetime of the measure (5 years) gives the annual cost of £51 per year.

Mitigation measure	Materials for implementation	Labour & machinery costs	Total investment costs (£ ha^{-1})	Lifetime (years)	Annual cost (£ ha^{-1})	Comments
						and £500 ha^{-1} respectively (ABC 2008)
Shelterbelts	Trees / shrubs	Planting	670	20	34	Source: Nix 2009
Sub-soiling	None	Contractor: £48 (based on Nix 2009)	48	3	24	may damage grass sward reducing productivity; in arable no loss of yield
Drainage	High	High	2000	25	80	Based on Nix 2009
Reduced tillage	None	None	0	N/A	0	
Zero tillage	May require specialist machinery	None	0	N/A	0	
Tramline management	None	None	0	N/A	0	
Coarser seedbeds	None	None	0	N/A	0	Note: not suitable for sugar beet, oilseed rape or grass (Cuttle *et al.* 2007)
Stocking density i.e. reduced	None	None	0	N/A	0	
Contour ploughing	None	None	0	N/A	0	
Swales (per unit)			212	15	14	Estimated cost is £12000 per farm (RPA 2003). Average size tillage area arable farm is 170 ha (FBS 2009). Assuming 33% of arable area 'drains' into swale
Earth bank (100m length)	None	218	218	5	44	Based on costs for digging a ditch (1.8m width, 0.9m depth) at £1.90 to £2.45 m^{-1} (Nix 2009)

Maintenance costs
Maintenance costs consist of labour and machinery use for the maintenance of the mitigation measures (Table 16). It also includes the operational costs of measures that require no investment or are annual operations, such as timeliness, reduced tillage or crop rotation.

Table 16: Maintenance costs mitigation measures

Mitigation measure	**Labour & machinery**	**Annual maintenance costs**	**Comments**
Cover crops (winter cover)	incorporating crop residues (£25 ha^{-1})	25	Sources: Cuttle *et al*. 2007
Cover crops (under sown maize)	incorporating crop residues (£25 ha^{-1})	25	Sources: Cuttle *et al*. 2007
Geo-textiles	Mowing (once a year) £1.25 ha^{-1} (based on Nix 2009)	1	Maintenance costs are minimal although some geo-textiles are designed to degrade therefore may need to be replaced periodically unless no longer required i.e. a cover crop has taken its place
Mulching	Negligible	0	
In-field buffer strips (6m)	Regular cutting in first 12-24 months to reduce weeds. Then annual cut of first 3 m next to crop and biannual cut of additional 3 m strip.	1.5	Mowing grass costs £25 ha^{-1}(Nix 2009); assuming one cut a year
Riparian buffer strips (6m)	Same as in-field buffer strip	1.5	
High density planting	Increase in seed costs: 10% per ha. Average seed costs for winter wheat is £49 ha^{-1} (Nix 2009)	5	Assumption: plant density is doubled on areas affected by soil erosion (5% of field area)
Crop rotation	Additional cultivation if done in spring	0	Costs included in change in gross margins
Timeliness	Costs of sowing winter crops early to provide crop cover during critical periods have been estimated at £70 ha^{-1} (RPA. 2003)	70	Costs associated with timeliness may range from zero to very high if timing of field operations clashes or delays result in yield losses
Land use change	Included in gross margins	0	
Agro-forestry	Variable	?	Dependent upon type of tree
Shelterbelts	Negligible	0	It is assumed that shelterbelts are not cut to allow maximum shelter
Subsoiling	None	0	
Drainage[2]	Negligible	0	
Reduced tillage	Increase in spraying	£50	Assuming 75% increase in sprays for weeds and slug control (annual spray costs for wheat is £149 ha^{-1}, of which

[2] Dredging of watercourses and rivers falls under the responsibility of the EA or IDBs. Farmers may want to clean out ditches on their land, but this is not done on an annual basis and the costs are at farm level. Annual maintenance costs of field drainage are negligible and therefore not taken into account.

Mitigation measure	Labour & machinery	Annual maintenance costs	Comments
			45% is herbicides and slug pellets; based on Nix 2009)
Zero tillage	Increase in spraying	£67	Assuming 100% increase in sprays for weeds and slug control (annual spray costs for wheat is £149 ha^{-1}, of which 45% is herbicides and slug pellets; based on Nix 2009)
Tramline management	Breaking up of compacted tramline	£20	Estimated costs for additional tine cultivation of tramline: £15 ha^{-1} (Bailey *et al*. 2007); £25 ha^{-1} (Anthony *et al*. 2009)
Coarser seedbeds	Increase in spraying	£34	Assuming 50% increase in sprays for weeds and slug control (annual spray costs for wheat is £149 ha^{-1}, of which 45% is herbicides and slug pellets; based on Nix 2009)
Stocking density i.e. reduced	Additional forage when livestock kept off pasture	40	Cuttle *et al.* 2007 estimated costs of reducing stocking rates when soils are wet: dairy at £30-45 ha^{-1}, beef at £25-40 ha^{-1}
Contour ploughing	Slowing down of field operations	32	Assumptions: 10% increase in costs for pre-harvest field operations, 25% increase in costs for harvesting
Swales	None	0	
Earth banks	Not known	0	

Hindrance to farming operations
Some mitigation measures may hinder field operations such as tillage, fertiliser spreading, herbicide spraying or harvesting because of obstruction (e.g. agroforestry, terraces, in-field buffer strips) or complication of harvesting (e.g. contour ploughing). This hindrance will result in a slowing down of the field operations, hence increasing the labour costs. However, no data are available on the costs of hindrance. Table 17 describes the type of hindrances that may be caused by the mitigation measures

Table 17: Costs of hindrance to farming operations due to mitigation measures

Mitigation measure	**Hindrance to farming operations**
Cover crops (winter cover)	None
Cover crops (under sown maize)	None
Geo-textiles	Minimal to moderate, can break up continuity of land, therefore additional time required to work the land
Mulching	None
In-field buffer strips	Moderate; breaks up continuity of land, therefore additional time required to work the land
Riparian buffer strips	None
High density planting	None
Crop rotation	None
Timeliness	Potentially high if contractors are used or equipment is shared
Land use change (arable to pasture)	None
Agro-forestry	High
Shelterbelts	Minimal, may hinder machinery along field borders
Subsoiling	None
Drainage	None
Reduced tillage	None
Zero tillage	None
Tramline management	None
Coarser seedbeds	None
Stocking density i.e. reduced	None
Contour ploughing	See maintenance costs
Swales	Minimal, normally located in marginal field corners or natural depressions
Earth banks	May alter direction in which tractors can work and limit size of machinery used on land

Loss of agricultural production

Some mitigation measures imply loss of agricultural production because land use is changed or land is taken out of production. In some cases this may result in substantial losses for a farmer. The costs of loss of agricultural production are typically dependent on the size of the area taken out of production and the value of the land cover as determined by market prices (Table 18).

Table 18: Costs of loss of agricultural production due to mitigation measures

Mitigation measure	**Loss of agricultural production**
Cover crops (winter cover)	Switch from winter cereals to spring cereals: £175 ha^{-1}
Cover crops (under sown)	None
Geo-textiles	High (likely to be in high value crop)
Mulching	None
In-field buffer strips	See Table 19
Riparian buffer strips	See Table 22
High density planting	None
Crop rotation	Changes in gross margin – see Table 20:
Timeliness	Potentially high if timing wrong or delays result in lost growing season
Land use change (arable to pasture)	Changes in gross margin – see Table 20:
Agro-forestry	If managed correctly may lead to diversification of productivity although overall yield of a single crop may be reduced.
Shelterbelts	Some yield reduction at field borders due to shading and competition for water and nutrients
Subsoiling	None, although grassland may be affected because of damage to the root system
Drainage	None
Reduced tillage	Potential yield reduction (6%) cereals (Quinton and Catt, 2004)
Zero tillage	Potential yield reduction (6%) cereals (Quinton and Catt, 2004)
Tramline management	None
Coarser seedbeds	Potential yield reduction
Stocking density i.e. reduced	£85 ha^{-1} for dairy (RPA 2003)
Contour ploughing	None
Swales	Minimal because located at less productive corners
Earth banks	some loss

Table 19 presents an overview of the gross margins of common arable crops, and the costs (£ ha^{-1}) of losing productive land to buffer strips or shelter belts assuming a field of 100 by 100 metres (1 ha).

Table 19: Costs (£ ha^{-1}) of loss of productive land due to mitigation measures at 2009 prices

Crop	Gross Margin (£ ha^{-1})	Buffer strips					Shelterbelts	Other
		2m	4m	6m	12m	24m		5% loss of land
Winter wheat (feed)	602	12	24	36	72	144	12	30
Winter wheat (milling)	559	11	22	34	67	134	11	28
Spring wheat (feed)	427	9	17	26	51	102	9	21
Winter barley (feed)	421	8	17	25	51	101	8	21
Winter barley (malting)	463	9	19	28	56	111	9	23
Spring barley (malting)	474	9	19	28	57	114	9	24
Field beans (winter)	440	9	18	26	53	106	9	22
Winter oilseed rape	510	10	20	31	61	122	10	26
Spring oilseed rape	335	7	13	20	40	80	7	17
Sugar beet	1006	20	40	60	121	241	20	50
Potatoes (early)	1529	31	61	92	183	367	31	76
Potatoes (main crop)	2435	49	97	146	292	584	49	122

Assuming a standard crop rotation for cereals (winter wheat – oilseed rape – winter wheat – field beans), the cost of losing productive land due to a 6m or 12m buffer strip would be £32 ha^{-1} or £64 ha^{-1} respectively. However, taking land for general cropping out of production that includes potato in a 1:6 rotation results in higher costs (£56 ha^{-1} or £112 ha^{-1} for 6m and 12m strips respectively).

Changes in crop rotation, timeliness or changes in land use may result in a change of land use. The costs associated with changes in land use also depend on land cover and market prices. If one type of crop is replaced by another type of crop, the loss of income is equal to the difference in the net margins. However, if arable land is turned into grassland, the farming enterprise is changed and the difference in net margin (taking into account fixed costs such as machinery and buildings) may be more appropriate. Typical losses of changes in land cover or land use (at 2009) prices are given in Table 20. If root crops such as potato or sugar beet are taken out of the crop rotation, the farmer has considerable losses in income. Although potato is typically grown in rotation (e.g. once every six years), the average annual loss is still considerable (Table 20).

Table 20: Costs (£ ha^{-1}) of land use change based on 2009 prices

Previous crop	New crop	Loss in gross margin (£ ha^{-1})	Rotation previous crop	Annual loss in gross margin (£ ha^{-1})
Winter wheat	Spring wheat	175	1:2	88
Winter barley	Spring barley	-11	1:2	-6
Potato	Winter wheat	1833	1:6	306
Sugar beet	Winter wheat	404	1:6	67
Potato in rotation	Winter wheat in rotation			327
Sugar beet in rotation	Winter wheat in rotation			89
Winter wheat in rotation	Grassland[1]			281
Potato in rotation	Grassland[1]			607
Sugar beet in rotation	Grassland[1]			369

[1] assuming extensive beef cattle (22-24 months finishing grass) at gross margin of £258 ha^{-1} (ABC 2009)

Table 21 contains a summary of the different types of on-site costs of mitigation measures and an average annual cost per hectare. Dividing the investment costs by the lifetime of the mitigation measures, and adding the annual maintenance costs gives the average annual cost. Note that many assumptions had to be made to allow estimation of these costs, such as the dimensions of the mitigation measures, crop rotations, crop prices, and field operations involved in implementing the mitigation measures. In reality, the costs for individual farmers may be very different. In particular the costs of agronomic measures are highly dependent on the value of current land use.

Table 21: Overview of on-site costs (£ ha^{-1}) of mitigation measures

Mitigation measure	Investment costs	Maintenance costs	Hindrance to farming operations	Loss of agricultural production	Total annual cost (£ ha^{-1})
Cover crops (winter cover)	148	25	None	Switch from winter cereals to spring cereals : £175	348
Cover crops (under sown)	75	25	None	None	100
Geotextiles	257	5	Negligible	£27 (cereals) to £47 (general cropping)	80 to 100
Mulching	100	0	None	None	50
In-field buffer strips (6m)	32	1.5	Some	£32 (cereals) to £56 (general cropping)	40 to 64
Riparian buffer strips (6m)	32	1.5	None	£32 (cereals) to £56 (general cropping)	40 to 64
High density planting	5	None	None	None	5
Crop rotation	None	25	None	Change in value of agricultural production	-6 to 306
Timeliness	None	70	Potentially high	Potentially high	70
Land use change (arable to grass)	Potentially very high if change in agricultural enterprise	None	None	Cereals to pasture: £281; General cropping to pasture: £607	281 to 607
Agro-forestry	503	Variable	Huge hindrance	Potentially high: major change in land use	25
Shelterbelts	670	0	Low	£11 (cereals) to £19 (general cropping)	44 to 52
Subsoiling	48	None	None	None	16
Drainage	2,000	Negligible	None	None	80
Reduced tillage	None	50	None	£32 (cereals)	82
Zero tillage	Possibly purchase of specialist machinery	67	None	£32 (cereals)	99
Tramline management	None	20	None	None	20
Coarser seedbeds	None	34	None	None	34
Stocking density	None	40	None	£85 ha^{-1} for dairy (RPA 2003)	125
Contour ploughing	None	32	not suitable for slopes > 10%	None	32
Swales	212	Negligible	May cause some hindrance	Dependent on size swale & land use	14
Earth banks	218	Negligible	Potentially high	£11 (cereals) to £19 (general cropping)	55 to 63

On-site financial benefits
The mitigation measures may also have on-site financial benefits, such as savings in field operations (labour and fuel), positive impacts on yield / productivity, financial benefits of 'by-products', and agri-environment payments under the Environmental Stewardship and English Catchment Sensitive Farming Delivery Initiative schemes (Table 22). These benefits accrue directly to the farmer.

Table 22: Overview of on-site benefits (£ ha^{-1}) of mitigation measures

Mitigation measure	**Savings in field operations**	**Impacts on yield**	**By-products**	**Agri-environment payments**	**Total annual benefit** (£ ha^{-1})
Cover crops (during winter)				HLS: £200 ha^{-1}	200
Cover crops (under sowing maize)	None	Retain status quo		HLS: £18 ha^{-1}	18
Geotextiles	None	Retain status quo	None	None	0
Mulching	None	Increase	None	None	0
In-field buffer strips (6m)	None	Retain status quo		HLS: £400 ha^{-1}	24
Riparian buffer strips (6m)	None	None		HLS: £400 ha^{-1}	24
High density planting	None	Increase (due to crop density) +10%?	None	None	
Crop rotation	None	None	Depending on changes	None	0
Timeliness	None	None	None	None	0
Land use change (arable to extensive grass)	None	N/A		HLS: £210 ha^{-1}	210
Agro-forestry	None	Retain status quo	Depending on tree species	HLS: £190 ha^{-1} (creating orchards); £95 ha^{-1} (managing orchards)	105
Shelterbelts	None	Retain status quo	None	HLS: £5 m^{-1} (for planting); £0.27 m^{-1} (maintenance)	52
Subsoiling	None	Increase?	None	None	0
Drainage	None	Increase?	None	None	0
Reduced tillage	Cuttle *et al*. 2007: £40 ha^{-1}	Retain status quo	None	None	40
Zero tillage		Retain status quo	None	HLS: 70	70
Tramline management	None	None	None	None	0
Coarser seedbeds	Rolling: £26 ha^{-1} (Nix 2009)	Retain status quo	None	None	26
Stocking density	None	Retain status quo	None	HLS: 40	40
Contour ploughing	None	Potential yield increase (16%) cereals (Quinton and Catt, 2004)	None	None	85
Swales / sediment traps	None	None	None	CSF: £6 m^{-2} (investment costs)	1
Earth banks	None	None	None	HLS: £3 m^{-1}	60

Savings in field operations
These are most likely to occur in the soil management measures such as reduced tillage.

Impacts on yield
Most mitigation measures are expected to impact yield over the longer term by maintaining or improving soil productivity, but immediate impacts may not be obvious. It is more likely that the mitigation measures which aim to prevent erosion will have a bigger positive impact on yield than the mitigation measures that trap sediments and runoff at the bottom of fields.

By-products
Some mitigation measures, such as cover crops or agro-forestry, may provide additional tradable products.

Agri-environment payments
Agri-environment schemes such as the Environment Stewardship and Catchment Sensitive Farming provide a financial reward for a selection of farming practices: buffer strips, land use change, shelterbelts (hedgerows), stocking density and swales. However, HLS agreements are awarded on a competitive basis, thus not all farmers may be able to obtain these.

Financial cost-benefit analysis of mitigation measures
The Net Present Value (NPV) is the most widely used criterion in cost-benefit analysis. It determines the present value of net benefits (or costs) by discounting the streams of benefits (*B*) and costs(*C*) at the rate *r* (set at 3.5%), arising between the present (t =0) and *t* time periods into the future. The NPV is thus calculated using the following equation:

$$NPV = \sum_{t=0}^{t} \frac{B_t - C_t}{(1+r)^t} = (B_0 - C_0) + \frac{B_1 - C_1}{(1+r)} + \frac{B_2 - C_2}{(1+r)^2} + \cdots + \frac{B_t - C_t}{(1+r)^t}$$

In addition, benefit-cost ratios (BCs) are calculated by dividing the total value of benefits by the total value of costs. Benefit-cost ratios between 0 and 1 imply that the costs are higher than the benefits, and vice versa for ratios higher than 1. For some mitigation measures the costs fall within a range (see Table 23) and this has been taking into account when calculating the NPVs and BCs. The range of the NPVs and BCs thus reflect the minimum and maximum estimated values for the benefits and costs associated with each mitigation measure.

The financial NPVs and BCs have been calculated for each mitigation measure, taking into the on-site costs and benefits that directly accrue to the farmer. A time period of 5 years has been assumed, as this is generally the time period of environmental stewardship agreements. Note that some mitigation measures have a lifetime that goes beyond the 5 years. The results are given in Table 23. The financial NPVs are typically negative, meaning that the costs of the mitigation measures are higher than the benefits. This explains why farmers are so reluctant to implement mitigation measures without compensation. The current payments available under the Higher Level Scheme are not sufficient to compensate for the costs incurred. Uncertain benefits, such as yield impact or retention of fertilisers have not been taken account.

Only a few mitigation measures have potentially positive financial NPVs: contour ploughing, agro-forestry, and earth banks. The costs associated with contour ploughing are low as it does not involve any investment costs or loss of agricultural production. Experiments suggest that yields may increase by 16 per cent (Quinton and Catt, 2004), possibly due to better water conservation on contoured plots (although yield is dependent on many other factors too, so this increase may not be attributable to the contour cultivation alone). However, contour ploughing is not suitable on slopes greater than 10 per cent or on rolling topography. It needs to be undertaken carefully to be effective as runoff can be channelled into slope depressions resulting in rill and gully erosion (Deasy et al., 2009). Agro-forestry seems profitable; however, it has to be noted that the costs associated with land use change has not been taken into account as this depends on what trees will be used. Switching to agro-forestry will also involve costs at farm-level as a farmer changes the farm enterprise which will require additional investment costs in fixed assets. These costs are situation dependent and not taken into account. The financial costs and benefits associated with earth banks are about equal, but it has to be noted that no data were available on the costs involved with establishing earth banks and the costs of digging a ditch were therefore taken as a proxy. In general, one can thus say that soil erosion mitigation measures imply negative returns for farmers, but some are less costly than others. Potential benefits for farmers, such as yield increase, are uncertain and often falls within the range of natural variability of yields.

Table 23: Analysis of on-site costs and benefits (£ ha^{-1}) of mitigation measures

Mitigation measure	**Lifetime**	**Annual financial costs**	**Annual financial benefits**	**Net annual benefit**	**Benefit-cost ratio** (for 5 year period)	**Financial NPVs** (for 5 year period at 3.5% discount rate)
Cover crops (during winter)	1	315	200	-115	0.64	-518
Cover crops (under sowing maize)	1	100	18	-82	0.18	-369
Geotextiles	5	80 to 100	0	-99 to -79	0	-473 to -383
Mulching	2	50	0	-50	0	-100
In-field buffer strips (6m)	5	40 to 64	24	-40 to -16	0.38 to 0.60	-163 to -75
Riparian buffer strips (6m)	5	40 to 64	24	-40 to -16	0.38 to 0.60	-163 to -75
High density planting	1	5	0	-5	0	-22
Crop rotation	1	-6 to 306	0	-306 to 6	0.02 to 7.0	-1382 to 27
Timeliness	1	70	0	-70	0	-316
Land use change (arable to extensive grass)	1	281 to 607	210	-397 to -71	0.35 to 0.75	-1792 to -321
Agro-forestry	20	25	105	80	1.32	116
Shelterbelts	20	44 to 52	52	0 to 8	0.83 to 0.88	-132 to -96
Subsoiling	3	16	0	-16	0	-48
Drainage	25	80	0	-80	0	-2000
Reduced tillage	1	82	40	-42	0.49	-191
Zero tillage	1	99	70	-29	0.71	-131
Tramline management	1	20	0	-20	0	-90
Coarser seedbeds	1	34	26	-8	0.78	-34
Stocking density	1	125	40	-85	0.47	-203
Contour ploughing	1	32	85	54	2.13	205
Swales / sediment traps	15	14	1	-13	0.07	-133
Earth banks	5	55 to 63	60	-2 to 6	0.98 to 1.12	2 to 39

The NPVs change when different discount rates and time periods are used. Note that it has been assumed that mitigation measures with a short lifespan (stubble mulch, sub-soiling and earth bank) were re-installed every 5 years. Table 24 shows the results of a sensitivity analysis with different discount rates and time periods. Although the NPVs change in terms of magnitude, mitigation measures with negative NPVs remain negative over a longer time period or under a different discount rate.

Table 24: Sensitivity analysis of financial NPVs of mitigation measures

Time horizon	5 years			10 years			15 years		
Discount rate	3.5%	5%	10%	3.5%	5%	10%	3.5%	5%	10%
Cover crops (winter cover)	-518	-497	-435	-954	-886	-705	-1321	-1191	-872
Cover crops (undersown maize)	-369	-354	-310	-679	-631	-502	-941	-848	-621
Geo-textiles	-473 to -383	-464 to -378	-438 to -363	-657 to -490	-628 to -474	-552 to -429	-811 to -581	-756 to -549	-622 to -470
Stubble mulch	-100	-100	-100	-181	-175	-156	-250	-233	-191
In-field buffer strips (6m)	-163 to -75	-177 to -73	-159 to -68	-290 to -111	-291 to -105	-238 to -90	-398 to -141	-380 to -130	-287 to -104
Riparian buffer strips (6m)	-163 to -75	-177 to -73	-159 to -68	-290 to -111	-291 to -105	-238 to -90	-398 to -141	-380 to -130	-287 to -104
High density planting	-22	-21	-19	-41	-38	-30	-56	-51	-37
Crop rotation	-1382 to 27	-1325 to 26	-1160 to 23	-2545 to 50	-2363 to 46	-1880 to 37	-3524 to 69	-3176 to 62	-2327 to 46
Timeliness	-316	-303	-265	-582	-541	-430	-806	-727	-532
Land use change (arable to pasture)	-1792 to -321	-1719 to -307	-1505 to -269	-3302 to -590	-3066 to -548	-2439 to -436	-4572 to -818	-4121 to -737	-3020 to -540
Agro-forestry	116	98	47	477	421	271	781	673	410
Shelterbelts	-132 to -96	-134 to -99	-138 to -108	-101 to -34	-106 to -44	-119 to -70	-74 to 18	-84 to 0	-107 to -46
Sub-soiling	-48	-48	-48	-87	-84	-75	-120	-112	-92
Drainage	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-2000
Reduced tillage	-191	-183	-160	-351	-326	-260	-487	-439	-321
Zero tillage	-131	-126	-110	-241	-224	-178	-334	-301	-221
Tramline management	-90	-87	-76	-166	-154	-123	-230	-208	-152
Coarser seedbeds	-34	-32	-28	-62	-58	-46	-86	-78	-57
Stocking density i.e. reduced	-203	-195	-171	-374	-347	-277	-518	-467	-342
Contour ploughing	205	196	172	377	350	279	522	471	345
Swales	-133	-127	-110	-254	-235	-185	-356	-319	-231
Earth bank (100m length)	2 to 39	6 to 41	16 to 47	2 to 69	7 to 69	21 to 70	2 to 94	8 to 91	24 to 85

Step 3: Determine the effectiveness of mitigation options on soil erosion.

Several studies have looked at the effect of mitigation measures on off-site impacts of soil erosion. The mitigation measures have been assessed on their effectiveness to reduce runoff, loss of soil sediments and loss of phosphorus. However, the effects are highly dependent on local circumstances (e.g. soil type, slope, crop, climate) and the results vary widely for each study (see Table 25) Note that only the effects of mitigation measures on water erosion have been studied. No data are available on the effects of the mitigation options on other forms of erosion (e.g. wind erosion, tillage erosion).

Table 25: Estimated effects of mitigation measures on soil erosion processes

Mitigation measure	Estimated reduction of runoff	Estimated reduction of soil loss	Estimated reduction of P loss
Cover crops (winter)		5% to 10% (Collins et al., 2009)	25% to 35% (Cuttle et al., 2007); 25% (Anthony et al., 2009)
Cover crops (under sown maize)			
Geo-textiles			
Mulching	20% (Bailey et al., 2007) to 43% (Deasy et al., 2009)	40% (Deasy et al., 2009) to 78% (Stevens et al., 2009)	30% to 60% (Bailey et al., 2007)
In-field buffer strips	9% to 98%, average of 72% (Stevens et al., 2009)	5% to 50% (Collins et al., 2009)	40% (Cuttle et al., 2007)
Riparian buffer strips		5% to 30% (Collins et al., 2009); 20% to 40% (Wood et al., 2007); 70% to 80% (Bradbury and Kirby, 2006); 84% (Deasy et al., 2009)	30% (Cuttle et al., 2007); 70% to 98% (Bradbury and Kirby, 2006); 25% (Anthony et al., 2009)
High density planting			
Crop rotation (spring crops)		5% to 10% (Collins et al., 2009)	50% to 70% (Cuttle et al., 2007); 10% (Anthony et al., 2009)
Timeliness			10% (Anthony et al., 2009)
Land use change (arable to pasture)		30% to 80% (Collins et al., 2009)	42% to 50% (Cuttle et al., 2007)
Agro-forestry		65% (Louwagie et al., 2009)	
Shelterbelts		5% to 20% for hedgerows (Collins et al., 2009)	10% to 50% for hedgerows (Cuttle et al., 2007); 5% (Anthony et al., 2009)
Subsoiling		1% (Collins et al., 2009)	50% to 70% for grassland (Cuttle et al., 2007); 25% (Anthony et al., 2009)
Drainage			
Reduced tillage	0% (Louwagie et al., 2009; Stevens et al., 2009)	5% (Collins et al., 2009) to 58% (Louwagie et al., 2009)	5% (Cuttle et al., 2007); 39% to 98% (Deasy et al., 2009); 10% (Anthony et al., 2009)
Zero tillage	0% (Stevens et al., 2009) to 29% (Louwagie et al., 2009)	5% (Collins et al., 2009) to 69% (Stevens and Quinton, 2009)	66% to 76% (Kronvang et al., 2005)
Tramline management	96% to 97% (Deasy et al., 2009)	5% to 10% (Collins et al., 2009); 72% to 97% (Deasy et al., 2009); 86% to 97% (Silgram et al., 2009)	75% (Silgram et al., 2010); 75% to 99% (Deasy et al., 2009); 50% (Anthony et al., 2009)
Coarser seedbeds			25% to 35% (Cuttle et al., 2007)
Stocking density		10% to 20% (Collins et al., 2009)	10% to 35% (Cuttle et al., 2007)
Contour ploughing	9% to 98%, average of 72% (Stevens et al., 2009)	1% (Collins et al., 2009); 9% to 98%, average of 72% (Stevens et al., 2009)	9% to 98%, average of 72% (Stevens et al., 2009); 25% to 35% (Cuttle et al., 2009)
Swales			
Earth banks			
Terraces			

Based on the results presented in Table 25, the mitigation options have been classified into six effectiveness classes (Table 26) following the methodology of Anthony *et al.* (2009). In case of missing data, mitigation options were classified based on the performance of other similar mitigation measures. Table 27 classifies the mitigation options based on their effectiveness for the control of runoff, soil loss and P loss. Table 27 also shows the estimated carbon sequestration for each mitigation option, based on estimates from ADAS (2006).

Table 26: Average % effectiveness classes and uncertainty range of mitigation methods

Class	Average	Uncertainty range	Erosion reduction
A	0	0	None
B	2	0 to 10	Very low
C	10	2 to 25	Low
D	25	10 to 50	Moderate
E	50	25 to 80	High
F	80	50 to 95	Very high

Table 27: Classification of mitigation options in terms of effectiveness

Mitigation measure	Reduction of runoff	Reduction of soil loss	Reduction of P loss	Carbon sequestration (kg C ha^{-1} yr^{-1}
Cover crops (winter)	C: 10%	C: 10%	D: 25%	479
Cover crops (under sown maize)	C: 10%	C: 10%	D: 25%	Unknown
Geo-textiles	E: 50%	D: 25%	D: 25%	612
Mulching	D: 25%	E: 50%	E: 50%	625
In-field buffer strips	E: 50%	D: 25%	D: 25%	612
Riparian buffer strips	E: 50%	E: 50%	E: 50%	612
High density planting	E: 50%	D: 25%	D: 25%	0
Crop rotation (spring crops)	B: 2%	B: 2%	E: 50%	0
Timeliness	B: 2%	B: 2%	E: 50%	0
Land use change (arable to pasture)	E: 50%	E: 50%	D: 25%	612
Agro-forestry	E: 50%	E: 50%	E: 50%	138
Shelterbelts	C: 10%	C: 10%	D: 25%	14
Subsoiling	B: 2%	B: 2%	D: 25%	0
Drainage	B: 2%	B: 2%	D: 25%	Unknown
Reduced tillage	B: 2%	D: 25%	D: 25%	40
Zero tillage	C: 10%	D: 25%	E: 50%	190
Tramline management	F: 80%	F: 80%	F: 80%	0
Coarser seedbeds	B: 2%	D: 25%	D: 25%	0
Stocking density	C: 10%	C: 10%	D: 25%	0
Contour ploughing	E: 50%	E: 50%	E: 50%	0
Swales	E: 50%	D: 25%	D: 25%	0
Earth banks	E: 50%	D: 25%	D: 25%	0

The annual costs of mitigation measures are plotted against their effectiveness class to reduce runoff, soil loss and loss of phosphorus in Figure 23a,b & c. The mitigation measures in the right bottom corner have the highest effect on soil erosion at the lowest cost; in other words, these are the most cost-effective. According to this assessment, tramline management, contour ploughing, mulching and riparian buffer strips are the most cost-effective mitigation measures.

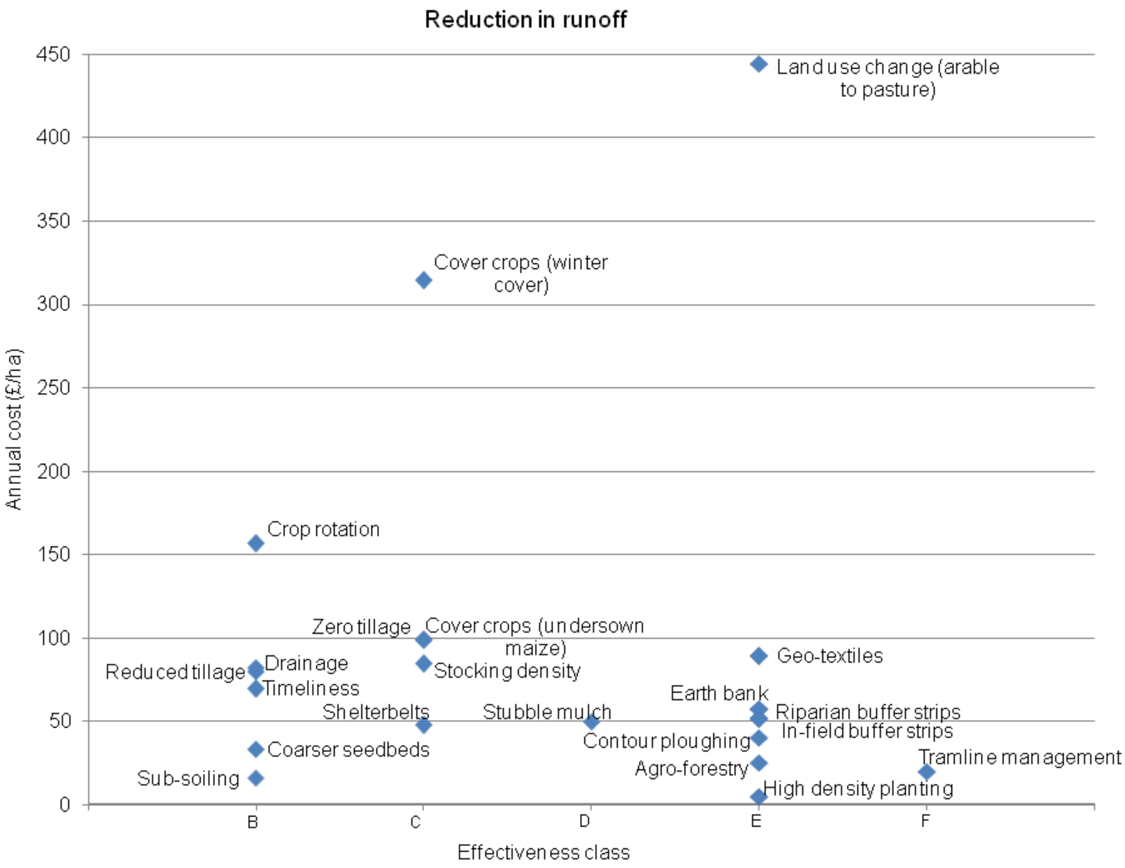

Figure 23a: Annual cost and effectiveness class of mitigation measures for runoff reduction

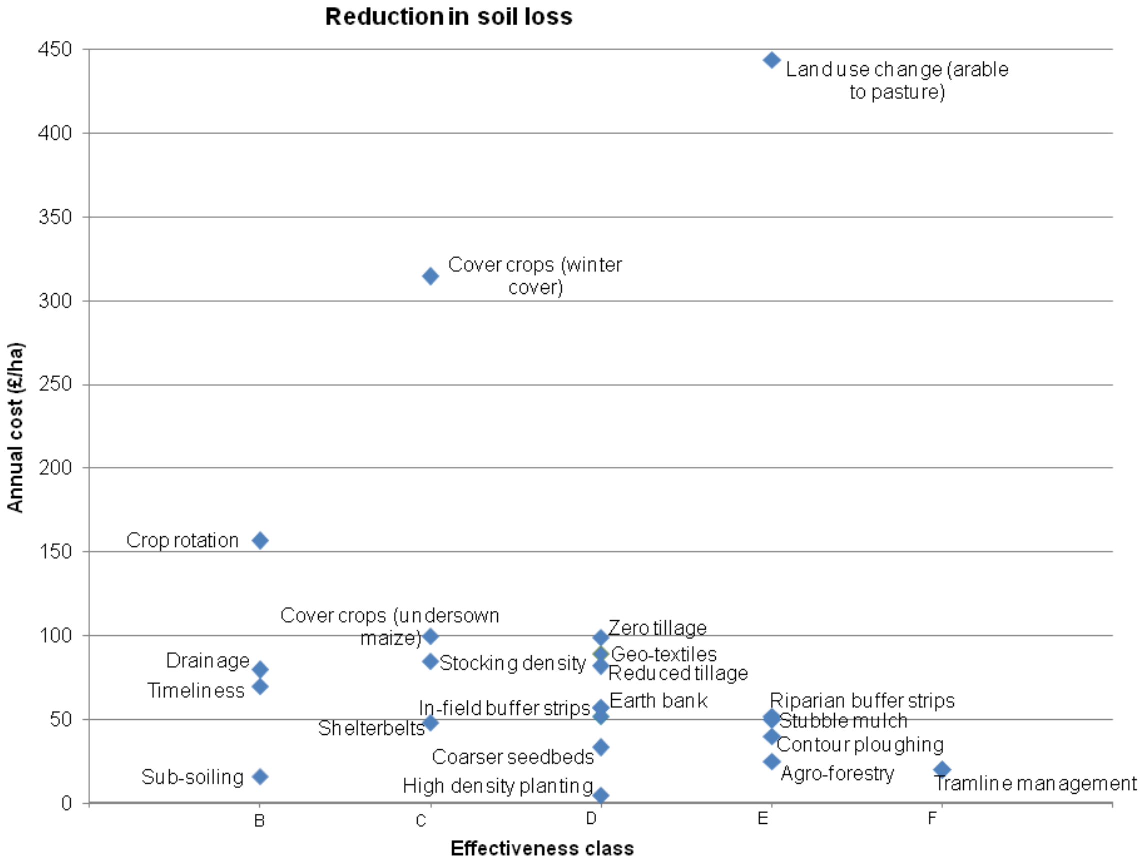

Figure 23b: Annual cost and effectiveness class of mitigation measures for soil conservation

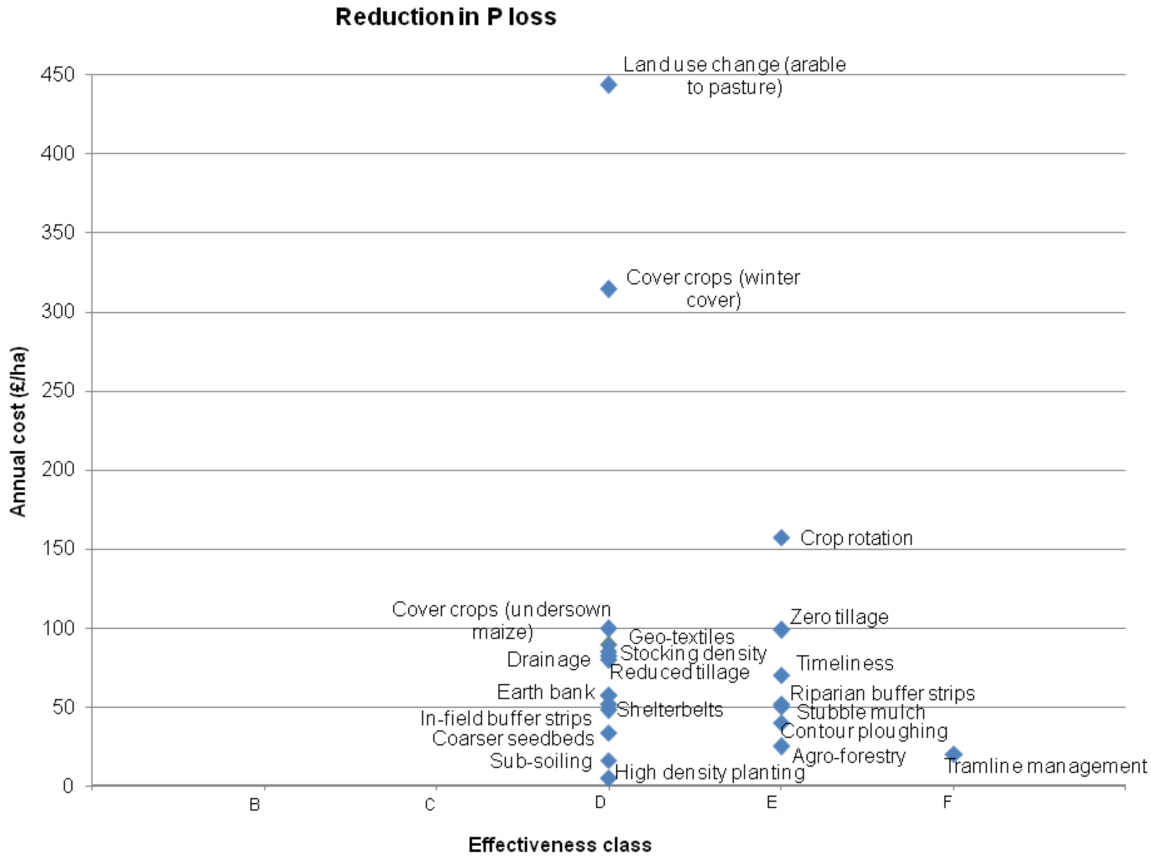

Figure 23c: Annual cost and effectiveness class of mitigation measures for reducing loss of phosphorus

Figure 24a, b & c plots the financial NPVs of the mitigation measures against the effectiveness class of the mitigation measures. The mitigation measures in the top right corner are most effective from a farmers' point of view; that is, these measures have the largest impact on soil erosion at the lowest farmer's cost. The mitigation measures tramline management, contour ploughing, earth banks, high density planting, in-field buffer strips and riparian buffer strips are most cost-effective from a farmer's point of view. Earth banks and in-field buffer strips, however, are implemented along the contour and require contour ploughing. As Deasy et al. (2009) point out there is a farmer resistance to contour ploughing in the UK because it requires skilful and meticulous tillage operations and it is only suitable for moderate and uniform slopes. These measures therefore are not suitable to be promoted as blanket recommendations. Tramline management, high-density planting and riparian buffer strips seem more appropriate measures for widespread adoption.

However, it is important to note that the actual cost-effectiveness of mitigation measures will differ for local circumstances. It is therefore advised that individual assessments are made at farm- or field-level before recommendations are made to farmers.

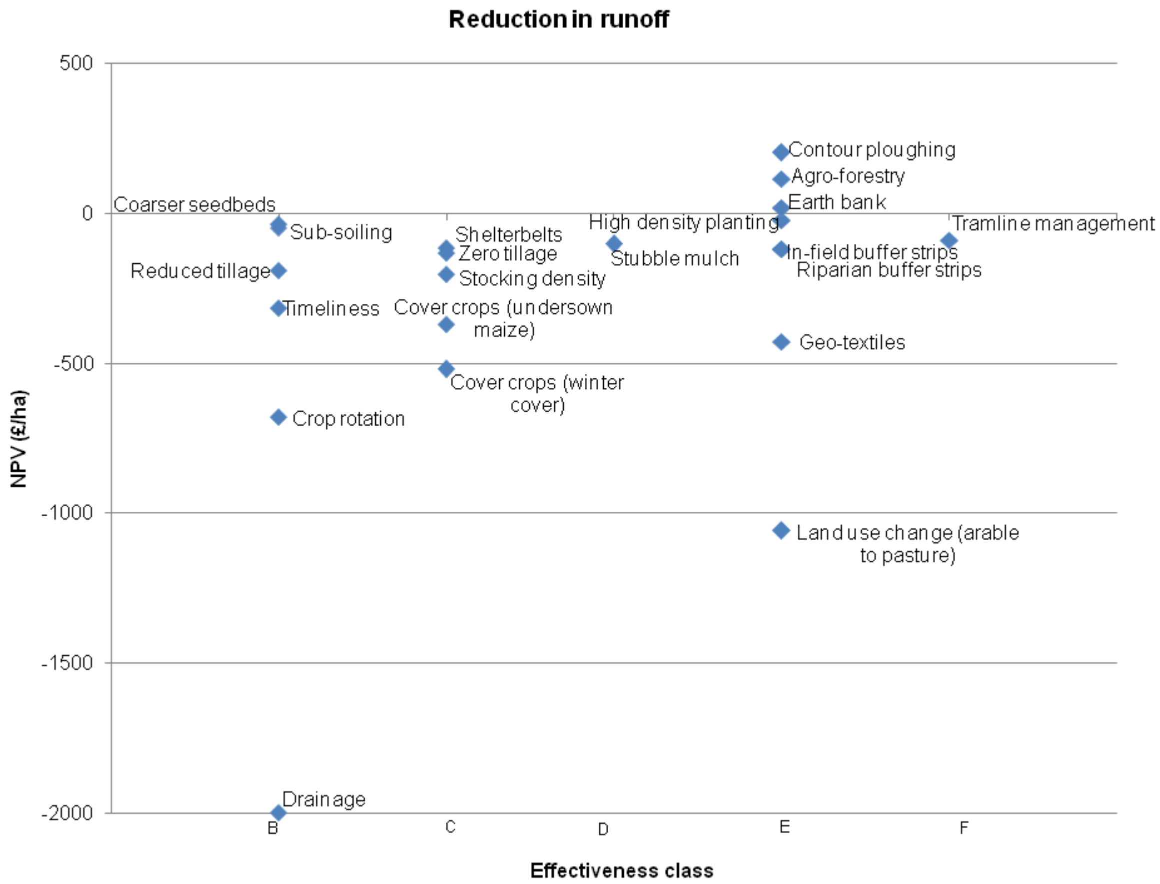

Figure 24a: Net Present Value (NPV) and effectiveness class of mitigation measures for runoff reduction

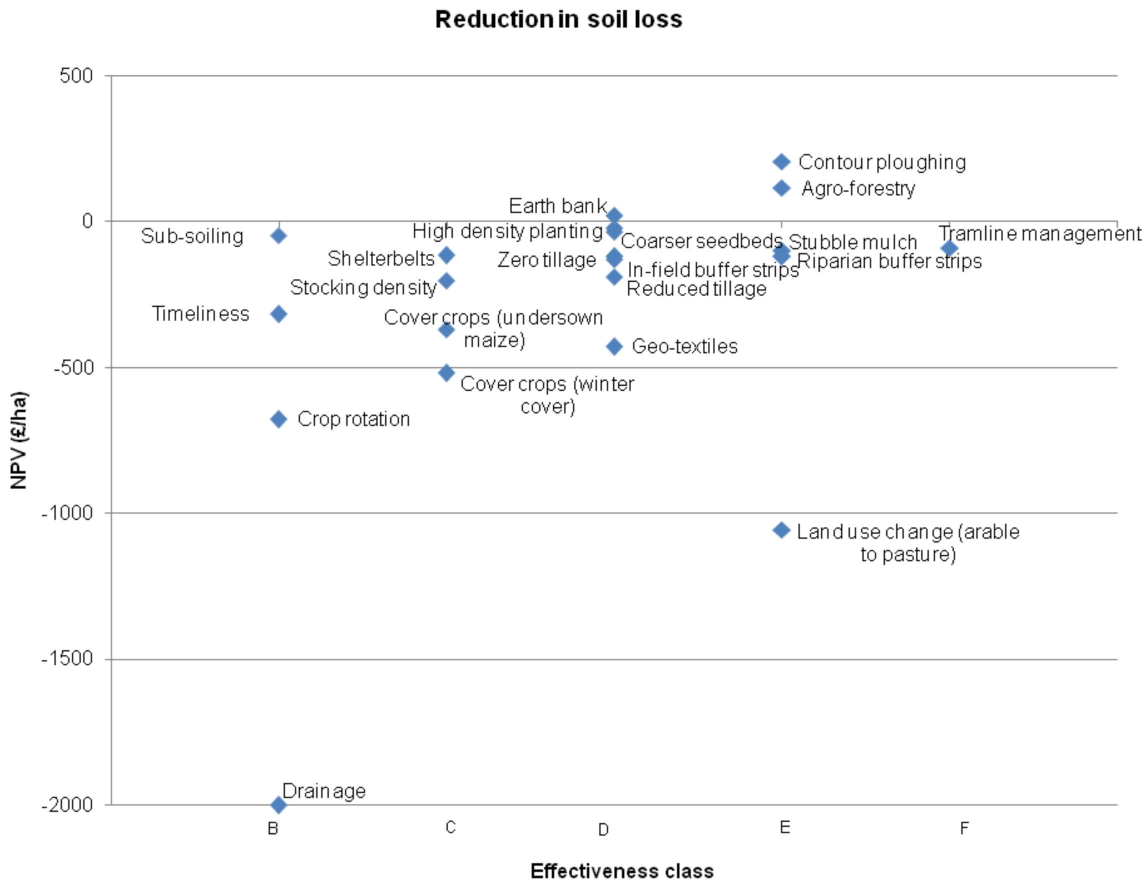

Figure 24b: Net Present Value (NPV) and effectiveness class of mitigation measures for soil conservation

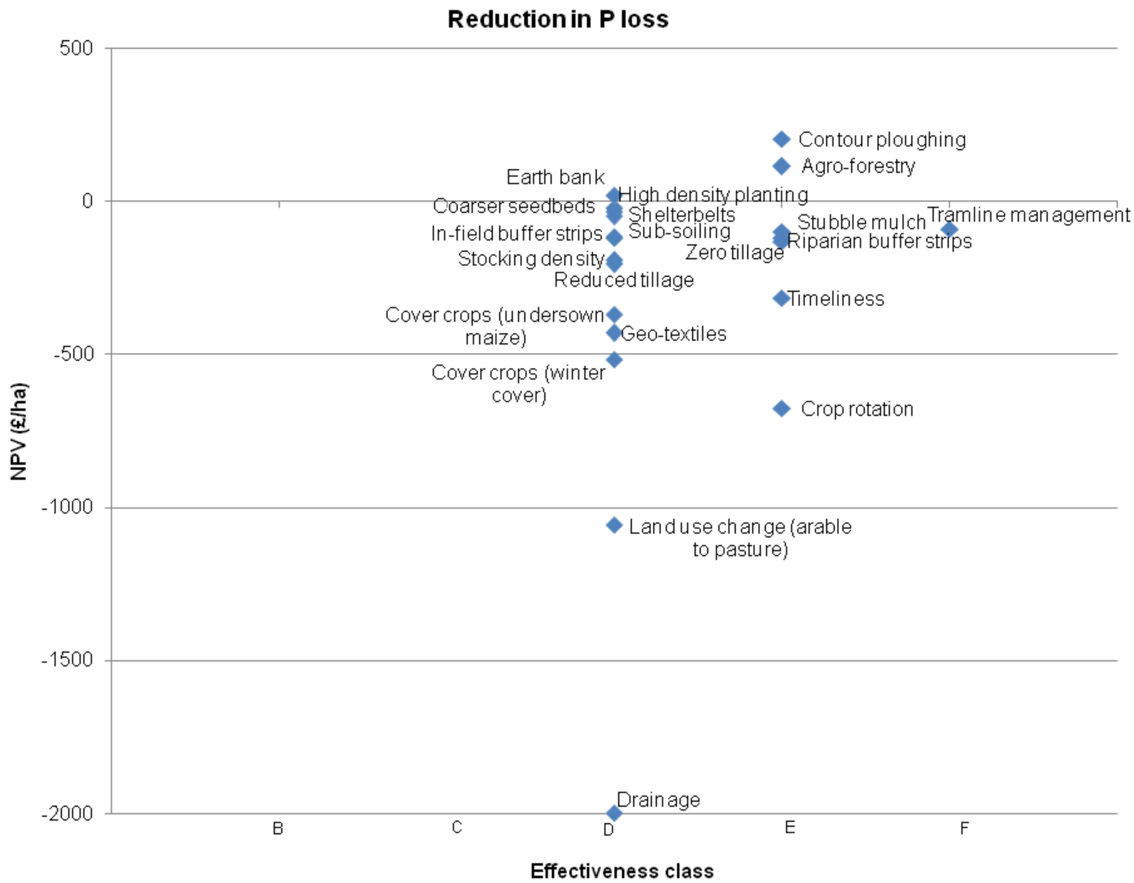

Figure 24c: Net Present Value (NPV) and effectiveness class of mitigation measures for reducing loss of phosphorus

Step 4: Value the impacts of mitigation options on specific ecosystem services.

In order to calculate the economic NPV of the mitigation measures, the impacts on a selection of ecosystem services are estimated based on secondary data. However, it has to be stressed again that the accuracy of these estimates are uncertain as there are many knowledge gaps and missing data.

Based on the data summarised in Table 14, the impact of the mitigation measures is estimated on the following ecosystem services: support of food, fuel and fibre production, carbon sequestration, water discharge, flood regulation, provision of drinking water, water quality, infrastructure and recreation (Table 28). The benefits are calculated as cost reductions (or costs foregone) due to reduced soil erosion impacts. Note that for flood regulation three different values (minimum, median and maximum) have been used to reflect the different estimates of flood damage costs due to soil erosion.

The total agricultural area in the UK is estimated at 18.7 million hectares (Defra, 2008). It is assumed that 17 per cent of the total agricultural land is affected by soil erosion (see Section C.1.). The total baseline costs (Table 14) have thus been divided by the total area affected by erosion (that is, 3.2 million hectares), and multiplied with the percentage of the total costs attributable to agriculture, to calculate the average baseline cost of soil erosion per hectare (see Table 28). However, it should be noted that the erosion induced costs on individual fields are context specific. For example, erosion induced costs are typically higher for arable land than for grassland. Similarly, the impacts of mitigation measures on erosion induced costs depend on the actual erosion rate and the location of the field within the landscape. However, due to lack of data on erosion-induced costs attributable to different land uses and topography, these factors have not been taken into account.

Care has been taken to avoid double-counting damage costs to similar ecosystem services. For that reason, the damage cost of soil fertility has been omitted as yield decline has been included. The costs associated with drainage and flood regulation are potentially correlated, but different types of costs have been considered, that is, the costs associated with dredging of water courses and the damage costs due to flooding. It is thus thought that the risk of double-counting costs associated with erosion has been kept to a minimum.

Table 28: Impact of mitigation measures on ecosystem services

a) 'On-site' ecosystem services (related to soil functions)

Ecosystem services		Soil erosion impact	National baseline cost (£)	% baseline cost attributable to agriculture	Baseline cost (£ ha^{-1})	Impact mitigation measures
Provision	Support of food, fuel and fibre production	Reduced yields due to soil erosion	£ 9 million (Evans, 1996)	100%	£2.83 ha^{-1}	Reduction in soil loss
Regulation	Regulating the flow of and filtering substances from water	Reduced water holding capacity	Benefit is highly site/catchment specific. Change in agricultural land use can impact local runoff generation, but only major land use changes (urbanisation or afforestation) have a significant effect on water storage at catchment level (Posthumus and Morris, 2007)			
	Carbon sequestration	Reduced soil carbon (organic matter content)	Estimates of ADAS (2006) are used.	100%	Dependent on mitigation measures (see ADAS, 2006)	Carbon sequestration
	Soil fertility / quality	Reduced soil productivity	To avoid double-counting, it is assumed that soil fertility is included in the category 'support of food, fuel and fibre production'			
Supporting	Support of below-ground biodiversity	Loss of soil biota	Valuation literature is not sufficiently detailed or extensive to allow the value of changes in soil erosion on biodiversity to be estimated (ADAS, 2006)			
	Support of above-ground biodiversity	Loss of (above ground) biodiversity	Valuation literature is not sufficiently detailed or extensive to allow the value of changes in soil erosion on biodiversity to be estimated (ADAS, 2006)			
Cultural	Protection of cultural heritage and archaeology	Exposure of archaeological features leading to increased risk of damage	There is lack of evidence on the value of the benefits or costs from soil management impacts on the archaeological heritage (ADAS, 2006)			
	Cultural landscapes	Reduced landscape value	There are too many unknowns – lack of valuation studies and not known how much can be apportioned to agriculture (or erosion) (Spencer et al., 2009)			

b) 'Off-site' ecosystem services

Ecosystem services		**Soil erosion impact**	**National baseline cost (£)**	**% baseline cost attributable to agriculture**	**Baseline cost (£ ha^{-1})**	**Impact mitigation measures**
Provision	Support of food, fuel and fibre production	Reduced yields due to sedimentation	No information available on yield loss caused by sedimentation.			
Regulation	Drainage / discharge of water	Siltation of water courses	£69.5 million (various sources, see Table 14)	76%	£16.62 ha^{-1}	Reduction in soil loss
	Flood regulation	Increased flood risk / damage	£29 million to £128 million (EA, 2007); £234 million (Spencer et al., 2008)	100%	Minimum £9.12 ha^{-1} ; median £40.26; maximum £73.61 ha^{-1}	Reduction in runoff
	Provision of drinking water	Water treatment costs to remove pollutants & sediments	£21.17 million (EA, 2007)	75%	£4.99 ha^{-1}	Reduction in soil loss
		Reservoir capacity	Benefit is highly catchment-specific			
	Water quality	Eutrophication of lakes	£27 million (EA, 2007)	100%	£8.49 ha^{-1}	Reduction in P loss
	Air quality	Air pollution affecting human health	No data available on the impact of soil particles on human health			
Supporting	Infrastructure	Obstruction of roads due to sedimentation	£8.74 million (Spencer et al., 2008)	95%	£2.61 ha^{-1}	Reduction in soil loss
	Wetland habitat	Sediments affecting wetland biodiversity	Valuation literature is not sufficiently detailed or extensive to allow the value of changes in sediment delivery on wetland biodiversity to be estimated			
Cultura	Recreation (angling)	Siltation of rivers affecting fish habitat.	£71 million (EA, 2007)	35%	£7.82 ha^{-1}	Reduction in soil loss

The economic NPV (Table 29) has been calculated using the same method as for the financial NPV, but including the benefits for on-site and off-site ecosystem services (Table 28). The agri-environment payments and cost savings that are direct benefits to farmers have not been taken into account for the economic NPV. Three NPV values have been estimated (mean, minimum and maximum value), in order to reflect the range of costs and benefits of each mitigation measures. The minimum and maximum values thus take into account the uncertainty of the effectiveness of the mitigation measures (see Table 27) and the costs associated with the loss of agricultural production (see Table 21). Most mitigation measures have negative economic NPVs. However, some mitigation measures, such as cover crops, land use change, agro-forestry and shelterbelts, are likely to have a positive impact on the support of biodiversity and landscape value, but these ecosystem services were not included in this assessment due to lack of data.

The mitigation measures that have an average positive economic NPV, and are thus worth promoting, are: tramline management, high density planting, mulching, and contour ploughing.

Table 30 shows the results of a sensitivity analysis with different discount rates and time periods for the economic NPVs.

Table 29: Analysis of costs and environmental benefits (£ ha^{-1}) of mitigation measures

Mitigation measure	Lifetime	Annual financial costs	Annual financial benefits	Net annual benefit	Benefit-cost ratio (for 5 year period)	Economic NPVs (for 5 year period at 3.5% discount rate)
Cover crops (during winter)	1	315	35 to 75	-279 to -239	0.11 to 0.24	-1202 (-1262 to -1080)
Cover crops (under sowing maize)	1	100	2 to 31	-98 to -68	0.02 to 0.31	-407 (-442 to -309)
Geotextiles	5	79 to 99	7 to 81	-93 to 1	0.07 to 1.02	-288 (-443 to -19)
Mulching	2	50	12 to 71	-38 to 21	0.59 to 3.57	43 (-47 to 223)
In-field buffer strips (6m)	5	40 to 64	7 to 81	-57 to 41	0.10 to 2.02	-97 (-262 to 181)
Riparian buffer strips (6m)	5	40 to 64	13 to 94	-51 to 54	0.21 to 2.35	-49 (-232 to 239)
High density planting	1	5	7 to 81	2 to 76	1.35 to 16.44	118 (8 to 342)
Crop rotation	1	-6 to 306	2 to 25	-304 to 24	0.01 to 25.00	-667 (-1372 to 108)
Timeliness	1	70	2 to 18	-68 to -52	0.03 to 0.25	-290 (-306 to -236)
Land use change (arable to extensive grass)	1	281 to 607	12 to 91	-595 to -190	0.02 to 0.32	-1825 (-2687 to -858)
Agro-forestry	20	25	13 to 94	-12 to 68	0.13 to 0.93	-314 (-444 to -80)
Shelterbelts	20	44 to 52	2 to 31	-50 to -13	0.01 to 0.22	-693 (-746 to -577)
Subsoiling	3	16	1 to 15	-15 to -1	0.09 to 1.57	-32 (-44 to 20)
Drainage	25	80	1 to 15	-79 to -65	0.00 to 0.04	-1984 (-1996 to -1932)
Reduced tillage	1	82	4 to 29	-78 to -53	0.05 to 0.35	-319 (-352 to -240)
Zero tillage	1	99	6 to 43	-93 to -56	0.06 to 0.43	-370 (-421 to -255)
Tramline management	1	20	26 to 111	6 to 91	1.31 to 5.56	212 (28 to 411)
Coarser seedbeds	1	34	4 to 29	-29 to -4	0.13 to 0.87	-99 (-132 to -20)
Stocking density	1	125	2 to 31	-83 to -54	0.02 to 0.37	-340 (-376 to -242)
Contour ploughing	1	32	13 to 94	-27 to 54	0.33 to 2.34	8 (-121 to 242)
Swales / sediment traps	15	14	7 to 81	-25 to 49	0.21 to 2.53	-4 (-114 to 220)
Earth banks	5	55 to 63	7 to 81	-55 to 27	0.11 to 1.51	-140 (-268 to 102)

Table 30: Sensitivity analysis of financial NPVs of mitigation measures

Time horizon	5 years			10 years			15 years		
Discount rate	3.5%	5%	10%	3.5%	5%	10%	3.5%	5%	10%
Cover crops (winter cover)	-1202 (-1262 to -1080)	-1153 (-1210 to -1036)	-1009 (-1059 to -907)	-2214 (-2324 to -1990)	-2056 (-2158 to -1848)	-1636 (-1717 to -1470)	-3067 (-3218 to -2756)	-2764 (-2901 to -2483)	-2025 (-2125 to -1820)
Cover crops (undersown maize)	-407 (-442 to -309)	-390 (-424 to -296)	-341 (-371 to -259)	-749 (-815 to -568)	-695 (-757 to -528)	-553 (-602 to -420)	-1037 (-1128 to -787)	-935 (-1017 to -709)	-685 (-745 to -520)
Geo-textiles	-288 (-443 to -19)	-287 (-436 to -29)	-283 (-413 to -57)	-316 (-602 to 180)	-312 (-577 to 148)	-300 (-511 to 66)	-339 (-735 to 347)	-331 (-688 to 288)	-311 (-572 to 142)
Stubble mulch	43 (-47 to 223)	37 (-49 to 210)	20 (-55 to 171)	83 (-84 to 413)	71 (-84 to 377)	39 (-84 to 283)	116 (-114 to 574)	96 (-111 to 509)	50 (-102 to 352)
In-field buffer strips (6m)	-97 (-262 to 181)	-95 (-252 to 172)	-87 (-225 to 147)	-153 (-455 to 360)	-144 (-425 to 332)	-121 (-345 to 257)	-199 (-618 to 510)	-183 (-560 to 457)	-142 (-419 to 326)
Riparian buffer strips (6m)	-49 (-232 to 239)	-48 (-224 to 228)	-46 (-200 to 196)	-63 (-401 to 468)	-60 (-375 to 432)	-55 (-305 to 337)	-74 (-543 to 660)	-70 (-493 to 592)	-60 (-369 to 425)
High density planting	118 (8 to 342)	113 (7 to 328)	99 (7 to 287)	217 (14 to 629)	201 (13 to 584)	160 (11 to 465)	300 (20 to 871)	271 (18 to 785)	198 (13 to 576)
Crop rotation	-667 (-1372 to 108)	-640 (-1316 to 104)	-560 (-1152 to 91)	-1229 (-2527 to 200)	-1141 (-2346 to 185)	-908 (-1867 to 147)	-1702 (-3500 to 276)	-1534 (-3154 to 249)	-1124 (-2311 to 183)
Timeliness	-290 (-306 to -236)	-278 (-294 to -227)	-244 (-257 to -198)	-534 (-565 to -435)	-496 (-524 to -404)	-395 (-417 to -322)	-740 (-782 to -603)	-667 (-705 to -543)	-489 (-516 to -398)
Land use change (arable to pasture)	-1825 (-2687 to -858)	-1750 (-2577 to -822)	-533 (-2156 to -720)	-3362 (-4950 to -1580)	-3122 (-4596 to -1467)	-2484 (-3657 to -1167)	-4657 (-6855 to -2188)	-4197 (-6177 to -1972)	-3075 (-4527 to -1445)
Agro-forestry	-314 (-444 to -80)	-322 (-446 to -98)	-344 (-453 to -148)	-155 (-394 to 275)	-180 (-402 to 220)	-246 (-422 to 72)	-21 (-352 to 575)	-69 (-367 to 468)	-185 (-403 to 209)
Shelterbelts	-693 (-746 to -577)	-692 (-743 to -580)	-689 (-734 to -592)	-712 (-811 to -498)	-709 (-801 to -510)	-701 (-774 to -543)	-728 (-865 to -432)	-722 (-846 to -455)	-708 (-799 to -513)
Sub-soiling	-32 (-44 to 20)	-32 (-44 to 17)	-34 (-45 to 9)	-57 (-80 to 38)	-56 (-77 to 33)	-53 (-70 to 18)	-78 (-110 to 54)	-77 (-106 to 42)	-64 (-85 to 23)
Drainage	-1984 (-1996 to -1932)	-1984 (-1996 to -1935)	-1986 (-1997 to -1943)	-1970 (-1993 to -1874)	-1972 (-1993 to -1883)	-1978 (-1995 to -1907)	-1958 (-1990 to -1826)	-1962 (-1991 to -1843)	-1972 (-1994 to -1885)
Reduced tillage	-319 (-352 to -240)	-306 (-337 to -230)	-268 (-295 to -202)	-587 (-648 to -443)	-545 (-602 to -411)	-434 (-479 to -327)	-813 (-897 to -613)	-733 (-809 to -552)	-537 (-593 to -405)
Zero tillage	-370 (-421 to -255)	-355 (-404 to -244)	-311 (-353 to -214)	-682 (-775 to -469)	-633 (-720 to -435)	-504 (-573 to -346)	-945 (-1074 to -649)	-851 (-967 to -585)	-624 (-709 to -429)
Tramline management	212 (28 to 411)	203 (27 to 395)	178 (24 to 345)	390 (52 to 758)	362 (48 to 704)	288 (38 to 560)	540 (72 to 1049)	487 (65 to 946)	357 (47 to 693)
Coarser seedbeds	-99 (-132 to -20)	-95 (-126 to -19)	-83 (-111 to -17)	-182 (-243 to -37)	-169 (-225 to -34)	-134 (-179 to -27)	-252 (-336 to -51)	-227 (-303 to -46)	-166 (-222 to -34)
Stocking density i.e. reduced	-340 (-376 to -242)	-326 (-361 to -232)	-286 (-316 to -203)	-627 (-693 to -446)	-582 (-643 to -414)	-463 (-512 to -330)	-868 (-959 to -618)	-782 (-864 to -557)	-573 (-633 to -408)
Contour ploughing	8 (-121 to 242)	8 (-116 to 232)	7 (-102 to 203)	15 (-224 to 446)	14 (-208 to 414)	11 (-165 to 329)	21 (-310 to 617)	19 (-279 to 556)	14 (-204 to 408)
Swales	-4 (-114 to 220)	-4 (-109 to 211)	-3 (-95 to 185)	-7 (-209 to 406)	-6 (-194 to 377)	-5 (-155 to 300)	-10 (-290 to 562)	-9 (-261 to 506)	-6 (-192 to 371)
Earth bank (100m length)	-140 (-268 to 102)	-143 (-265 to 89)	-151 (-259 to 52)	-251 (-487 to 195)	-246 (-465 to 167)	-233 (-407 to 96)	-345 (-672 to 272)	-328 (-622 to 228)	-284 (-500 to 124)

Note: values between brackets indicate the minimum and maximum values for the economic NPVs

C.4. Discussions and Conclusions

Mitigation measures that constitute minor adaptations to conventional agricultural practice appear to be most cost-effective in reducing soil erosion. These are also more likely to be adopted by farmers as they are less costly and require minor changes in farm management in comparison to mitigation measures that involve large investments or land use change. According to this assessment, tramline management, high density planting, buffer strips, stubble mulch and coarser seedbeds are the most cost-effective mitigation measures. Contour ploughing also appears to be cost-effective, but is not applicable under all circumstances and therefore cannot be widely promoted. However, only a few mitigation measures appear to be profitable (tramline management, high density planting, mulching and contour ploughing) even though environmental benefits are taken into account.

A lack of data hampers the assessment of the cost-effectiveness of mitigation measures. There is little information available on the costs of the mitigation measures. Studies that assessed the effect of mitigation measures on soil loss mainly consider water erosion, but other erosion processes are rarely taken into account. Studies on the impacts of the mitigation measures on ecosystem services and their values are almost non-existent and therefore represent an important knowledge gap.

This study has major limitations because of gaps in data and knowledge. Available data and resources have been reviewed for the purpose of this study, but the following knowledge gaps appeared:

1. Secondary data in the form of published scientific papers, reports and Defra research projects were reviewed to establish the current environmental baseline (in particular Evans 1996, ADAS 2006, EA 2007, and Spencer et al. 2009). These reports are the best sources available and commonly used. Caution is required however; national cost figures of damages related to soil erosion are crude estimates. It is not possible at present to put a figure on the robustness and reliability of these national estimates on damage due to soil erosion. Existing data are often based on case studies that have been extrapolated to national scale. National data on soil erosion rates that underpin many estimates (e.g. Evans 1996) are based on measurements taken in the 1980s and may thus well be out of date because of changes in land use and intensity of production. Spencer *et al.* (2008) also stated that there is currently insufficient evidence available to quantify off-site damages from soil erosion. Also, there is no information on how soil erosion impacts soil functions.

2. UK studies carried out on the impact of mitigation measures on soil erosion have only considered erosion caused by water (rainfall and/or surface runoff). There are no data available on the effect of mitigation measures on erosion by wind, tillage translocation or by co-extraction on root crops or farm vehicles.

3. The value of environmental impacts depends on the socio-economic context. Some impacts can be valued based on market prices, but this is not possible for most externalities (hence why they are externalities in the first place). No values are available for various ecosystem services (such as biodiversity, cultural heritage, cultural landscapes, air quality or wetland habitats) that may be impacted by soil erosion. Values can be estimated based on contingent valuation techniques, but these have well-known limitations. How society values environmental services varies over time (political and social priorities change over time), location (scarcity is subject to spatial variation), and scale of assessment. These are general challenges encountered in the valuation of ecosystem services.

4. Soil erosion is a diffuse problem and this makes it difficult to extrapolate data between different scales. The bio-physical environment typically determines the magnitude of the impacts of soil erosion. How much damage is caused by soil erosion in a particular field depends on the soil type, land use and management, topography, the location within the landscape and antecedent conditions and events. Two fields may have similar erosion rates,

but the proportion of soil that ends up in watercourses or on roads causing off-site damage may be different because of differences in connectivity[1].

5. It is assumed that a linear relationship exists between mitigation measures and impacts on soil erosion. In reality, however, this is often not the case. The impact of mitigation measures on soil erosion may increase or decrease over time. Furthermore, soil erosion in the UK is often associated with extreme rainfall events. Events resulting in soil erosion may alternate with years of no erosion at all. There is currently no evidence available as to how effective mitigation measures may be under extreme weather events, which given predicted UK climate change scenarios (UKCP09) represents an important knowledge gap.

6. It is also unlikely that the damage to ecosystem services caused by soil erosion is a linear relationship as assumed in this study. Ecosystem services are subject to thresholds and tipping points; sedimentation may have little effect on an ecosystem service until a threshold or tipping point is reached. Although this is a crucial point there is currently no scientific evidence available to provide guidance on this topic.

This exercise revealed that a generic assessment of the cost-effectiveness of mitigation measures has many limitations as the costs and the effects of the mitigation measures typically depend upon local conditions. Two methods are proposed to deal with the spatial and temporal variability of cost-effectiveness of different mitigation measures:

1) Assessments of cost-effectiveness of mitigation methods made at the field- and farm-scale, gathering site specific data.
2) Collation of data sets to enable a Geographical Information System (GIS) risk-based model to be built based on multiple data layers

Option 1 would provide the more accurate assessment but would require more resources to achieve. While option 2 offers the potential to provide a national assessment that could be used to assess different future scenarios but would only be as robust as the data used to build the model. Therefore investment is needed to improve our present understanding of erosion rates by water, wind, co-extracted and by tillage, including validation of mobilisation and delivery in multiple landscapes and considering different mitigation options.

While recognising the limitations of the data presented here, the results provide a useful starting point for identifying potentially the most cost-effective erosion mitigation measures. The comprehensive review of currently available data and knowledge has enabled important gaps in our present understanding to be revealed. These knowledge gaps must be addressed in order to achieve a robust cost-benefit analysis of mitigation measures aimed at controlling soil erosion.

[1] Connectivity refers to the passage or pathway of water or soil particles from one part of the landscape (the source) to another (the receptor), generating runoff and sediments flows within the catchment. Connectivity is determined by land use & management, landscape features and topography of the landscape (see: Posthumus, H., C.J.M. Hewett, J. Morris and P.F. Quinn (2008) Agricultural land use and flood risk management: engaging with stakeholders in North Yorkshire. *Agricultural Water Management* 95(7): 787-798)

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