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The published version may be accessed at http://onlinelibrary.wiley.com/.

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Implications of the proposed Soil Framework Directive on Agricultural Systems in Atlantic Europe - a Review

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Abstract

The main threats to soils outlined in the pending Soil Framework Directive (SFD) are: contamination, loss of organic matter, erosion, compaction, sealing, salinisation and desertification. The first four threats are pertinent to agricultural systems in Atlantic Europe, but vary in their extent between countries depending on the spatial soil distribution. Loss of soil biodiversity has not been included as a potential threat in the SFD due to lack of information that is currently available both spatially and temporally to facilitate any legislation to protect it. This paper gives emphasis to the four main threats outlined above associated with Agricultural systems in Atlantic Europe. Each soil threat is discussed in relation to the agricultural management calendar for cultivated and grazed grassland soils. The paper discusses current soil protection policies and possible changes to such legislation with the adoption of the SFD by member states.

Keywords: Soil Quality, Soil Protection, Compaction, Erosion, Contamination, Soil Organic Matter

Introduction: Brief history of the Soil Framework Directive

Soil has been recognized as a vital non-renewable resource which requires sustainable management to ensure the viability of food and fibre production, nutrient retention and cycling and filtration of water into the future. A Soil Communication was first proposed in 2002 and underwent a consultation process (Van-Camp, 2004) which resulted in the development of the Draft Soil Framework Directive COM (2006) 231 and the proposal of the Directive (SFD) (COM (2006) 232) in 2006. The SFD aims to establish a common framework to protect, preserve and prevent further degradation to soil and its associated functions. To date this Directive has not yet been ratified by Member States. It is supported by Impact Assessments (SEC (2006)1165 and SEC (2006) 620) that analyse the different options for soil protection. Under the SFD the main threats to soil quality are recognised: erosion (water, wind and tillage); decline of soil organic carbon; compaction; contamination; sealing, salinisation, landslides and desertification (Soil Strategy in 2006 (COM (2006) 231). The latter three threats will not be considered in this paper as they are not relevant to Agricultural systems in Atlantic Europe (Figure 1). The definition of soil quality as adopted by the Soil science Society of America and the European Commission (EUR 23438 EN, 2008) is that of Allan et al. (1995) whish states “Soil quality is the capacity of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal production, maintain or enhance water and air quality and support human health and habitation”.

Currently the only legislation pertaining to soil relates to other Directives or Regulations such as the Nitrates-, Habitats-, Sewage sludge- and Water Framework Directives and the Kyoto Protocol. The Water Framework Directive (COM 2000/60/EC, 2000) requires a reduction in soil erosion, while the Nitrates Directive (COM 91/676/EEC)) encompasses a number of soil quality issues for the protection of water courses as implemented by Member States. A number of regulations protect soils from contamination such as organic pollutants and heavy metals (Erhardt & Prüeß, 2001); dioxins and dioxin-like PCBs (COM 2002/69/EC, 2002); impure fertilizer (EC 2003/2003, 2003) and veterinary medicinal products (COM 2001/82/EC, 2001).

In addition to the current legislation which directly or indirectly relates to the protection of soils, the introduction of "good agricultural and environmental conditions" as a result of CAP reform "cross compliance" specifies maintenance and protection of soils (EC, 1257/99 and 1259/99). Member States are required to implement Reg. EC/2078/92, which was the legal framework for environmental protection (Van-Camp, 2004). Such measures incorporate management strategies to reduce soil erosion, enhance SOC in arable soils, maintain soil structure (EC, 1257/99 & 1259/99), and avoid severe poaching and over-grazing (EC 1257/99 & 1259/99) through sustainable agricultural management.

The aims of this review are to present potential soil threats and propose potential mitigation options for ensuring protection of soil quality associated with farm practices in managed agricultural systems. Such agricultural systems include: 1) arable systems dominated by cereal crops and also with root vegetables and other crops such as oil seed rape and forage maize and 2) grassland systems dominated by dairy, beef and sheep livestock grazing. This paper will not address the soil threats generically, but will describe them in relation to particular soil management practices (for a detailed explanation see EEA (1995), Eckelmann *et al.* (2006) and Huber *et al.* (2008).

Soil Management Practices for Temperate Arable Soils in Atlantic Europe

The intensification of cereals, root vegetables and horticultural production has led to dramatic changes in soil cultivation over the last 100 yr, due to the growing demand for food resources required by an ever increasing global population and product consumption. However, more recently (last 5-10 yr), the introduction of the Good Agricultural Environmental Conditions (GAEC) guidelines under Cross Compliance (EC 1259/99, 1999) and the growing adoption of soil conservation management techniques have aimed to reduce land degradation processes from arable agriculture. The SFD aims to incorporate current good soil management guidelines into environmental legislation to ensure that such practices are applied multilaterally across the EU. Figure 2 demonstrates the threats to soil quality associated with different crop management practices and potential mitigation management strategies.

Soil organic carbon

Soil cultivation is the principal agronomic activity reported to reduce soil organic carbon (SOC) stocks. Indeed, changes in land use via large-scale cultivation of soils have resulted in a decrease in global SOC levels, with losses estimated at ca. 78 Gt yr^{-1} (Smith *et al.*, 2005). The main mechanism for SOC loss is associated with ploughing (Figure 2) and is hypothesised to result from a) increased decomposition of SOC due to soil aeration and b) soil aggregate destruction, increased aggregate turnover and a reduction in aggregate formation (Oades, 1984; Six *et al.*, 1999). The process by which management disturbances alter the soil C balance were first postulated by Tisdall & Oades (1982) and Oades (1984). Later studies demonstrate that soil C and aggregate formation are correlated, with organic matter associated with larger aggregates being less persistent than that associated with smaller fractions (Paustian *et al.*, 1997).

A decline in SOC conditions has been highlighted in many legislative reports and scientific literature as contributing to a decline in soil quality/health and can result in increased soil erosion, loss of nutrients and an increased susceptibility to compaction. (Van Camp *et al.*, 2004). It has been suggested that the critical level of SOC is 2% (SOM 3.4%) below which soil structural stability will suffer a significant decline (Greenland *et al.*, 1975).

However, this threshold value is currently under debate within the scientific literature and is considered to be dependent on pedo-climatic conditions (Verheijen *et al.*, 2005). It is essential to define a baseline from which a decline can be monitored either through National monitoring schemes or through the adoption of EU statistics (Jones *et al.*, 2004). The introduction of “good agricultural conditions” as a result of CAP reform specifies maintenance of soil organic matter (EC, 1257/99 and 1259/99). EU Member states are now required to monitor SOC levels in long term tillage soils to ensure that sustainable management practices are put in place to reduce any further decline in soil organic carbon (DAFF, 2009). However, the baseline against which to measure changes in SOC content can be subject to substantial spatial variation due differences in soil and vegetation characteristics (Conant & Paustian, 2002). Generating a baseline from soil type alone has been shown to be inadequate, with data on altitude, pH, scale and a stratified range of land-use categories required in order to explain spatial variation (Bell & Worrall, 2009). In terms of compliance to Articles 3.3 and 3.4 of the Kyoto Protocol, the Good Practice Guide for Land Use, Land Use Change and Forestry recommends that SOC baselines should be set at a field scale prior to any land management or land use change and that this be carried out for each soil drainage class (IPCC 2003).

Mitigation Strategies to prevent decline in soil organic carbon

Various land management practices have been shown to increase soil C (Campbell *et al.*, 2005), notably: reducing tillage intensity, eliminating winter fallow, and increasing residue inputs from higher yields. However, the effectiveness of these practices may vary depending on soil type and climatic conditions.

Conservation Tillage: No till or reduced tillage intensity (collectively referred to as conservation tillage, subsequently) are considered to increase storage of SOC relative to conventional tillage practices, and as a knock on effect, reduce soil erosion through the development of a litter layer. Conservation tillage also enhances aggregate stability in the soil which slows decomposition of organic matter by providing protection within soil aggregates (Six *et al.*, 2000). However, the net effect of conservation tillage on SOC build-up is unclear and has been shown to be dependent on clay content and climate (Verheijen, 2005). Furthermore, in terms of a total greenhouse gas inventory, increased nitrous oxide emissions arising from alterations in water-filled pore space may offset any potential C gain (Farquharson & Baldock, 2008).

Cover cropping: The elimination of winter fallow, either by cover cropping or increased volunteer growth increases SOC by several methods. Increased C gain by the fallow season growth, especially during early autumn, reduces net C fallow season losses (Hollinger *et al.*, 2005). Blomback *et al.* (2003) based on 6 yr of continuous winter cover cropping in Sweden report an increase in SOM of only 2% compared to where no cover crop had been used. Also, fallow season cover increases water use, keeping soils drier longer, and reducing the rate of soil decomposition (Desjardins *et al.*, 2005). However, when costs of establishment and destruction are taken into account, the economics of using cover crops to increase SOC may become unfavourable.

Crop residues: Whilst root derived C is generally thought to make the largest relative contribution to total soil aggregate associated C, the reincorporation of residues (either total straw or stubble) to the soil will also tend to increase soil C as these residues form the basis for new soil organic matter, the main store of carbon in the soil (Puget & Drinkwater, 2001). This residual C induces SOC stabilisation via SOM-mineral interactions, whereby the SOM becomes covalently associated with clay particles (Six *et al.*, 2004).

Organic matter amendments: Manure amendment is considered to improve both the nutrient status of the soil and increase SOC levels via direct inputs of new carbon. Increases in SOC of between 1 – 4 tC ha^{-1} and increased accumulation of macroaggregate-protected C and N have been observed following applications of organic manures over ten year periods (Aoyama *et al.*, 1999 & Mikha & Rice, 2004). Isotope tracer studies have demonstrated that labile C from the liquid fraction of slurry is initially incorporated into the soil microbial and water soluble pools with subsequent C additions derived from the particulate C fraction (Bol *et al.* 2003). However, these inputs may also induce a ‘priming effect’ on microbial activity, resulting in large increases in soil CO_2 efflux (>50%) following slurry application resulting in ca. 20% of the incorporated slurry remaining in the SOC pools after two months (Glaser *et al.*, 2001 & Kuzyakov & Bol, 2006).

Crop rotation and landuse conversion: Crop rotation can include using short-term leys within an arable system or inclusion of a range of crops within an all arable system. However, there are little data available to quantify the effect of rotation on SOC increases in tillage soils in Atlantic Europe. The conversion of tillage land either to grassland or forestry may lead to a substantial increase in SOC sequestration. Grassland establishment on arable soils has been estimated to increase SOC levels by 0.6 to 1 tC ha^{-1} yr^{-1} (Conant *et al.*, 2001).

Erosion

The loss of fertile topsoil due to erosion on arable land is a growing problem in Western Europe and has been identified as a threat to soil quality (Boardman *et al.*, 2009). A review by Fullen (2003) provides a comprehensive discussion of soil erosion issues and relevant national policies in France, Germany, Republic of Ireland, U.K. and the Netherlands. A modified definition of tolerable soil erosion has been proposed by Verheijen *et al.* (2009) where ‘any actual soil erosion rate at which a deterioration or loss of any one or more soil functions does not occur’ and actual soil erosion is ‘the total amount of soil lost by all recognised erosion types’. Tolerable rates of soil loss can be inferred from natural rates of soil formation consisting of mineral weathering and dust deposition. Using this methodology the upper limit of tolerable soil erosion, as equal to the soil formation rate would be ca. 1.4 tonne ha^{-1} yr^{-1} (lower limit 0.3 tonne ha^{-1} yr^{-1}, indicative of European conditions). Actual soil erosion rates for tilled, arable land in Europe are on average 3 to 40 times greater than the upper limit of tolerable soil erosion. Erosion has numerous effects on soil properties, including thinning by removal of topsoil, textural coarsening, decline of soil organic matter and loss of nutrients (Guerra, 1994). In Atlantic Europe the main incidence of erosion is as a result of water. It is estimated that 115 million ha, or 12% of Europe's total land area, is affected (EEA, 1995). Soil water erosion in the UK is primarily a regional phenomenon associated mainly with sandy tillage soils in the southwest and southeast of England (Chambers *et al.*, 2000). Soil type is important when determining the erosion risk from an arable field: sandy soils are particularly vulnerable to erosion due to low organic matter content and poor structural stability (Quinton & Catt, 2004). The UK Department for Environment, Food and Rural Affairs (Defra) highlights potatoes, winter cereals, sugar beet, maize and grazed fodder crops as having the highest erosion risk based on crop cover (Defra, 2005). Root crops such as potatoes or carrots in Scotland commonly remove 1 tonne soil ha^{-1} per year (Frost & Speirs, 1996).

The incidence of severe erosion resulting in transport of suspended sediment tends to be highly dependent on hydrological storm events (Edwards & Withers, 2008). Although much erosion also occurs over periods of prolonged lower-intensity rainfall (Robinson, 1999), it can occur at any time of the year provided the conditions susceptible to erosion are present (Chambers *et al.*, 2000). In Navarre, Spain high erosion rates were found in 17 cultivated catchments ranging from 0.33 to 16.19 kg soil m^{-2} yr^{-1}, with abandoned fields having greatest losses. Rill and ephemeral gully formation were the main causes of erosion losses (Santisteban *et al.*, 2006).

Mitigation Strategies to prevent erosion

Various land management practices have been shown to minimise erosion risk on susceptible soils; low erosion risk crops and cover crops, tillage timing and intensity and the application of buffer strips (Figure 2). In the UK as part of the cross compliance regime (Defra, 2006), farmers are required to carry out a field erosion risk assessment as a means of reducing risk to acceptable levels.

Low risk and cover crops: Chambers & Garwood (2000) suggest that low risk crops like oilseed rape which establish an early crop cover should be sown. A review of runoff and erosion prevention using cover crops is provided by Zuazo & Pleguezuelo (2008), which calls for the development and re-establishment of plant cover in areas prone to erosion. The Nitrates Directive (COM (91/676/EEC)) as implemented in Ireland sets out cover crop requirements where arable land is ploughed between 1 July and 15 January. These regulations require the emergence of green cover from a sown crop within 6 weeks of ploughing.

Tillage timing and intensity: High losses of soil and particulate bound nutrients may be avoided by conservation tillage in autumn, which would protect soil structure through minimal disturbance and allow soil biota to remain undisturbed. Soil organic carbon may accumulate which adds to soil aggregation, thus maintaining reasonable soil structure. Protecting the soil from degradation allows water infiltration to plant roots, reduces runoff, and allows leaching nutrients to interact with the natural attenuation capacity of soil. Ploughing and shallow cultivation of sloping fields in spring instead of ploughing in autumn could reduce particulate transport in soils prone to erosion.

Buffer strips: Prevention of soil erosion requires a multi-pronged approach including promotion of soil conservation by a funded service, with established cost implications, mapping resources and annual monitoring of the problem. Rational land use policies such as set-aside on soils that are prone to erosion, grass strips in arable areas, and buffer strips in riparian zones are mitigation options (Fullen, 2003). Buffer strips retard overland flow migration and capture particulate P before discharge to a waterbody. The width of vegetation buffer strips in grassland may need to be quite large (up to 30 m (Zhang *et al.*, 2009)) at both sides of a waterbody and may only prevent particulate P while not preventing all losses of dissolved fractions (Fenton *et al.*, 2008). Best management practices on steep vulnerable slopes aims to minimise soil erosion losses which in turn limit nutrient losses to a waterbody. Geotextiles made from natural or synthetic fibres can be installed on such slopes to minimise erosion. The efficacy of geotextiles varies considerably and successful prevention is linked with the control of rainsplash detachment, transport and the erosivity of overland flow (Rickson, 2006). Topographical management through vegetative barriers or emplacement of berms re-directs runoff to reactive buffer strips (with high P sequestration components e.g. ochre or flocculants e.g PAM) or sedimentation ponds, which can be removed and spread on land at a later stage.

Compaction

The principal cause of soil compaction in managed tillage systems is the force applied to the surface of the soil from field machinery traffic. As a result of increasing axle load weights from larger machinery in conjunction with the high tyre pressures a considerable force is applied onto the soil. Håkansson (1985) reports from Swedish research that an axle load of 10 tonnes increases bulk density and soil strength to a depth of 50 cm. The inherent condition of soil when the load is applied is also of major importance, and drainage status, texture and structural stability may have a strong impact on susceptibility to compaction (Spoor *et al.*, 2003). Soils at or near field capacity are particularly prone to rutting, smearing and plastic deformation near the surface and have reduced bearing capacity below the plough layer. For example, the use of power harrows and heavy machinery to produce a fine tilth suitable for precision seed drilling in the autumn can weaken topsoil structure, particularly in weakly structured fine sands and light silts, resulting in pores becoming clogged with clay and silt after a rainfall event and development of a surface crust or cap (Palmer *et al.*, 2007).

Soil compaction can result in poor soil structure which in turn causes a reduction in rooting depth, workability and water infiltration, contributing in worst case scenarios to waterlogging in flat areas or overland flow, runoff and erosion in sloping areas (Dexter, 2004). It has also been found to contribute to reduced crop yields, inefficiency of applied fertilizers (Ball *et al.*, 1997), increased N_2O emissions (McTaggart *et al.*, 1997) and a reduction in methane oxidation rates (Ball *et al.*, 1999).

Soil compaction can take two forms, 1) surface compaction (within the tilled layer), which in most cases can be alleviated through the next tillage operation (Batey, 2009); and 2) subsoil compaction (found beneath the plough layer). In Europe it is estimated that 32% of subsoils are highly compacted and 18% are moderately vulnerable to compaction (Horn & Fleige, 2009). Once subsoil compaction occurs it can be extremely difficult and expensive to alleviate (Jones, 2002). Soils where compaction occurred at depths greater than 40 cm may be considered permanently damaged (Håkansson & Reeder, 1994).

There is currently very little regulation pertaining to the protection of soil in relation to compaction. The maintenance of soil structure is recognized under GAEC (EC, 1257/99 and 1259/99) as essential to reduce soil compaction and associated environmental problems such as erosion and waterlogging (Defra, 2006). Van den Akker *et al.* (2003) note that “it is currently common practice to compensate the detrimental effects of soil or subsoil compaction on crop production by improving drainage and supplying more nutrients and water (irrigation).” They suggest that these actions lead to further environmental decline through increased diffuse pollution and they called for European-wide action to assess the full extent of compaction occurring across the range of land-uses in Europe and further investigation of the impact of compaction on environmental pollution.

Mitigation Strategies to prevent compaction

The prevention of soil compaction in the first place is the most effective tool to combat this threat as even medium levels of soil compaction can cause significant damage to soil functions (Eckelmann *et al.*, 2006). The mitigation options for soil compaction are driven by land management practices. Chamen *et al.* (2003) provide an overview of the key factors and practices associated with subsoil compaction, highlighting: 1) machinery loads and ground pressure of tyres, 2) suitable timing and depth of cultivation and 3) number of passes of the vehicle in the field for each management practice.

Machinery loads: Compaction may occur from all machinery trafficking but the weight of the vehicle load is dependent upon the crop choice and operational event. Håkansson & Medvedev (1995) report significant compaction to depths exceeding 0.4 m when the axle load >6 Mg. The axle load is continuously increasing with the production of larger machinery. However, this can be compensated for by the use of dual tyre systems on tractors, increase in tyre widths or deflation of tyre pressures (Batey, 2009). Håkansson *et al.* (1985) argue that simply deflating tyre pressures is not significant enough and requires a reduction in axle load as well. Arvidsson & Keller (2007) conclude that deflation of tyre pressure alone only has a significant improvement on the stress applied to surface soil structure and shows no change in stress at constant axle loads on subsoil.

Timing of machinery operations: The timing of machinery operations is often difficult to schedule with the increased use of contract machinery and labour, where farmer based decisions on the condition of their field are not taken into account (Palmer *et al.*, 2007). However, the scientific literature clearly emphasises how important good soil moisture conditions are to reduce compaction (Batey, 2009). Chamen *et al.* (2003) suggest shallower ploughing or zero-tillage should be applied when subsoil conditions are moist.

Number of machinery passes: Chamen *et al.* (2003) suggest that the number of wheel passes following the same track also increases the stress applied to the subsoil. However, the adoption of “permanent wheel tracks” through controlled traffic farming is increasing in its application (Tullberg *et al.* 2007). This system applies GPS systems within the tractors to establish a route of permanent tramlines which are considered sacrificial to ensure that limited compaction occurs in the remainder of the field. Chamen *et al.* (2003) do stress that the tracks should be planned in relation to field drainage systems.

Contamination

In arable soils, nutrient and trace element contamination can have serious implications for soil quality in two ways: 1) elevated soil concentrations 2) diffuse contamination leading to the damage of other ecosystems. The elevation of contaminant concentrations such as metals and organic compounds in soil can lead to the inhibition of crop growth (Cameron *et al.*, 1997) and toxicity of soil organisms (Creamer *et al.*, 2008). Although the potential harmful effects of these compounds in sludge applied to soils are not yet fully understood (Laturnus *et al.*, 2007), the application of sludges with high metal contents have been shown to have a long lasting effect on the composition of the soil microbial community (MacDonald *et al.*, 2007). In addition, the application of pesticides to crops may result in pesticide residue accumulation (Flury, 1996) and associated secondary metabolite products.

The diffuse contamination of nutrients such as N and P may affect the quality of arable soils to function in their role in protecting other resources such as air and water (Carton & Jarvis, 2001). Sources of diffuse contamination of arable soils are typically associated with either soil fertility amendments (e.g. lime, mineral fertilizer and manure) or the application of crop protection products (e.g. biocides, pesticides, fungicides) (Figure 2). Diffuse contamination may occur through either leaching or surface run-off with sediment into watercourses.

The introduction of microbial pathogens into soils by the application of animal slurries and manures, and municipal sludges can pose a threat to soil quality. Over 150 different microbial pathogens may be present in untreated faecal material, with new enteric pathogens being regularly discovered (Gerba & Smith, 2005). The principal pathogens of concern within European agricultural catchments include pathogenic *Esherichia coli*, *Campylobacter* spp., *Salmonella* spp., *Cryptosporidium* spp., *Giardia* spp., and viruses. Pathogens released into the environment can pose a risk to human and animal health by contamination of waterbodies and food (Bicudo & Goyal, 2003).

Mitigation Strategies to prevent soil contamination

The control of contaminants to the soil through agricultural practices is extremely well established with a plethora of legislation controlling the amount of contaminant allowed within the soil and products from the soil. For example, Article 174 of the EC Treaty outlines a need to prevent and reduce the introduction of dangerous substances into soil (COM (2006) 232), while COM 2002/69/EC (2002) documents consideration of soil for the official control of dioxins and the determination of dioxin-like PCBs in foodstuffs. The purity of mineral fertilizers regarding metal content is already controlled to some extent within EU legislation (Anon, 2003). Guidelines regarding the maximum concentrations of organic pollutants and metals in both the receiving soils, and the materials being landspread, are in place at both EU level (Erhardt & Prüeß, 2001) and Member States through legislation and good practice guidelines (Anon, 2008). In addition, the Nitrates Directive (COM 91/676, 1991) seeks to limit diffuse nutrient losses from agriculture to freshwater bodies by restricting mineral fertiliser use in designated vulnerable zones in the U.K. and applied at a National level in countries such as Denmark, Ireland and The Netherlands.

Nutrient management planning: Planning of fertilizer and manure application rates that match crop requirements is an important tool available for reducing potential nutrient loss to water (Coulter & Lalor, 2008). Various national action programmes are in operation in a number of European countries and regions that regulate nutrient management planning (ten Berge & van Dijk, 2009).

Organic manures and slurries: The potential risk of pathogens on soil quality can be reduced through the physical and/or chemical treatment of organic materials, or by avoiding crops that are intended for fresh consumption by humans or animals. Methods of application such as soil injection or immediate incorporation into soil can also reduce the risk of contaminant loss from these materials, particularly by overland flow. The risk of contamination of water bodies can also be reduced by avoiding soils and soil conditions that are likely to provide a rapid transport vector.

Soil Management Practices for Temperate Managed Grassland Soils

Grassland systems in temperate climates are typically associated with a potential to produce high annual herbage dry matter yields, with seasonally variable grass growth rates. In Atlantic Europe, particularly in Ireland, N. France and the UK, ruminant livestock production is based on grazing of grass *in situ*. The seasonal variation in growth rates usually results in a requirement for animals to be housed during periods of low grass growth during which time the animal diet is based on conserved grass forages that have been harvested and stored during high growth periods. Developments in grazing management technologies are increasing the length of the grazing season, thereby reducing the housed period. The main events in grassland management are presented in Figure 3 with their associated threats to soil quality and potential solutions.

Erosion

In grassland systems, erosion is related to sediment loss in runoff to a waterbody. The amount of erosion and associated nutrient transfer in grassland is expected to be minimal due to the continuous vegetative cover. However, there have been studies in Ireland (Kurz *et al.,* 2006) and in the U.K where during individual rainfall events molybdate reactive P exceeded European Freshwater Fisheries Directive (25 mg L^{-1}) and USEPA (80 mg L^{-1}) guide values.

Mitigation Options to prevent erosion

Recently lowland grassland systems with intensified dairy systems have been re-evaluated in relation to their erosion potential (Bilotta *et al.*, 2007) and future research needs to meet water quality deadlines under the Water Framework Directive have been identified by Brazier *et al.* (2007). These include processes that dominate the delivery of nutrients and particulate matter from grassland to a waterbody, real time data during storm and base flow, and the characterisation of pathways from surface and subsurface soils.

Vegetated buffer margins. These have the advantage of trapping soil particles and particulate P and by slowing the flow of runoff to such an extent that P sequestration may be achieved. The choice of width and placement of such buffer strips on the landscape is difficult as runoff is not only infiltration excess driven but also saturation driven with contributions from shallow groundwater. Topographic management diverts runoff water to specific areas where runoff may be treated through increased infiltration into the soil or by chemical amendment. Many fact sheets for erosion prevention on grassland are available for water managers and farmers as part of the COST 869 project (COST, 2009).

Compaction

Due to the climatic regime of Atlantic Europe the potential for poaching (penetration of the soil surface by animal hooves) is particularly prevalent in spring, autumn, winter and during high intensity rainfall events. Compaction within grassland systems is two-fold: 1) surface compaction by grazing of animals – either in high stocking densities or at inappropriate soil moisture conditions, 2) subsurface compaction through passes of heavy machinery to provide chemical fertilisation, spreading of housed slurry store or cultivation of tilth for reseeding (Figure 3).

Surface soil compaction often occurs due to repeated trampling (poaching) leading to the reduction in soil strength resulting in weak soil structural units at the surface of the soil, reduced soil infiltration and increased nutrient loss to water (Heathwaite & Johnes, 1996). While symptoms of soil compaction through poaching are very evident at the surface or top 5 cm of the soil, damage to macroporosity may occur to a depth of 10-15 cm (Drewry, 2006). This process, while damaging in the short term, can be easily rectified through natural physical (wetting and drying cycles) and biological (earthworm burrows and root channels) amelioration. However, the relatively recent trend in Atlantic Europe is to increase the length of grazing in the winter (out-wintering) as a result of economic benefits (reducing the housing period and therefore associated feed and storage costs), but this can be extremely detrimental to grass swards, especially on recently sown leys (Palmer *et al.*, 2007) and contribute to overland flow of particulate N, P and K into nearby streams (Kurtz *et al.*, 2006).

Sub-surface damage occurs as a result of repeated machinery operations during moist soil conditions, (see description under arable soils for more details). The application of fertilisers in spring to enhance first grass growth of the year can result in damage to soil structure and result in increases of soil bulk density and inefficient utilisation of applied N (Douglas & Crawford,1998). As a result of the Nitrates Directive (COM (91/676/EEC, 1991), restrictions exist on the spreading of slurry for ca. 3-4 months (October – Jan) per year depending upon the agro-climatic zone. This reduces the main period when soils will be approaching/exceeding field capacity and therefore the potential for serious structural damage as a result of high soil moisture conditions. However, with current legislation in Ireland (Anon, 2009), slurry storage capacities often reach their maximum load by the end of the closed period to thus necessitate immediate spreading as soon as legislation permits. This does not currently take into account field soil moisture conditions and as a result serious damage can be incurred by machinery operations, particularly due to the weight (approx 8-14 tonnes) of a full slurry tanker (Raper, 2005).

Mitigation Strategies to prevent compaction

Mitigation strategies can be applied to reduce both surface and sub-surface compaction in grassland systems.

Surface compaction: The key solution to reducing surface soil compaction is to decrease treading intensity either through lower stocking densities or through careful management and timing of grazing and rotation and housing of animals. Drewry & Paton (2000) suggest removal of animals for several rotations following soil damage to allow for the natural rejuvenation of the soil structure to a depth of 5-10 cm.

Subsoil compaction: Ball *et al.* (1997) suggest reduced ground-pressure tyre systems as effective in preserving crop yields and minimising structural damage in grassland systems. Traffic operations should only be conducted when soil moisture conditions are <60% of field capacity (Raper, 2005), however, in Atlantic Europe climatic conditions may result in wet soils well into spring.

Contamination

Diffuse contamination of grassland soils often receives most attention from animal health and water quality perspectives rather than for its impact on soil quality. Nutrient additions, as either mineral fertilizers or as organic manures, are applied to grassland soils to maximise grass production yields. Application rates should be determined by the production potential of the sward and soil based on the management system and stocking rate (Coulter & Lalor, 2008).

Applications of municipal sludge are more common on arable crops than on grassland. The potential threats of contamination posed by metal and organic contaminants from sludge on arable soils are also pertinent to grassland. Chaudri *et al.* (2008) found that the population of indigenous N fixing *Rhizobium sp*. bacteria was reduced in association with elevated soil Zn levels following sludge cake application. However, no consistent effect of Cd and Cu dosage was found.

Recycling of manures by landspreading, or the direct deposition of faecal material by grazing animals, can result in the introduction of microbial pathogens into soils. The incidence of pathogens in farm animals is influenced by factors such as season, animal breed, age, housing, nutrition, antibiotic use, pathogen exposure, stress and on farm hygiene (Brabban *et al.*, 2004) with farm animals often carrying pathogens asymptomatically (Semenov, 2008). Soil is for the main part an inhospitable environment for landspread enteric bacteria as conditions differ greatly to that within the primary host (Winfield & Groisman, 2003). As such, soil is often considered a dead-end environment for many bacterial pathogens. There is increasing evidence, however, that this view needs to be reviewed with long term survival and even growth in some soil types being recently reported. Whether these organisms continue to cause a health-risk is as yet unknown. Protozoan and viral pathogens have the capacity to survive for long periods of time in soil. This combined with their high incidence rates in certain farm animals, their often low-infectious dose rate, and their resistance to some disinfection methods have generated increased concern about these pathogens.

Mitigation Strategies to prevent contamination of soils

As with mineral fertilizers, manure applications should be targeted towards times when there is a nutrient demand by the grass crop in order to reduce the potential for nutrient loss (Schröder, 2005). The EU Nitrates Directive (COM (91/676/EEC), 1991) and subsequent national action programmess, such as in Ireland (European Communities, 2009), set limits on the stocking density and fertilizer application rates that can be applied to grassland soils. These limits also require more efficient utilisation of organic fertilizers, resulting in reductions in mineral fertilizer rates and nutrient surpluses. Heavy metal contamination resulting from fertilizer applications is a potential risk, but is addressed under EU regulations regarding fertilizer quality (EC, 2003/2003, 2003). Directive; COM 2001/82/EC (2001) is concerned with the application of veterinary medicinal products to soil.

Nutrient management planning: Nutrient management planning based on soil fertility levels, and farm productivity targets, such as outlined by Coulter & Lalor (2008), and enforced through the Water Framework Directive (COM 2000/60/EC, 2000), can be an effective tool for minimising the impact of nutrient additions on water and air quality.

Reduction of Pathogens: Further research into the occurrence, fate, survival and spatial distribution of microbial pathogens in the soil environment is essential as current knowledge on pathogen interaction with the complex soil environment is inadequate (Santamaría & Toranzos, 2003; Unc & Goss, 2004). In addition, survival times and die-off rates of microbial enteropathogens in soils are critical to the risk posed, with the natural decay of pathogenic microbes in soil preventing further transmission of infectious disease (Lang *et al.*, 2003).

Soil organic carbon

Grassland systems generally have good soil organic matter status. Indeed, grassland (both rough grazing and intensive pasture) is a significant component of global C balance, accounting for 32% and 22% of global and European land area, respectively (EEA, 2006). Recent studies of European grassland sequestration estimate a net sink of between 40 and 110 MT C yr^{-1} (Vuichard *et al.*, 2007) with a mean sequestration rate of 104 g C m^{-2} yr^{-1}, which equates to 43% of the European biospheric sink (Soussana *et al.*, 2007).

Grassland management can modify SOC inputs via alterations in carbon uptake, the allocation of biomass between shoots and roots and the rate of root turnover. Grazing pressure influences grassland organic carbon levels by altering the levels of C returned via excretion. Balanced against this increase in C input is the concomitant increase in defoliation and treading, both of which reduce leaf area and canopy C uptake. Moderate grazing and rotational grazing practices have been shown to increase C sequestration by increasing shoot turnover and altering the plant community structure towards deep rooted species (Schuman *et al.*, 2001). However, high grazing intensity has been linked to increases in CO_2 and CH_4 losses from soil (Soussana *et al.*, 2007).

Mitigation Strategies to prevent decline in organic matter

The application of fertilisers to grassland systems, especially degraded grass systems can increase SOC via a direct increase in ecosystem net primary production. Soussana *et al.* (2004) demonstrate that whilst moderate N fertilisation increased C mineralisation, this was outweighed by increases in organic matter input. The addition of organic manures also increases SOC sequestration compared with mineral fertiliser addition by up to 4t C ha^{-1} (Jones *et al.*, 2007). Studies by Tilman *et al.* (2001) & Steinbeiss *et al.* (2008) suggest that sward diversity contributes to increased C sequestration via increased sward productivity, with increased species richness promoting higher levels of SOC sequestration to a greater soil profile depth.

Conclusion

This paper reviews the soil threats and potential mitigation options for ensuring protection of soil quality associated with farm practices in managed agricultural systems. These threats include loss of soil organic matter, erosion, compaction and contamination. As outlined in the introduction, there are components of the potential mitigation strategies which are incorporated into some existing legislation, however, in many cases this legislation requires the voluntary adoption of best practice guidelines. Ratification of the SFD will result in the unification of soil measures under one Directive and provide a common approach and level playing field for member states with regard to soil protection.

Loss of soil biodiversity is recognised as a potential threat within the Soil Strategy, but is not currently listed as a key threat within the Directive due to the difficulty in quantifying changes in biodiversity status at a European or even National scale. However, it is recognised that further research and monitoring are required to assess the degree of decline and the implications for soil quality.

Hartemink (2008) emphasizes that the renewed interest in soil related research and soil legislation is a result of an increased requirement for agricultural production for continuing increases in global population. This increased demand for food requires a spatial soil resource which is now in competition with the increasing demand for land for the production of biomass crops. The functions of providing food and raw materials along with the other soil functions (providing a platform for infrastructure, a nutrient reservoir, filtration of water and habitat for biodiversity) are completely dependent upon soil's productive capacity (Hartemink, 2008) and therefore require protection equal to that of air and water. In order to raise awareness of the role of soils, rigorous scientific debate and improvements in knowledge exchange to the general public are essential to ensure that measures are put in place to protect soils and reduce further soil degradation.

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Figures

Fig 1. The Atlantic biogeographical region in Europe (EEA, 2009)

Fig.2. The main operational events in the arable cycle (solid rectangles), their potential threats to soil quality (circles), solutions to the threats (in italics) and the inclusion of trade-offs (dashed rectangles) where a management practice can have positive as well as negative effects.

Fig.3. The main operational events, threats, solutions and trade-offs (represented as in Fig. 2) in the grassland cycle. We have shown grazing as a continuous event to reflect the move towards year-round grazing in some countries.