Soil Organic Carbon:
A review of ‘critical’ levels and practices to increase levels in tillage land in Ireland

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Introduction

It is an inherent part of the EU CAP that in order to receive the single farm payment a farmer must meet (amongst other thing) a minimum environmental standard (cross compliance) and to keep land in Good Agricultural and Environmental Condition (GAEC). The GAEC conditions are set by the EU but the actions to achieve them are defined by Member States, the conditions include; standards related to soil protection, maintenance of soil organic matter and soil structure, and maintenance of habitats and landscape, including the protection of permanent pasture.

The importance of soil organic matter was brought into sharp focus in the 2009 guidance for growers applying for the Single Farm payment by the inclusion of the following statement:

"Under GAEC farmers must "maintain soil organic matter levels through appropriate practices". If a parcel has been under tillage cropping continuously for 6 years or more, you must ensure through soil sampling that organic matter levels are maintained through the use of appropriate farming practices. Where organic matter levels are depleted (< 3.4% organic matter) it may be necessary, depending on soil type, to adopt farming practices that will restore organic matter levels in the soil. Compliance with this requirement will be checked in the course of cross compliance inspections.
The Department will communicate with applicants who have applied on such parcels on their SPS application in areas identified as potentially having low levels of organic matter. These applicants must determine the percentage soil organic matter levels in 2009 and where found to be less than 3.4%, remedial action appropriate for the soil type must be undertaken."

In response to this statement the purpose of this report is firstly to assess the validity of a single 'trigger' value of soil organic matter – particularly with respect to different soil types. Secondly the report seeks to review a range of options for 'remedial action' to assess the practicality of their application and the success or otherwise that they may have in increasing soil organic matter levels.

How much soil organic carbon is needed?

The concentration of soil organic matter (SOM) or soil organic carbon (SOC) is seen as an important determinant of soil function. Increased levels of SOM have been reported as improving crop nutrition, aggregate stability (soil structure), water retention and ease of cultivation and seedbed preparation. Soil organic matter has also been linked to improved soil aeration and aiding in the resistance of a soil to compaction and enhanced soil biodiversity. Therefore a decline in SOM conditions has been highlighted in many legislative reports and scientific literature as contributing to a decline in soil quality/health (Van Camp *et al*., 2004).

A reduction in SOM as a result of tillage practices has been established (Lal *et al*., 1994 Jones *et al.*, 2004) whereby the tillage turns over the topsoil exposing it to rapid drying, releasing organic compounds into the atmosphere (mineralisation), this continuous practice leads to the breakdown of stable soil aggregates and results in a decrease in available SOM in the soil, over time.

Soil texture, moisture status and available nitrogen can affect the stability of SOC, for example, given the same environmental conditions, a sandy soil will have a lower moisture content than a clay soil and consequently will have a lower carbon content due to higher carbon oxidation (Robert *et al*., 2004).

It has been suggested that a critical level of SOC is 2% (SOM 3.4%), below which soil structural stability will suffer a significant decline (e.g. Kemper and Koch, 1966 & Greenland *et al*., 1975). However, Loveland and Webb (2003) argued that these authors had used this 2% figure as a 'rule of thumb' to indicate soil stability, rather than a measure of soil physical properties in the field.

There is a plethora of literature relating SOC or SOM to aggregate stability in soils under climatic conditions similar to those in Ireland (e.g. Chaney and Swift, 1984; Christensen, 1986 & Blair *et al*., 2006). However, there is debate in the literature as to whether total SOM is indeed the determinant of soil physical properties or whether it is in fact the level of 'fresh' or 'active' SOM which determines, for example, aggregate stability (e.g. Tisdale and Oades, 1982). Tisdale and Oades (1982) also ranked SOM compounds for the time-scale over which they affected soil aggregate stability: mono- and poly-saccharides had the quickest and strongest effect starting within 2-3 weeks and then declining over 4-6 months, cellulose had a lesser effect which peaked at 6-9 months and the effect of ryegrass residues reached a peak at 3 months, plateaued for the next 4-6 month then declined over the following 3-4 months.

A number of authors have examined the relationship between aggregate stability and SOC and SOM, and found linear relationships with no obvious critical limit (e.g. Stengel *et al*., 1984; Chaney and swift, 1984; Ekwue, 1990 and King and Evans, 1989). Conversely, there are additional literature reports that show no relationship between SOM or SOC and aggregate stability (e.g. Carter *et al*., 1994; Macrae & Mehuys, 1987 & Perfect and Kay, 1990).

The impact of SOC or SOM on other aspects of soil quality have also been widely reported with contradictory evidence as to whether increased levels have a positive or negative effect on soil function or indeed any effect at all. Loveland and Webb (2003) in a review of reported data on availability of micronutrients concluded "there is no consistent effect of SOC on crop uptake of Zn or Cu". In terms of available water capacity (AWC) they also concluded, that there were no threshold values below or above which soil water holding capacity changes markedly with SOC content". There has been a lot of work reported investigating the impact of SOM on crop nutrition and yield, this work has either involved the natural or artificial stripping of top soil (e.g. Battiston *et al*., 1987; Tanaka and Aase, 1989) or long term differences brought about mainly through the application of manures. Given the number of possible effects of these treatments it is impossible to disentangle the impact of SOM level directly from all of the other possible effects. Johnson *et al.* (1991) reported an experiment at Woburn in the UK that started in 1937 with approx 1% SOC and decreased over the next 30 years to about 0.5% SOC, over the 30 years where fertiliser applications were adequate there was a yield increase, despite the loss in SOC. Loveland and Webb (2003) in a review of a large number of projects investigating the effect of SOC on potential yield concluded "*…very tentatively* (this can not be too strongly emphasised) that, irrespective of soil type, if SOC decreases to ca. 1% it may not be possible to obtain potential yields…". They further concluded that "In some of these studies, satisfactory crop yields were, nevertheless, obtained from soils of SOC concentration <<2%. We conclude that data from agricultural systems which require the mineralisation of SOM to maintain crop yields, and in which decreases of SOC below a certain level may lead to insufficient nutrient release, have been erroneously applied to temperate agricultural systems in which adequate nutrient supply is obtained from fertiliser."

Bhogal *et al.*, (2008) reviewed the impact of various soil quality indicators on the soil functions of environmental interaction and habitat support, for almost all of the relationships they looked at, they concluded that there was little clear evidence of a breakpoint which could be used as a 'prompt value'.

This lack of an obvious 'prompt' or 'trigger' value for SOC is perhaps most clearly explained by the work of Verheijen *et al.* (2005), using data from 2448 arable and ley-arable sites in the 1980 England and Wales National Soil Inventory they concluded that clay content and annual rainfall were the most important factors determining SOC content. They proposed 'indicative soil organic carbon management ranges' (Table 1) based on clay content and precipitation.

Table 1. Indicative SOC ranges for tillage-tillage/ley and permanent grassland soils (Verheijen *et al*., 2005)

	Tillage/ tillage-ley						Permanent grassland	
Rainfall	<650 mm yr^{-1}		650 - 800 mm yr^{-1}		800 - 1100 mm yr^{-1}			
Clay content (%)	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
0-10	0.5	1.6	0.5	2.1	0.6	3.4	1.0	4.2
10-20	0.7	2.2	0.7	2.8	1.0	3.8	1.5	4.7
20-30	1.0	2.8	1.1	3.4	1.5	4.3	2.0	5.3
30-40	1.2	3.5	1.5	4.0	1.9	4.7	2.4	5.7
40-50	1.5	4.1	1.8	4.7	2.3	5.3	2.9	6.3

Conclusion

It is clear that higher levels of SOC are desirable from both an agronomic and environmental perspective and that soil function may be adversely affected by a lack of SOC. This review of the literature demonstrates that it is very difficult to determine at what level of SOC content, soil structure and function are adversely affected. A "trigger or threshold value" is questionable, rather a critical level for any soil will be dependant on a number of factors, the most significant of which appear to be climate and clay content. What does seem clear from the literature is that soil function will not be adversely affected where SOC is above 2%.

It also appears from the literature reviewed that as SOC declines towards lower levels the yield potential and workability of the soil will decline in parallel with adverse environmental performance. Whilst no one level of SOC below 2% can be used to determine soils in poor condition, observation of the functionality of the soils below 2% SOC, in terms of crop production would be a useful indicator of unsustainable farming practices and prompt to adjust management or tillage practices.

Impact of Husbandry practices on soil organic carbon and crop production

There has been concern that modern farming practices have led to a decline in soil quality and soil organic carbon (SOC) in particular (e.g. Webb *et al*., 2001 and Riley and Bakkegard, 2006). A number of husbandry practices have been reported or promoted as resulting in an increase in SOC in particular, reduced or minimal tillage (e.g. Stern, 2006), straw incorporation, cover cropping and incorporation of organic manures or wastes.

In order to assess the potential benefit of adopting any of these practices, the potential improvement in SOC must be balanced against the cost of implementation and any agronomic benefits or disadvantages in terms of crop yield, pest, disease and weed pressure. The review will be restricted to data arising from similar agroclimatic zones (moist-temperate) as it has been shown that the impact of management on SOC is dependant on climate (Ogle *et al*., 2005), with tropical moist climates being most responsive, followed by tropical dry then temperate moist and least responsive being temperate dry climates. This report will therefore review any relevant published literature and available data from Irish field experiments on each of the management practices, to assess their viability for adoption into practice.

Minimum Tillage

Organic carbon

Tillage practice is generally classed into three broad categories:
Conventional – mould board ploughing to a depth of 20 cm or more, followed by cultivation and drilling
Minimum/reduced or conservation – non-inversion tillage normally to a maximum depth of 10-15 cm
No or Zero tillage – direct drilling or broadcasting seed directly into the stubble of the previous crop

Zero or reduced tillage is frequently used in arid areas such as Australia and America primarily to conserve soil moisture. It is less commonly used in North Western Europe where soil moisture for establishment is a less critical consideration, except in particular instances, for example, 'autocast' establishment of oilseed rape. The main problems associated with zero tillage that have limited its uptake include, a build up of weeds (Derksen *et al*., 1993), disease problems and increasing soil compaction.

A large number of medium-long term studies have assessed the impact of tillage practice on SOC, however the majority of these have been done in arid or semi-arid areas, where the increased soil water conservation allows a greater frequency of cropping with associated increases in SOC due to greater return of crop residues (Paustian *et al.*, 1997).

Estimates of potential increases in SOC-C due to changing tillage practice vary widely. King *et al.* (2004) estimated that zero tillage would increase storage by 145-235 kgC ha^{-1} yr^{-1} and minimal tillage by 40 kgC ha^{-1} yr^{-1}, whilst Smith *et al.* (2005) estimated them at 400 kgC ha^{-1} yr^{-1} and 200 kgC ha^{-1} yr^{-1} respectively, and Oorts *et al*. (2007) indicated 140 kgC ha^{-1} yr^{-1} from zero tillage.

Based on the results of Powlson & Jenkinson (1981) who found little overall difference in SOC between conventional and reduced tillage, but did find a significantly different distribution in SOC within the soil profile, Baker *et al.* (2007) have questioned the validity of the findings of these more recent studies because less than 30 cm of the soil depth had been sampled.

Because of the uncertainty surrounding published data in terms of sampling depth and location of the work in atypical climatic regions, Bhogal et al. (2008) reviewed the results of UK based tillage experiments. They concluded that the average C storage as a result of zero tillage was 310 kgC ha^{-1} yr^{-1} with a standard error of 176, which was not statistically different to zero. They reported that there were no published results of SOC storage after minimal tillage in the UK but based on the work of Smith *et al.* (2005) assumed it to be half of that of zero tillage.

It has also been reported that some of the benefits in terms of SOC carbon storage of zero tillage could be offset in green house gas (GHG) emission terms, by an increase in N_20 emissions (Six *et al*., 2004). Li *et al.* (2005) reported that in net GHG emission terms the saving through increased SOC through no-till could be completely off-set by increased N_20 emissions and Ball *et al*. (2008) reported that in a spring barley crop in Scotland grown after a ley the N_2O-N flux in the 3 months following fertiliser application were 13.3 kg/ha following No-till but only 3.5 kg/ha following ploughing.

There is little or no published data on the impact of tillage practice on SOC storage in Ireland. On-going trials are, however, now beginning to yield some information. A long term winter wheat field experiment has been running at Oak Park since August 2000, with a factorial combination of cultivation (ploughing and minimum tillage) and straw removal or incorporation. In 2008 the plots were sampled to 60 cm soil depth in 15 cm increments and analysed for %C concentration. Preliminary analysis suggests that minimum tillage resulted in a significant increase in SOC compared to ploughing, 1.83 cf. 1.56% in the 0-15 cm soil horizon ($p<0.001$), but there was no significant effect between 15 and 60 cm (Van Groeningen and Forristal personal communication).

While the tillage systems outlined above are described as discrete systems, in practice there is significant overlap of systems. Some practitioners of the min-till system work to a depth close to that of ploughing, with similar levels of soil cultivation, although the soil is mixed rather than inverted. Ploughing equally can be carried out to different depths and modern ploughs both mix and invert the soil. It is incorrect to assume that all minimum tillage systems are similar. The effect on soil carbon of a cultivation system is a function of its working depth, the intensity of cultivation, and the extent of soil inversion. Complete cultivation systems must also be considered. For example if a shallow min-till cultivation system is not sustainable without occasional ploughing or alternative cultivation to a deeper depth, because of compaction / weed problems, then the impact of these extra operations on soil C must be considered.

Economics

Minimum tillage systems which cultivate at a much shallower depth than ploughing use less energy and have the potential to reduce machinery costs. A study by Teagasc (Forristal *et al*., 2009), using the Oak Park Machinery Cost Programme to estimate machinery costs, showed that the use of minimum tillage systems can reduce establishment costs compared to plough-based systems (Table 2). This study also showed the system to have labour efficiencies and labour demand patterns that suited larger scale operations. While the cost differences are substantial, where there is a need for additional grass weed control measures, the minimum tillage system can lose its' cost advantage. Large areas are needed to justify ownership of both minimum-tillage and conventional tillage systems. The risk of failure to get a crop established, in autumn where weather is below optimum, is much greater with minimum tillage systems.

Table 2. Crop establishment machinery costs

System	Plough	Min-till	Plough	Min-till
Annual Area (ha)	100	100	400	400
Machinery Establishment Cost (€/ha)	148	82	138	80
Relative Cost	100	55	93	54

Agronomy

The key agronomic implications of altering tillage practice as indicated above have been identified as weed, disease and compaction problems. Because of these issues many farmers who have adopted minimum tillage practices in the UK operate a rotational ploughing policy, where they plough one in every 3-5 years.

Weeds

The impact of changing tillage practice on weed numbers will depend on the weed species present and their biology, in terms of longevity in the soil and levels of dormancy amongst others.

Feldman *et al.* (1997) assessed the numbers of weed seed in the seed bank in both the 0-5 cm and 5-10 cm soil profiles after 3 years of continuous wheat cropping. Four cultivation practices were tested; mouldboard ploughing, disc cultivations, chisel plough and no-till. At the end of the 3 year period the numbers of weed seeds in the 0-5 cm layer differed markedly with 8191, 7606, 31990 and 70471 seeds m^{-2} in the plough, disc, chisel and no-till treatments, respectively. The results were slightly different in the 5-10 cm layer with 7579, 15209, 26942 and 31708 for each of the 4 cultivation treatments, respectively. The numbers of identified weed species also differed between the cultivation treatments with 8, 6, 12 and 12 species identified in each of the cultivation treatments, respectively across the 0-10 cm soil depth.

Benjamin *et al.* (2009) modelled the impact of various tillage practices on the number of weed plants of 3 species (black grass, barren brome and chickweed) surviving each season of a 5 year winter wheat sequence. The modelling assumed a starting weed seed bank of 2,500 seeds m^2 split 20:80 between the shallow (0-5 cm) and deep (5 cm-25 cm) soil layers. They considered both cultivation practice and sowing date of the crops but for simplicity we will look just at the medium sowing dates (14^{th} October). The cultivation sequences modelled across the 5 years were; continuous minimum tillage, minimum tillage with a rotational plough in year 3, and minimum tillage in year 1 followed by 4 years of ploughing. The predicted final weed populations as a percentage of the population in year 1 are in Table 3. Whilst their predictions for all 3 species was that numbers would build most following continuous minimum tillage and decline most with continuous ploughing, the scale of the change differed between species. Sterile brome was predicted to increase to 1669% of its starting population with continuous minimum tillage whilst chickweed was predicted to increase to only 176%.

Table 3. Model predicted final weed populations following a range of cultivation practices as a percentage of the first year populations (Adapted from Benjamin *et al.*, 2009).

Weed species	**Black grass (%)**	**Sterile Brome (%)**	**Chickweed (%)**
Cultivation practice			
Minimum tillage	1101	1669	176
Rotational ploughing	103	601	68.7
Ploughing	7.5	0.2	29.5

The results of the winter wheat cultivation trial carried out by Teagasc at Knockbeg, confirm the model predictions particularly in relation to grass weeds. In the third year of repeated minimum tillage there were significantly higher numbers of Annual meadow grass (*Poa annua*) plants (46.1 plants m^{-2}) compared to 8.0 plants m^{-2} following ploughing, the straw having been removed in both cases. While Irish research on the effect of tillage systems on weeds is limited, growers who have adopted minimum tillage are incurring greater grass weed control costs than those establishing crops conventionally. Sterile brome can be a particular problem in Irish minimum tillage fields. Forristal *et al.* (2009) estimated extra grass weed control costs to be from €33.50 to €67/ha.

Disease

For many of the major pathogens of cereals in Ireland one of the primary sources of infection is disease carried over in stubbles and trash from previous crops, either in the same or neighbouring fields.

The use of non-inverson tillage has been shown to increase the severity of a number of diseases including: Take-all - *Gaeumannomyces graminis var. tritici* (Jenkyn *et al*., 1995), Leaf scald - *Rhycosporium secalis* (Arvidsson, 1998). Head Blight (and hence risk of mycotoxins in grain) – *Fusarium graminearum* (Bateman *et al*., 2007).

Conversely, whilst Eyespot *Oculimacula yallundae* and *O. acuformis* is a trash borne disease, the use of non-inversion tillage has been shown to reduce the risk of disease development (Jalaluddin and Jenkyn, 1996), it is hypothesised that this is due to the maintenance of anatagonists that suppress the disease.

The main disease of wheat in Ireland is Septoria leaf blotch (*Mycosphaerella graminicola*), despite this disease being trash borne there are no reports of increased severity under non-inversion tillage systems. This is probably because inoculum is rarely limiting in terms of disease epidemic development even under UK conditions (Paveley, pers. comm.), where disease pressure is significantly lower than Ireland. The disease is also wind borne and travels readily from field to field (Kildea, 2009), therefore changing agronomic practice or rotation would not be expected to have a significant effect on disease development.

The effect of cultivation practice and therefore degree of burial of straw on trash borne diseases was demonstrated in a split field comparison of winter barley grown using plough vs minimum tillage at Oak Park. In only the second season of minimum tillage in 2001-2, minimum tillage had increased the incidence of Net blotch (*Pyrenophora teres*) to 72.9% plants infected compared to 29.8% where stubbles had been buried with the plough. Leaf scald (*R. secalis*) was also increased from 0% infection following ploughing to 3.0% following minimum tillage. However, in a neighbouring replicated experiment comparing straw incorporation and cultivation method, the incidence of barley yellow dwarf virus (BYDV) was significantly reduced in two out of three years (2002-2004) by 71% and 44% in minimum tillage compared to ploughed plots.

Soil compaction

No-till or minimum tillage has been widely reported as improving soil condition (e.g. Franzluebbers, 2002), however it has also been reported as causing increased soil compaction in the soil layers immediately below the cultivated depth, with associated loss in crop yield (e.g. Meyer *et al*., 1996; Ahl *et al.*, 1998)

The Teagasc cultivation work on winter wheat carried out at Knockbeg was assessed for the impact of cultivation practice on soil structure after 3 years of repeated non-inversion or plough based tillage. Soil compaction was assessed using a cone penetrometer down to 44 cm soil depth and shear vane readings taken at 4 and 12 cm below the soil surface.

The results of the cone penetrometer tests (Figure 1) reflected the effects reported in the literature, in that soil compaction was greater at shallower soil depth following non-inversion tillage that with ploughing, however, over this three year period the degree of compaction was probably insufficient to have any adverse effect on crop growth. There may, however, have been more severe compaction had one or more of the 3 years been a wet autumn. Shear vane readings also indicated more compacted soil at the 12 cm depth with min-till than with ploughing, again this is as would be expected as the 12 cm depth was below the depth of min-till cultivations but above the plough layer (Figure 2)

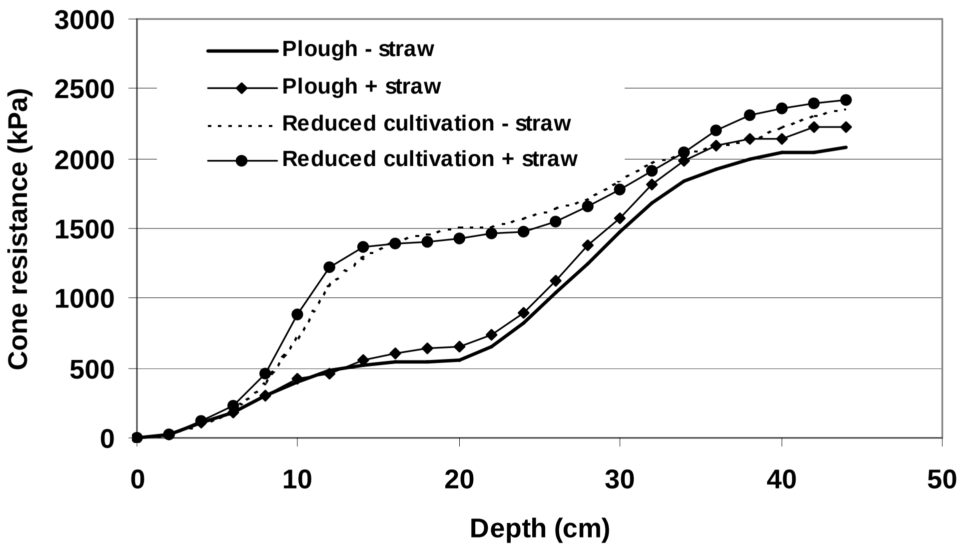

Figure 1: Cone penetrometer resistance – winter wheat, Knockbeg – December 2003

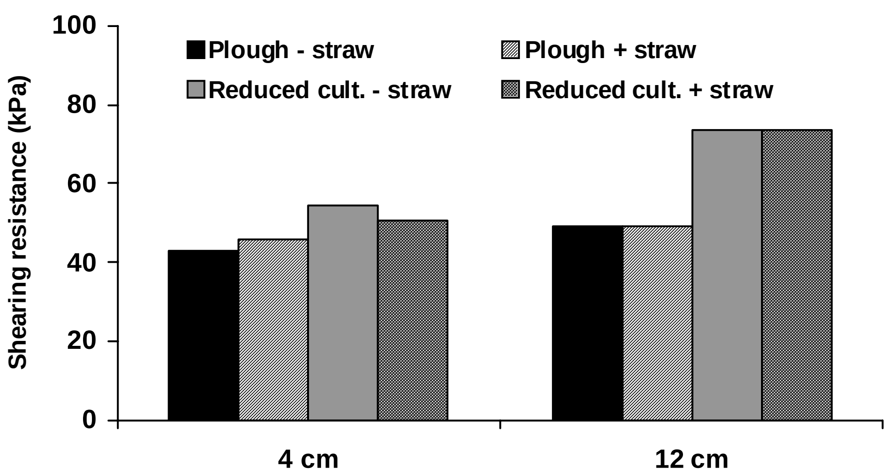

Figure 2: Soil shear strength – winter wheat, Knockbeg

In order to alleviate soil compaction problems as well as grass weed problems which can result from adoption of minimum tillage many growers have reintroduced ploughing on a rotational basis. However, this may result in the partial or complete loss of SOC accumulated in the preceding years of minimal tillage, indeed, Koch and Stockfisch (2006) reported the loss of 0.47 kg m^{-2} of SOC in the 6 months following rotational ploughing. In a previous study Stockfisch *et al.* (1999) demonstrated that a single plough cultivation was sufficient to completely revert the increase in SOC accumulated over the previous 20 years of minimum tillage.

Conclusions

It appears on a brief analysis that the adoption of minimum or non-inversion tillage may result in increased accumulation (or reduced rate of decline) of soil organic carbon, however, the effects are far greater with no-till than with minimum tillage. It also appears from the literature that the size of the effects are often over estimated due to the shallow sampling depths used in many studies and the accumulation of SOC in the upper layers of the soil in non-inversion tillage systems. There is also some doubt as to whether in GHG emission reduction terms increased SOC storage due to non-inversion tillage results in any net benefit as the saving could be offset by increases N_2O emissions.

There are potentially significant economic drivers for the adoption of minimum tillage, but these are dependant on a number of factors, in particular, the size of the farming enterprise. In agronomic terms there are both benefits and disadvantages to the adoption of non-inversion tillage. In terms of disease risk there are a number of diseases of economic importance in Ireland that would be exacerbated and others that would be diminished, the appropriateness of minimum tillage will therefore depend to an extent on the rotation of crops grown.

The evidence seems fairly conclusive that the adoption of minimum tillage tends to exacerbate problems with grass weeds, and can lead to soil compaction at relatively shallow depths in the soil although the latter is most likely to be caused by the use of inappropriate techniques, particularly, in wet soil conditions. These 2 problems often lead for practical reasons to the adoption of rotational ploughing, and it appears that this practice is likely to reverse any gains in accumulation of SOC due to the preceding use of minimum tillage.

Straw/crop residue incorporation

Organic carbon

The mean accumulation of SOC calculated across 8 European experiments as a result of straw incorporation has been calculated as 70 kgC ha^{-1} yr^{-1} t^{-1} of straw applied (Smith *et al*., 2000, a, b, c). A more recent review of the English data from straw incorporation experiments calculated an average SOC increase of 50 kgC ha^{-1} yr^{-1} t^{-1} straw incorporated with 95% confidence intervals of 20-80 kgC ha^{-1} yr^{-1} t^{-1} (Bhogal *et al.*, 2008). Taking the carbon content of straw as 400 kg t^{-1} these represent mean efficiencies of 12.5 – 17.5%.

The long term winter wheat field experiment run from Oak Park at Knockbeg showed a significantly higher SOC as a result of straw incorporation as opposed to straw removal of 1.75% vs 1.63% in the 0-15 cm soil horizon (p=0.020) and 1.64% vs 1.55% in the 15-30 cm soil horizon (p=0.019), but there was no effect below 30cm depth in the soil. The greatest overall SOC in the 0-15 cm horizon was achieved through a combination of straw incorporation and minimum tillage which resulted in SOC of 1.91%, but it was not significantly better in the lower soil horizons.

The estimates from the Knockbeg experiment are based on wheat cropping, whilst the largest single tillage crop in Ireland is spring barley, from which significantly lower straw yields will be produced, closer to 4 rather than the 6 t ha^{-1}. It should also be borne in mind that the majority of straw is already returned to the land albeit after being used as bedding or feed for livestock.

Economics

Direct incorporation of straw has a relatively small direct cost, however, the loss of sales of straw off-farm can be significantly greater, particularly in years of low cereal production and short supply. The value of the straw crop is estimated at between 60€ ha^{-1} for wheat and 100€ ha^{-1} for barley.

Agronomy

Weeds

Despite an extensive literature search no relevant published literature describing the effect of straw incorporation vs straw removal on weed issues could be found. Whilst there was a body of work produced in the early 1990's this largely related to the introduction of the straw burning ban and compared burning residues with incorporation. This work is of little relevance to the current consideration as the act of burning will destroy weed seeds. The lack of relevant literature is therefore likely to be because there is no expected impact of the removal or otherwise of straw on the return of weeds seeds to the soil. Poor incorporation of straw residues, for example through no-till approaches such as 'Autocast' establishment of oilseed rape and poor distribution of straw residues by the straw chopper on the combine have been anecdotally reported in the UK as adversely affecting weed control. Poor distribution of crop residues resulting in mats of organic matter protecting the soil surface from the application of soil residual herbicides or germinating weed seedlings from the application of contact herbicides have been reported as affecting weed control, but can also adversely affect crop emergence. Such effects are the result of poor crop husbandry and would not be expected to be a significant factor in well managed systems where crop residues are returned to the land.

This lack of consistent effect of straw disposal method was reflected in the cultivations and straw incorporation work carried out in winter wheat by Teagasc at Knockbeg Co

Laois. Assessment made in autumn 2002 prior to herbicide application showed that removal of straw decreased the number of annual meadow grass (*Poa annua*) plants under the plough cultivations but increased them under the minimum tillage cultivations.

Disease

Many of the disease issues discussed in relation to non-inversion tillage were due to the importance of trash as a source of inoculum for many of the key diseases. The issues in relation to the incorporation of straw are therefore likely to be common, and indeed to be exacerbated if straw incorporation and non-inversion tillage are combined and result in increased levels of straw residues present on the soil surface. The issues raised below should therefore be considered to be in addition to those discussed in the minimum tillage section.

Jenkyn *et al.* (2001) assessed the impact of the amount of straw incorporated on both foliar, stem base and root diseases of wheat. Straw was incorporated at rates of between 0 and 20 t ha^{-1}. Over a number of sites and seasons they could find no impact of straw incorporation on foliar disease levels in winter wheat. There were however, effects on the level of eyespot which declined with increasing incorporation rate although the biggest response was between 0 and 5 t ha^{-1} incorporated. There was no similar effect on sharp eyespot or brown foot rot, but on one site they found a small but significant increase in take-all severity with increasing rates of straw incorporation.

Conversely, Rodgers-Gray and Shaw (2000) recorded increased infection with Septoria leaf blotch (*Mycosphaerella graminicola*) up until GS30 of winter wheat but subsequently levels were lower where straw had been incorporated. They also recorded significantly reduced; powdery mildew (*Blumeria graminis*), brown rust (*Puccinia triticina*) and brown foot rot (*Fusarium* spp.) due to straw incorporation possibly due to increased leaf silica levels.

Soil compaction

There appears to be limited if any published work that has compared soil compaction following the incorporation or removal of straw residues. However, given that the repeated incorporation of straw into soil has been demonstrated to increase SOC and that the SOC concentrations in soil have been demonstrated by a number of authors, to increase soil structural stability (e.g. Tisdall and Oades, 1982; Davies, 1985) and reduce soil damage due to cultivation (e.g. Watts and Dexter, 1997) it seems likely that incorporation of straw residues will to a small extent help protect against soil damage.

Conclusions

Straw incorporation can have beneficial effect on the soil from an agronomic as well as environmental perspective, and in terms of other direct agronomic effects appears neutral. However, straw is a valuable commodity to the dominant livestock industries in Ireland, and to encourage its direct incorporation into the soil could have significant adverse effect on the economics of those industries. The value of the straw in nutritional terms would be enhanced by first utilising it for livestock bedding or feed and returning it to tillage land as manure, there are of course logistical issues to overcome to facilitate this.

Organic matter incorporation

In addition to the incorporation of in-situ sources of organic carbon such as straw there is the opportunity to increase SOC through the importation of organic carbon into the tillage system. The main potential source of imported organic carbon is in the form of livestock manures (40 million tonnes p.a.). The majority of this is from grazed ruminant animal systems where it is already efficiently used on the farms that produce the manure, almost exclusively on grassland. While intensive pig and poultry units may need to export these manures from their farms, the total quantity available is limited and there are logistical constraints to delivering the material from source to much of the tillage crop area of the country. There is also the potential to utilise other materials such as green composts, biosolids and paper crumble, although the supply of such materials in Ireland is limited (Anon, 2008). The use of biosolids from sewage treatment plants is currently limited by difficulties with producer quality assurance schemes.

Organic carbon

There is debate in the literature as to whether the rate of SOC increase is dependant entirely on the amount of organic carbon applied or whether the rate is dependant on the form of organic carbon. A number of authors have reported linear increases in SOC related to the amount of organic carbon applied (e.g. Dick and Gregorich, 2004; Rasmussen *et al*., 1980; and Bhogal *et al.*, 2006 & 2007), whilst others, have reported that the rate of SOC accumulation is dependant on the source of organic carbon (e.g. Johnson *et al.*, 1989). Johnston *et al.* (1989) found that the rate of SOC accumulation was slower with farmyard manure (FYM) than it was with sewage or vegetable composts.

In a recent review in the UK, Bhogal *et al.* (2008) reviewed a large body of relevant studies from the UK and other results and concluded that there was some variation in rate of SOC accumulation depending on the source of organic carbon input, mean values are presented in Table 4.

Table 4. Estimates of SOC accumulation per hectare per year per tonne of dry solids applied from a range of sources of organic carbon (adapted from Bhogal *et al*., 2008)

Organic carbon source	SOC accumulation (kgC ha^{-1} yr^{-1} t^{-1} dry solids applied)
Animal manures	60
Sewage sludge - raw	130
Sewage sludge – digested	180
Green waste compost	60
Paper crumble	60

Agronomy

Weeds

There are no reported or predicted adverse or beneficial impacts of organic matter incorporation on weeds

Disease

Given that many of the sources of imported organic matter are derived from mainly non-tillage sources or would have undergone a composting stage that meets EU regulations they would not be expected to be a source of crop pathogens. However, the addition of organic materials will alter the nutrient status of the soil and crop and may therefore have an indirect effect on disease levels in the crop by altering the crops susceptibility to disease. This may arise through direct interaction of the pathogen with the nutritional status of the host (for example yellow rust increases with increased N concentration in wheat) or indirectly through increased crop growth altering the microclimate within the crops canopy in favour of the pathogen.

In contrast to the effect of straw incorporation which increased Septoria leaf blotch (*M. graminicola)* early in the season but reduce it late in the season, the addition of manure has been shown to increase the severity right through the season (Rodgers-Gray and Shaw, 2000). Conversely the same authors also showed that addition of manures significantly reduced rust (*P. triticina*).

Conclusions

Whilst there is clearly potential to increase SOC through the incorporation of organic carbon compounds imported onto tillage land the efficiency of capture of the organic carbon into SOC is relatively low. For example, once the carbon content of the various materials is taken into account the efficiency of capture of organic carbon from compost is 43% however for manures which are the most readily available in Ireland it is even lower at only 23%.

The rate at which SOC can be increased using these materials will also be limited by the amount which can be applied whilst still complying with legislation to limit losses of nutrients to the environment. Most of the animal manures available in Ireland are slurries typically with Dm contents of less than 10%. Under the nitrates directive growers are effectively limited to an application of approx 25 t/ha of slurry (which at 4% DM equates to 1 tonne dry matter) every second season or an accumulation of 30 kg C/ha/yr. Assuming a bulk density of 1.3 and depth of 20 cm this would equate to an increase of ~0.001% SOC per year. Therefore this is not a realistic means of increasing SOC in the short or medium term.

Cover cropping

Cover or catch cropping was originally used in mixed farming situations to provide over-winter fodder for livestock prior to the planting of a spring crop, for example stubble turnips (e.g. Geisler *et al*., 1979). Interest in cover crops underwent a resurgence in the early 1990's as concerns over over-winter leaching of nitrates into ground waters increased. Their use has been demonstrated, by a number of authors (e.g. Shepherd and Lord, 1996 & Hooker *et al*., 2008), to reduce free nitrate in the soil following the harvest of the previous crop and reduce leaching into ground waters. They have also been of interest to reduce surface losses of soil particles and nutrients to surface waters, although their usefulness in this regard is of some doubt (Ulen, 1997).

Because the growth of cover crops represents an additional input of organic carbon into the farming system compared to leaving the land fallow, they present the opportunity to increase or slow the decline of SOC in tillage situations.

Organic carbon

Publications covering the direct effects of cover crop use on SOC are limited. However, Blomback *et al*. (2003) based on 6 years of continuous over-winter cover cropping in Sweden reported an increase in SOM of only 2% compared to where no cover crop had been used.

It is reasonable to assume that the efficiency of SOC accumulation from the incorporation of cover crops would not differ significantly from that achieved with incorporation of green waste compost i.e. 60 kgC ha^{-1} yr^{-1} t^{-1} of dry solids incorporated. Cover crop experiments in carried out at Oak Park, Co. Carlow in 2004 resulted in cover crop dry matter accumulations of between 1 and 3t ha^{-1} of dry matter accumulation. The rate of accumulation of SOC could therefore be assumed to be between a half and a third of that which could be achieved by the incorporation of straw. Taking 3000 kg Dm per ha at 40% carbon and 30% efficiency of retention, soil depth of 20cm and bulk density of 1.3 this would lead to an increase of ~0.014 percentage points in SOC content per year.

Economics

The economic impact of incorporating cover crops into the rotation depends on a number of factors; the choice of cover, cost of planting and destruction and effects on a subsequent crop.

The use of natural regeneration of 'volunteer' plants of the previous crop and weeds is the cheapest with little or no direct cost to the grower. The only costs that could be incurred would be for a surface cultivation of the previous crop stubble to encourage germination and for glyphosate to destroy the cover prior to planting the following crop. Under current legislation it is a legal requirement for land not being sown to winter crops to have an overwinter green cover, and this is the cheapes option available. Where a sown cover crop is used an additional seed cost will be incurred as well as an additional planting cost. Depending on the species an extra destruction cost may also be incurred (e.g. chopping). The cost of seed for sown species can range from ~ €10-€100/ha depending on species and seed rate. There will also be rotational restrictions associated with some cover crops which may require more expensive options to be used (e.g. brasscia cover crops shouldn't be used where oilseed rape is included in the rotation).

The cost of planting and additional destruction (over and above what would be required for natural regeneration) can range from 205€ to 285€ ha^{-1} (assuming contractor charges for the operations) Therefore unless a cover crop provides a benefit to a subsequent crop it will incur a net cost on the system.
In an experiment carried out over a number of seasons at Oak Park comparing three overwinter cover systems (bare fallow, natural regeneration and mustard cover crop) under two tillage treatments (reduced tillage and ploughing) there was no consistent difference between the overwinter covers in terms of grain yield. This would indicate little benefit of sown cover crops on subsequent crops and indicates that a sown cover crop would be a net cost on the system, which in the absence of very high grain prices would equate to greater than the profit in growing the crop.

Agronomy

Weeds

The impact of cover cropping on weed burden should not be particularly significant and may even be beneficial if weeds germinate in the intercropping period without setting seed. With perennial weeds such as docks and scutch grass the destruction of the covers using glyphosate should result in good control.

There is a risk of species used as cover crops becoming weeds later in the rotation, this may be particularly high when oily seeds such as brassicas or seeds with variable dormancy are used.

Disease

The use of any cover crop particularly if established using minimal cultivations will result in the over-wintering of volunteer crop plants, which can act as a source of disease inoculum for the following crop. This effect will however be most significant for natural regeneration of stubbles where there is little or no competition with volunteer plants. This effect will be greatest for soil borne diseases such as take-all and the trash borne diseases outlined in the sections above. Conversely, in continuous cropping situations such as continuous spring barley where antagonists to diseases such as take-all can build up, the use of naturally regenerated cover crops may have a beneficial suppressing effect on disease levels in the crop.

Conclusions

Whilst cover crops have the potential to improve SOC levels the rate at which they will do so will be limited by the crop dry matter that can be produced over the winter period, and their impact is therefore predicted to be low. However, cover crops do offer other environmental benefits on light soils particularly such as reducing leaching of nitrates.

The use of cover crops is likely to be limited by the financial costs of their use rather than any significant adverse agronomic effects, the agronomic impact is likely to be positive but not sufficiently so to make them economically viable.

Duration of effects

The effects on SOC outlined above are the initial rates of change that can be expected once a change in farming practice has been initiated. Bhogal *et al*. (2008) stated that once a change in management practice had occurred, the SOC moves towards a new equilibrium value that is characteristic of the soil type, land use and climate.

The long term 'Classical' experiments such as the Broadbalk experiment in the UK which has been running since 1843, demonstrates that about half of the long term (c. 100 years) SOC accumulation will occur in the first 20 years after a change in management and that the rate of SOC change slows dramatically after 50 years (Figure 3 from: Coleman *et al.,* 1997).

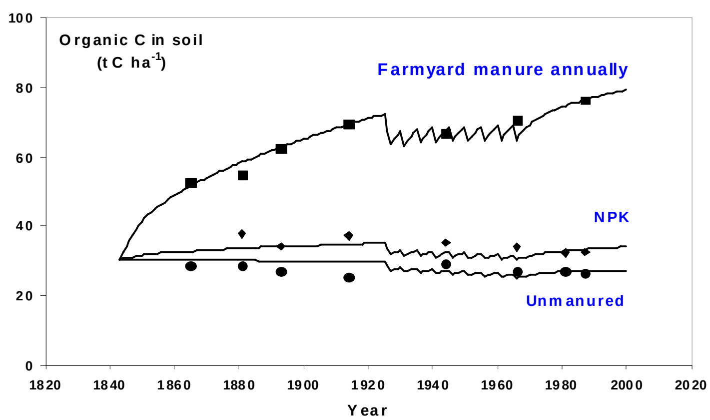

Figure 3: Accumulation of Organic C in the soil in the Rothamsted Broadbalk experiment

By definition therefore if a change in management is to have any long term effect on SOC the change must be initiated and continued indefinitely. Once management reverts to previous practice the SOC will revert to its previous equilibrium value. It is also clear that changing SOC levels is a long term objective and changes from season to season will be much less that the error in measurement, unless dramatic additions of organic matter are made. Monitoring such changes requires measurements to be made over a decade or more before there can be certainty that any shift to a new equilibrium level is occurring.

Discussion and Conclusions

Whilst the figure of 2% SOC has been suggested by some authors as a ‘critical’ value, below which soil function and environmental performance will be adversely affected, there does not seem to be strong evidence that this is the case. However, what does appear to be clear from the literature is that there is unlikely to be a problem with the functionality of a soil if it has a SOC above 2%. A threshold value of 2% SOC above which a soil could be classified as being in ‘good condition’ seems reasonable. But some more precise method of evaluating soil condition will be required to identify soils with less than 2% SOC which are in poor condition.

There is strong evidence that the SOC content of a soil will be strongly influenced by its clay content and annual precipitation. A SOC of 2% may in fact represent an unachievable aspiration in some circumstances particularly on light soils. In such circumstances there is strong evidence that a soil can perform adequately both in terms of productivity and in its environmental functions at well below 2% SOC.

It is also clear that particularly in temperate regions once a soil has been subjected to a certain form of land use for a number of years (50-100) it will reach an equilibrium level of SOC, rather than continuing to decline or increase from its original level.

In terms of most soil functions, there is strong evidence that avoiding unsustainably low SOC levels is desirable. It appears however that at such low levels the productivity of the soil would be adversely affected as well as its environmental performance, and the negative impact on productivity should prompt an economic response from the land owner to alter land use practices. Maintenance of a soils environmental and agronomic performance are therefore mutually compatible objectives.

There are a number of husbandry practices that can be employed which will ensure that the soil reaches a higher equilibrium level of SOC, however the rate of change will be slow, taking in the order of a decade in most cases for the change to be detectable, even in replicated field experiments and longer with the variability associated with field sampling. It is also clear that any change in husbandry practice must be maintained for a number of years and the effects are readily reversible once a change to original practice occurs.

It is also clear that some of the practices that might be employed to increase SOC levels have a significant cost to the grower either directly or indirectly through agronomic impacts that increase costs (e.g. increased herbicide or fungicide use, with other potential environmental costs) or limit yield potential. In some circumstances particularly on light land it would appear that the only method of achieving 2% SOC would be to take land out of tillage farming, and revert it to permanent grassland or forest. Such drastic action would have significant implications for the country in terms of exposure to volatility of food prices and supply on the world market, and in purely scientific terms would be unjustifiable as the sustainable level of SOC required would in all probability be significantly below 2% SOC.

This review indicates that rather than having 2% SOC as a ‘critical’ value, below which soil is assumed to be in poor condition and potentially costly remedial action must be taken, it would be more scientifically justifiable to take it as a ‘precautionary threshold’ value above which no action is required. Soils with less than 2% SOC should be subjected to further examination to ascertain if they are in good environmental and agronomic condition. These further measures could include observation of:

- Erosion
- Gullies in the field
- Compaction
- Slumping
- Capping
- Crumb structure
- Productivity

It would also be very worthwhile to make growers aware of the benefits of higher SOC levels in maintaining both the environmental functioning and productivity of their land. This would address environmental targets in conjunction with promoting productivity.

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