Science of the Total Environment 805 (2022) 150342

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Full Inversion Tillage (FIT) during pasture renewal as a potential management strategy for enhanced carbon sequestration and storage in Irish grassland soils

Andrew P. Madigan [a,b], Jesko Zimmermann [c], Dominika J. Krol [a], Michael Williams [b], Michael B. Jones [b,*]

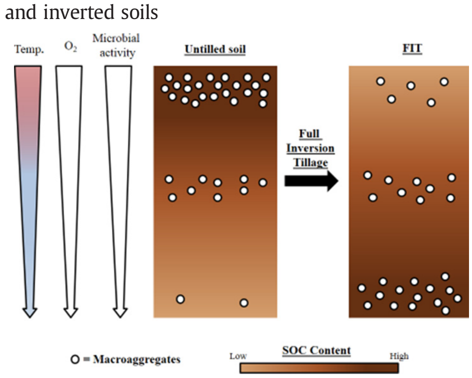
[a] Department of Environment, Soils and Land Use, Teagasc, Johnstown Castle, Wexford, Ireland
[b] Department of Botany, Trinity College Dublin, The University of Dublin, Dublin 2, Ireland
[c] Department of Agrifood Business and Spatial Analysis, Rural Economy & Development Programme, Teagasc, Ashtown Research Centre, Dublin 12, Ireland

HIGHLIGHTS

- Storage of carbon (C) in grassland soils is an effective method of C sequestration.
- Grassland soil C is increased by several management practices including re-seeding.
- Combining full inversion tillage and re-seeding stores significantly more C.
- Up to 26% of Ireland's grasslands are suitable for full inversion tillage.

GRAPHICAL ABSTRACT

Vertical profiles of untilled and inverted soils



ARTICLE INFO

Article history:
Received 17 June 2021
Received in revised form 10 September 2021
Accepted 10 September 2021
Available online 15 September 2021

Editor: Manuel Esteban Lucas-Borja

Keywords:
Carbon sequestration
Soil carbon storage
Grassland
Full inversion tillage
Pasture renewal
Soil organic matter
Ireland
Climate change

ABSTRACT

It has been suggested that the sequestration of CO_2 by agricultural soils offers a means to reduce atmospheric greenhouse gas (GHG) concentrations and in turn mitigate the impacts of climate change. Carbon sequestration by grassland soils, which account for more than 60% of agricultural land use in Ireland, could contribute to a successful net reduction of atmospheric GHG emissions in accordance with the COP21 Paris Agreement. However, current estimates of soil carbon sequestration are variable and it is likely that many permanent grasslands are close to saturation. A literature search shows that soil carbon sequestration is enhanced by a variety of different management strategies, although one option that has only been examined to date in New Zealand is full inversion tillage (FIT) during grassland renovation. FIT involves inverting topsoil, generally to depths of 30 cm, resulting in the movement of C-deficient subsoil to the surface and the burying of carbon-rich topsoil. In this review, we hypothesise that over the next ~30 years the new topsoil could incorporate large amounts of soil organic carbon (SOC) from the re-seeded sward vegetation and that the buried carbon will be retained. We assess the current capability of Irish grassland soils to sequester carbon and suggest a potential role of FIT during grassland renovation. An analysis of the distribution of grasslands in Ireland using the Land Parcel Identification System (LPIS) suggests that ~26% of Ireland's agricultural grasslands are suitable for FIT.

* Corresponding author.
E-mail address: mike.jones@tcd.ie (M.B. Jones).

https://doi.org/10.1016/j.scitotenv.2021.150342

Contents

1. Introduction

Over the last century, industrial and agricultural activities have greatly intensified, resulting in significant increases in atmospheric concentrations of greenhouse gases (GHG's) (Hegerl et al., 2019; Wang et al., 2020). This in turn has directly impacted climatic conditions across the world, resulting in rising temperatures and more frequent occurrences of extreme and destructive weather patterns (Leisner, 2020; Azevedo et al., 2020). To counteract the impacts of increasing GHG levels, the United Nations Framework Convention on Climate Change (UNFCCC) proposed various mitigation strategies at the Paris Conference of Parties (COP21) convention in 2015, with an overall aim to limit the global temperature increase to well below 2 °C, and ideally 1.5 °C, relative to pre-industrial levels, over the coming decades (Minasny et al., 2017; UNFCCC, 2015). In order to achieve these targets integrated assessment models have consistently shown that there will be a need to actively remove CO_2 from the atmosphere and sequester it long-term using negative emission technologies (NETs) (EASAC, 2018; Rogelj et al., 2021)). NETs are any process that removes CO_2 from the atmosphere and stores it in the biosphere or geosphere. Terrestrial ecosystems, vegetation and soils, act as sinks for CO_2, thus offering potential NET opportunities for reducing atmospheric CO_2 levels (Pugh et al., 2016; Strassmann et al., 2008). Furthermore the long-term accumulation of soil organic carbon (SOC) additionally offers multiple benefits along with GHG reduction, including improved agricultural productivity and more stabilised food security (Lal, 2004). On the basis of the importance of soil organic carbon (SOC) in the process of carbon sequestration, COP21 adopted a '4-per-mille' initiative, with the aim of globally increasing stock carbon levels in agricultural soils by 0.4% annually (Minasny et al., 2017; IPCC, 2019). However, the evidence is that, in many circumstances, there are severe limitations in achieving this goal (Poulton et al., 2017; Baveye et al., 2018; Martin et al., 2021) and that the utilisation of optimised practices for enhancing soil carbon sequestration will be region- and site- specific (Minasny et al., 2018). Numerous factors including land use history, current land management, soil physiochemical characteristics, microbial composition and climate, influence the accumulation of SOC, and in turn therefore the long-term capability of a soil to sequester carbon (Jones and Donnelly, 2004; Lal, 2013; IPCC, 2019). As a consequence, strategies to increase SOC sequestration in the future need an improved understanding of these factors and the way that they operate under each agricultural land management practice (Chenu et al., 2019; Soussana et al., 2019).

Agricultural land use in Ireland is predominantly grass based, with grassland and rough grazing occupying approximately 4.3 Mha or ~ 61% of land cover in 2016 (Haughey, 2021). Irish grasslands represent the second largest stock of soil carbon after peatlands/wetlands and are estimated to contain 53% of the national soil carbon stocks with 769 ± 163 Mt. of carbon held within the top 50 cm of soil (Khalil et al., 2013). However, there is evidence that soils under long term permanent pastures already have large topsoil carbon stocks which means that the scope for continued accumulation of additional carbon in these surface soils may be limited (Whitehead et al., 2018). This has resulted in warnings for caution in ascribing large, potential climate change mitigation to enhanced soil management (Schlesinger, 2000; Schlesinger and Amundson, 2019). However, because most of the soil carbon and grass roots are in the upper 15 cm there may be potential to sequester additional carbon by burying C-rich topsoil and bringing the C-deficient subsoils to the surface by inversion tillage during pasture renewal (Whitehead et al., 2018; Lawrence-Smith et al., 2021). A literature search has shown that very few studies have directly investigated the net effects of FIT on SOC stocks in managed grasslands, but a recent report by Calvelo Pereira et al. (2017) has shown that, in New Zealand grasslands, there was an increase of nearly 14 t C ha^{-1} over four years following pasture renewal associated with FIT. Pasture renewal (reseeding) is frequently necessary at intervals of five to ten years because the yields and quality of temperate managed permanent grasslands progressively decreases during ageing due to sward deterioration brought about by a range of factors including compaction, poor drainage and weed invasion (Necpalova et al., 2013; Carolan and Fornara, 2016).

In this review, focusing on Irish agricultural grasslands, we (i) identify the various factors influencing the development of soil carbon stocks throughout a temperate grassland soil profile and review the effects of common grassland management practices on these stock levels, (ii) explore the potential for enhanced long-term carbon sequestration in Irish grassland soils by the one-time application of pasture renewal by reseeding following full inversion tillage (FIT), (iii) make a preliminary assessment of the current potential for carbon sequestration in Irish grassland soils if FIT pasture renewal is implemented, and finally (iv) we estimate the grassland area in Ireland suitable for FIT, as a precursor for future research to determine the sequestration potential of this management practice in Irish agriculture.

2. What factors influence SOC accumulation and stabilisation in grasslands?

i) Soil carbon sequestration processes.

Soil carbon sequestration is the process of transferring CO_2 from the atmosphere into the soil through the plants, plant residues and other organic solids which are retained as part of the soil organic matter (humus) (Chenu et al., 2019). Long-term carbon sequestration in soil is strongly dependent upon the rate of SOC decomposition and the stability of SOC (Don et al., 2013; Dungait et al., 2012). Soil respiration causes the breakdown of organic carbon by soil microbes, resulting in the release of CO_2 into the atmosphere (Fatichi et al., 2019; Franzluebbers, 2018). Spatial separation of SOC from soil microbes via physical occlusion within soil aggregates limits substrate availability, thus reducing SOC decomposition (Dungait et al., 2012; Six and Paustian, 2014). Aggregates range in size from macroaggregates (> 250 μm), to microaggregates (53–250 μm) and silt plus clay aggregates (< 53 μm) (Six et al., 2000). Various physiochemical processes and biotic products influence the development of aggregates from primary soil particles (Wang et al., 2018). Processes may include ligand exchange and polyvalent cation bridging, while products from root and microbial exudates along with organic matter provide binding material for the soil particles (Bronick and Lal, 2005; Jastrow et al., 2007; Bailey et al., 2019; Six et al., 2002b). SOC decomposition is particularly restricted in microaggregates and silt plus clay aggregates due to limited oxygen availability and SOC accessibility for soil microbes, thus offering greater long-term sequestration capabilities (Torres-Sallan et al., 2018; Six et al., 2002; Six et al., 2002b). SOC also forms more stable chemical bonds with fine mineral particles (i.e. fine silt and clay), which may be protected by the formation of microaggregates (Dungait et al., 2012; Baldock and Skjemstad, 2000; Wiesmeier et al., 2019; Beare et al., 2014; Torres-Sallan et al., 2017). Overall, therefore, macroaggregates are the least stable form of soil aggregation, with a turnover time of less than a decade (Six et al., 2002b; Six et al., 1998). In contrast, microaggregates can remain stable for up to a century, while silt plus clay aggregates may remain unaltered in excess of 100 years (Six et al., 1998; Von Lützow et al., 2006). The carbon sequestration potential of a soil is thus enhanced relative to the proportion of these smaller aggregates throughout the soil profile. In particular, soils of higher silt and clay content offer a greater likelihood of long-term carbon sequestration, as this fraction can store up to 90% of the total SOC in agricultural soils (Torres-Sallan et al., 2017; Creamer and O' Sullivan, 2018; Flessa et al., 2008; Ghafoor et al., 2017). However, this can vary across soils as the type of clay (i.e. mineralogy) and its physiochemical characteristics also influence the SOC stabilisation process (Torn et al., 1997; Beare et al., 2014).

ii) Land management practices.

Various land management practices can influence soil carbon stocks and potentially lead to increases in soil carbon sequestration and carbon storage. The main pathways to maximising SOC sequestration have been summarised by Sykes et al. (2020) and Chenu et al. (2019) to be the result of optimising the crop productivity and carbon inputs to the soil and minimising the CO_2 losses by microbial mineralisation, while the addition of carbon produced outside the production system by application of manure also increases carbon stocks. Table 1 lists a number of management practices that have been demonstrated to increase soil carbon sequestration and storage in temperate grassland soils. It also shows some of the potential additional benefits or disadvantages of the practices. For example, the addition of inorganic and organic fertilisers such as manure to soil can both directly and indirectly increase SOC levels along with improving plant productivity in grasslands (Arrouays et al., 2002; Jokubauskaite et al., 2016, Sykes et al., 2020) while beneficially altering soil parameters such as structure, water holding capacity and erosion susceptibility, that indirectly improve SOC stability (Shehzadi et al., 2017; Brady and Weil, 2002; Pan et al., 2009).

Land management practices which optimise soil pH to enhance agricultural productivity normally require reducing soil acidity via liming (Hamilton et al., 2007; Fornara et al., 2011; Sykes et al., 2020). Coincidentally, various chemical and biological processes associated with SOC accumulation and stability are also altered by the change of soil pH. The availability of additional calcium carbonate through liming generates more organo-calcium aggregates, thus enhancing the stability and long-term sequestration potential of SOC (Tu et al., 2018). However, the increased pH can both weaken the stability of some organo-Al aggregate complexes and result in an increase in soil microbial carbon respiration rates (Paradelo et al., 2015; Miyazawa et al., 2013). Therefore, various soil characteristics must be taken into consideration prior to liming to ensure the effects to SOC stocks and the long-term carbon sequestration capability of a soil are beneficial.

Other management practices influencing SOC levels include irrigation and changes in the species composition of grasslands. Irrigation can have a negative impact on soil carbon stock levels, as soil conditions become more suitable for carbon mineralisation due to enhanced soil microbial activity (Whitehead et al., 2018). SOC levels are generally greater in grasslands where swards are composed of multiple species (Fornara and Tilman, 2008; Nobilly et al., 2013). Additionally, the inclusion of deep rooting and rhizomatous species in swards may further enhance SOC stocks, as the primary source of SOC in grassland soils is associated with root exudate and root particulate matter (Li et al., 2019; Crow et al., 2009).

iii) SOC distribution throughout the soil profile.

The SOC stocks of grasslands tend to be highly stratified from the surface downwards with the top-soils (0-15 cm) containing

Table 1
Literature survey of the effects of changes in temperate grassland management on soil carbon sequestration and co-benefits or disadvantages.

Management practice	Potential soil carbon sequestration	Estimated uncertainty	Reference	Additional benefits	Disadvantages
Increased fertiliser on nutrient poor permanent pasture (N&P)	0.3- 0.4 t C ha^{-1} $year^{-1}$	>50%	Arrouays et al. (2002)	-Enhanced productivity.	-Increased N_2O emissions. -Additional financial costs. -Enhanced water pollution risk.
Manure application	Cattle slurry – 2.16 Sludge pellets – 4.53	±2.28 ±1.73	Jones et al. (2006)	-Enhanced productivity.	- Increased soil respiration. - Increased CH_4 emissions.
Long term liming	Limed – 0.70 t C ha^{-1} $year^{-1}$ (Un-limed – 0.25 t C ha^{-1} $year^{-1}$)	n.a.	Fornara et al. (2011)	- Lower N fertiliser requirements. Counteracts soil acidity.	
Increased duration of grass leys	0.1-0.5 t C ha^{-1} $year^{-1}$	>50%	Arrouays et al. (2002)	-Reduced financial costs.	-Declining productivity.
Extensive grazing compared to mowing	NGGB, flux measurements[a] - 0.62 t C ha^{-1} $year^{-1}$	±0.77 t C ha^{-1} $year^{-1}$	Koncz et al. (2017)	-Reduced GHG emissions from land use.	-Lower usage intensity of grass supply.
Convert arable to grassland	1.44 t C ha^{-1} $year^{-1}$	n.a.	Vleeshouwers and Verhagen (2002)	-Reduced run-off losses.	-Big change in farming practices.
Re-seeding grazed grassland	1.125–1.454 t C ha^{-1} $year^{-1}$ (low – high N application)	± 0.839 t C ha^{-1} $year^{-1}$	Watson et al. (2007)	-Enhanced productivity. -Reduced weed invasions.	
Re-seeding by direct drilling intensively managed grassland	NECB flux measurements[b] -1.89 t C ha^{-1} $year^{-1}$	Mean of two plots.	Rutledge et al. (2017)	-Enhanced productivity. -Reduced weed invasions.	
Higher species diversity in N depleted soils	0.649 t C ha^{-1} $year^{-1}$	± 0.076 t C ha^{-1} $year^{-1}$	Fornara and Tilman (2008)	-Reduced fertiliser requirement.	-Lower nutritive value of sward. -Benefits dependant on soli quality.
Biochar application	0.03–1.0 t C ha^{-1} $year^{-1}$	n.a.	Smith (2016)	-Improved soil quality	-Potential for sink saturation. -Decreased soil albedo.

n.a. = not available.
[a] NGGB = Net Greenhouse Gas Balance.
[b] NECB = Net Ecosystem Carbon Balance.

considerably higher quantities of carbon relative to sub-soils. The top-soils are therefore moderately limited in regards to their ability to further sequester carbon (Linsler et al., 2013; Whitehead et al., 2018; Chenu et al., 2019). SOC decomposition is also greatest in the topsoil region, where conditions for microbial activity are most favourable. Consequently, soil carbon sequestration is non-linear with depth. Long-term experiments show that increases in top-soil carbon are greatest soon after a land-use or land management change (Post and Kwon, 2000; Chan et al., 2011). As the soil reaches a new equilibrium after 20-100 years no further change takes place (Smith et al., 1997; West et al., 2004). This is referred to as sink saturation. The 'effective stabilisation capacity' of a soil relates to the soil carbon sequestration potential as the carbon stock increases due to changed management (Stewart et al., 2007). In contrast, the sub-soils continue to offer considerable potential in relation to long term SOC sequestration as they are low in SOC content and thus are in an unsaturated state with a high effective stabilisation capacity (Beare et al., 2014; Paustian et al., 2016). Soil carbon losses through respiration is also reduced at depth as environmental conditions such as lower temperatures, reduced organic matter availability, as well as lack of oxygen and nutrients are unfavourable for microbial activity (Don et al., 2013; Dungait et al., 2012; Whitehead et al., 2018).

3. What are the current carbon stocks and SOC sequestration rates in Irish grassland soils?

Ireland has a land area of 6.9 Mha, with a temperate climate consisting of seasons varying across a moderate temperature range and relatively high rainfall throughout the year (Keane et al., 2004). The temperate climate is conducive to grass growth for almost 10 months per year. Thus, a large proportion (~ 65%) of the land area in Ireland is used for agriculture, the majority (91%, 4.3 Mha) of which is accounted for by grasslands and rough grazing (DAFM, 2015; Creamer and O' Sullivan, 2018; Aksoy et al., 2016). Furthermore, in comparison with many other western European countries, Ireland has a greater proportion of permanent grassland to temporary leys (Smit et al., 2008) which are particularly beneficial for carbon sequestration (see Table 1 and Arrouays et al., 2002).The predominant Irish grassland soils with high moisture and clay content are well suited to SOC accumulation due to both reduced soil microbial activity and greater stabilisation of organic carbon (Creamer and O' Sullivan, 2018). As a result, it is generally recognised that Ireland's soils have one of the highest mean concentrations of SOC in Europe. The SOC of these soils show a strong vertical gradient. Based upon empirical data of 806 sampled agricultural soil profiles, Simo et al. (2019) found that 54% of the carbon in the top 100 cm of soils was contained within 0-30 cm depth, with an additional 36% represented between 30 and 50 cm, and the final 10% found between 50 and 100 cm. Specifically for Irish grasslands, Khalil et al. (2013) found that 57% of SOC in the top 100 cm is between 0 and 30 cm, with 21% at a 30-50 cm depth and 22% in the remaining sub-soil. Data on the vertical distribution of SOC in the top 30 cm of grassland soils in Ireland are limited but we have extracted information from 144 profile sites from the Irish Soil Information System (SIS) (Creamer et al., 2014). Fig. 1 shows the distribution of SOC stocks across improved (by drainage, re-seeding and increased fertiliser application) and unimproved grassland soils with a mean value of 64.9 t ha^{-1} in the top 15 cm and 46.0 t ha^{-1} in the 15 to 30 cm layer. The significance of the difference was confirmed using the Kruskal-Wallis Rank Sum Test ($p < 0.01$). The type of grassland, however, had no significant influence on the SOC stocks. Jointly, these studies confirm that Irish soils contain large amounts of soil carbon stock in the surface layer, which is likely to constrain the ability of the top-soil to further accumulate carbon, especially in the long-term. Conversely, sub-soils contain less carbon, and therefore offer a significant potential for enhanced carbon sequestration as they have a greater effective stabilisation capacity (Kiely et al., 2017). A measure of stratification has been termed the SOC stratification ratio by Lawrence-Smith et al. (2021) and is the C stock (t ha^{-1}) in the 0-15 cm layer divided by the C stock in the 15-30 cm layer. The average ratio for Irish grassland soils based on data in Fig. 1 is 1.41.

A review of the literature indicates that currently there are limited data available on measured rates of carbon sequestration in temperate grassland soils (Freibauer et al., 2004; Minasny et al., 2017). Table 2 summarises estimates that have been derived from either direct measurements of soil carbon accumulation over periods of at least 10 years or carbon flux measurements using eddy covariance over at least one annual cycle. Three of the estimates are from publications including Irish grasslands and in addition there is an estimate from a modelling exercise (Khalil and Osborne, 2018). The highest estimates of current carbon sequestration rates of well managed swards in Ireland are considerably higher than those made elsewhere, at 2.15 t C ha^{-1} yr^{-1} (Byrne et al., 2007), but it should be noted that there are large uncertainties associated with all of these measurements (Soussana et al., 2007).

We conclude that, because of the very limited number of studies of soil carbon dynamics in Irish grassland soils, it is not currently possible to make reliable quantitative assessments of the magnitude of soil carbon changes under most management practices and further research is therefore required to determine the site management, soil conditions and plant species that may govern whether grasslands will continue to sequester carbon over a prolonged duration (West et al., 2004; Kiely

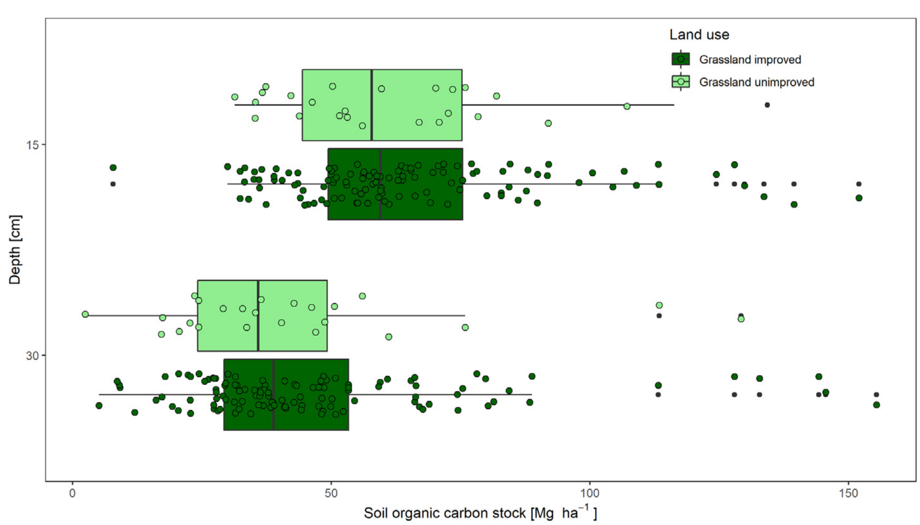


Fig. 1. Soil organic carbon stocks from 144 soil profiles taken in improved and unimproved grasslands in Ireland. The layers represent average values from 0 to 15 cm and 15 to 30 cm. The points represent recordings from each profile.

Table 2
Literature survey of observed rates of carbon sequestration in temperate grassland soils.

Reference	Soil carbon sequestration (t C ha^{-1} $year^{-1}$)	Source of information	Location/grassland type
Lal (2017)	0.10 ± 0.175	Collation and synthesis of peer-reviewed publications.	Managed temperate pastures globally.
Rutledge et al. (2015)	0.61 ± 0.53	Field scale eddy covariance and carbon balance.	Intensively managed pasture grazed rotationally. New Zealand.
Schipper et al. (2014)	0.52	Top 0.3 m soil profiles.	Drystock grazing hill country, New Zealand
Chan et al. (2011)	0.499 not limed 0.552 limed	Soil sampling over 13 years.	Perennial pastures, temperate Australia
Byrne et al. (2007)	2.05 (Farm A) 2.15 (Farm B)	Farm scale carbon balance and eddy covariance.	Southern Ireland. Intensively managed ryegrass –dominated, grazed grasslands.
Soussana et al. (2007)	1.04 ± 0.73	Field scale eddy covariance.	Nine contrasted grassland sites across Europe including Ireland.
Watson et al. (2007)	1.125–1.454	Soil sampling over 10 years.	Northern Ireland. Newly established perennial ryegrass.
Khalil and Osborne, 2018)	0.53	Modelled using IPCC density change factors.	Irish permanent grasslands.

et al., 2017). Capturing the impacts of changes in management will be challenging and will require the establishment of a large number of long-term monitoring sites (Soussana et al., 2004). In addition, there is an opportunity for the introduction of new and innovative forms of management in order to maximise the sequestration potential of grasslands. In the following section we review the potential that full inversion tillage, involving a once-off inversion of soils to depths of 30 cm, associated with the re-sowing of the grassland sward, and recently introduced in New Zealand (Beare et al., 2020; Hedley et al., 2020), has for significantly increasing soil carbon sequestration rates over relatively short periods of time in Irish agricultural grasslands.

4. How does full inversion tillage (FIT) increase SOC sequestration potential?

i) Overview

Full inversion tillage is a land management practice involving a once-off inversion of agricultural soils to depths of 30 cm (Calvelo Pereira et al., 2017; Hedley et al., 2020). In some cases, deeper inversions up to 150 cm are referred to as 'deep ploughing' (Alcántara et al., 2016; Hussein et al., 2019) or 'flipping' (Schiedung et al., 2019). Irrespective of the depth of ploughing, the inversion transposes SOC-rich top-soil into the sub-soil region, and in turn SOC-deficient sub-soil becomes established as a new top-soil horizon (Schiedung et al., 2019; Paustian et al., 2016), as illustrated in Fig. 2. This process offers potential for greater carbon sequestration throughout the soil profile due to: (i) the greater carbon stabilisation capacity of the new SOC-deficient top-soil which is generally higher in silt and clay content (Wiesmeier et al., 2019), (ii) reduced mineralisation of the translocated SOC-rich top-soil in the sub-soil region (Chung et al., 2010), and (iii) greater vertical penetration of roots, which allows for increased deposition of C from roots (e.g. exudation and turnover) (Cai et al., 2014; Tefs and Gleixner, 2012; Crow et al., 2009).

Until recently, there have been remarkably few studies exploring the associations between full inversion tillage or deep ploughing and enhanced soil carbon sequestration (Chaopricha and Marin-Spiotta, 2014; Alcántara et al., 2016). However, recent studies in New Zealand on permanent pastures have provided valuable evidence that this management practice may have a potential role in future agricultural practices. Results from these studies are summarised in Table 3. Calvelo Pereira et al. (2017) found that four years after FIT of a field re-sown with ryegrass and white clover the soil carbon mass to approximately 30 cm increased on average by 3.5 t C ha^{-1} yr^{-1}. Schiedung et al. (2019) investigated the stability and stock changes of SOC in pasture grassland on highly-productive sandy loam soils over a 20 year period post full inversion soil flipping (mean depth of 140 cm). The burial of top-soil (0–30 cm) from these resulted in a one-time sequestration of 160 ± 14 t SOC ha^{-1}, while the annual top-soil sequestration rate for flipped soils averaged 9.4 t C ha^{-1} yr^{-1}. Top-soil (0–15 cm) stocks were

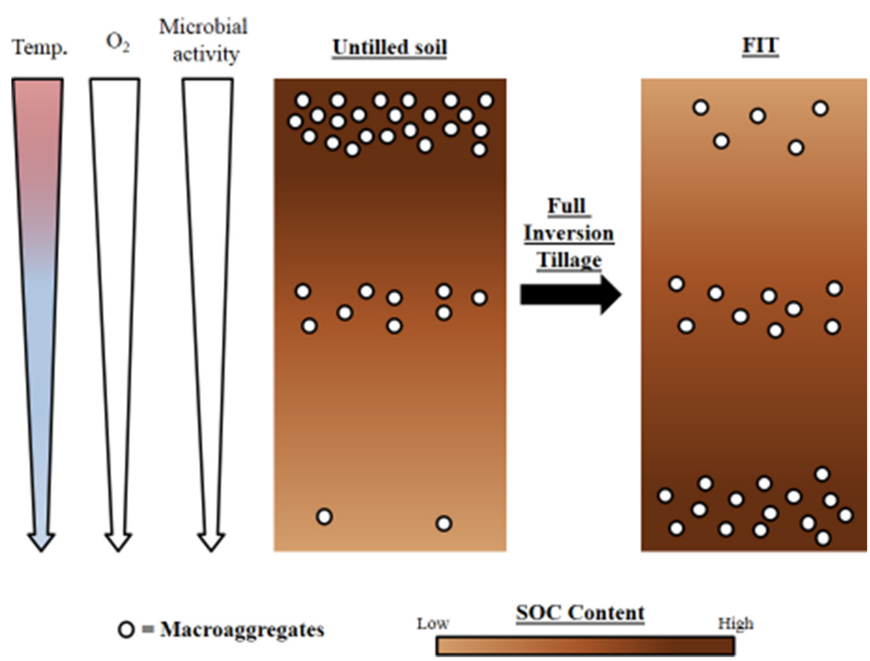


Fig. 2. Diagrammatic representation of the profile of carbon distribution in soils before and after Full Inversion Tillage (FIT).

Table 3
Literature survey of the effects of full inversion tillage (FIT) on soil carbon sequestration in the new top-soil of grasslands and croplands.

Land use (post FIT)	Location	Inversion depth (cm)	Duration (post FIT) (years)	Total C stock increase (t ha^{-1})	Increased sequestration rate (t ha^{-1} $year^{-1}$)	Reference
Pasture grassland	New Zealand west coast	170	20	179 ± 40	1.2–1.8 (0-15 cm) 3.6 (0-30 cm)	Schiedung et al. (2019)
Ryegrass/Clover on poorly drained soil	New Zealand	25	4	~ 18%	3.475	Calvelo Pereira et al. (2017)
Pasture grassland	New Zealand soils representing 80% of grassland area	30	20	Modelled change in surface 15 cm 8 -13	0.40–0.65 (0–15 cm)	Lawrence-Smith et al. (2021)
10 cropland soils	Germany	55 - 90	36–48	13	0.302	Alcantara et al. (2017)

initially higher in un-flipped soils compared to flipped soils, however no significant difference was observed 20 years post flipping. This indicates that flipped sub-soils build up SOC stock, and thus sequester atmospheric CO_2, greater than un-flipped soils, in part due to a greater effective stabilisation capacity caused by a higher carbon saturation deficit. Furthermore, deep burial of top-soils resulted in a 69% increase of the total SOC stock (0–150 cm) after 20 years, with almost 75% of the total SOC below 30 cm depth (Schiedung et al., 2019). This suggestion of buried top-soil carbon conservation is consistent with reports indicating that the breakdown of subsoil SOC is a slow process, with significant mineralisation of buried carbon taking place over a long period of time (*i.e.* centuries) (Wang et al., 2014; Gleixner, 2013).

An earlier study of arable crop land use, Alcantara et al. (2017) found that SOC stocks were 42% greater in soils deep ploughed (55–90 cm), 36-48 years prior to sampling compared to reference soils (to 100 cm depth). Deep ploughed top-soils showed a greater potential for further carbon sequestration after 45 years, as indicated by 15% less SOC in comparison to reference top-soils, while top-soil SOC mineralisation was reduced by 67% in deep ploughed soils.

A recent modelling exercise by Lawrence-Smith et al. (2021) estimated the carbon stock changes in New Zealand pasture grassland soils following a hypothetical full inversion tillage to 30 cm. In a 20 year period following FIT and pasture renewal the soil carbon was estimated to increase by between 8 (in sedimentary soils) and 13 t ha^{-1} (in Allophanic soils). This assumed that the surface 15 cm recovered to 80% of the pre-FIT stocks.

Collectively, the above studies suggest that deep burial of top-soil enhances overall SOC stocks over a prolonged period, with a capability to maintain accumulated SOC at depths in both grasslands and croplands, but that the rates of carbon accumulation are considerably higher in grassland than in cropland. In general, almost three times more SOC in the sub-soil region (below 30 cm) is associated with microaggregates and silt plus clay particles in comparison with the top-soil, thus indicating that sub-soil SOC has a greater potential for long term carbon sequestration (Torres-Sallan et al., 2017; Torres-Sallan et al., 2018; Denef et al., 2004). However, the stability of soil aggregates are also influenced by physiochemical characteristics such as soil composition and texture, and these factors must be considered when assessing the stability of SOC throughout a soil profile (Gaiser et al., 2009). Overall, FIT or deep ploughing can produce new top-soil conditions that are more conducive to developing stable complexes between SOC and soil mineral particles, and thus offer a potential for enhanced long-term carbon sequestration, particularly in grassland soils (Six and Paustian, 2014; Six et al., 2002; Alcántara et al., 2016). Therefore, based on experimental evidence, primarily from trials in New Zealand, we conclude that full inversion tillage associated with pasture renewal appears to offer a potential management strategy for a significant contribution by the Irish agricultural sector to reducing GHG emissions, although as of yet we lack experimental evidence to support this hypothesis. However, confidence in this conclusion is based on the similarities between climate and soil carbon status in Ireland and New Zealand. In both countries the largest land use is grazed pastures, consisting of productive perennial grasses and legumes. Both countries have temperate climates and although in New Zealand the mean annual temperature is warmer at 16 °C in the north, it is 10 °C on south island, while Ireland's annual mean is 9.5 °C. Mean annual rainfall for Ireland is 1230 mm while for New Zealand it is 1366 mm. In relation to soil carbon status, the New Zealand case study of Lawrence-Smith et al. (2021) 'targeted' soils for FIT during pasture renewal with pre-inversion SOC stratification ratios in the top 30 cm that were > 1.4 for sedimentary soils. This is the same mean value we obtained for the SOC stocks shown in Fig. 1 for the Irish soil survey.

ii) An estimate of grassland area in the Republic of Ireland suitable for full inversion tillage

As we have indicated, the use of FIT in grassland management to increase carbon sequestration should be accompanied by grassland renovation, which involves the sowing of grass and clover seed mixes. Currently, approximately 140,000 ha of grassland in Ireland is resown annually with a mixture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) (Humphreys and Casey, 2002; Necpalova et al., 2013). It is estimated that around half of this takes place in tillage (cropland) areas in mixed-arable-grassland enterprises. Generally such swards are sown down for at least four years and often for considerably longer. The remainder involves grass to grass resowing to renovate permanent grasslands. Re-sowing swards is an expensive operation and the justification depends on obtaining a financial benefit from more intensive production (Velthof et al., 2010). Agricultural advisors in Ireland generally recommend that the more intensive grasslands used primarily for silage are re-sown every 5 to 10 years (Teagasc, 2017).

An estimate of grassland suitable for FIT as a practice for increasing soil carbon sequestration was calculated using a range of data available on agricultural grassland distribution in the Republic of Ireland. An initial area of total grassland in Ireland was estimated using the Land Parcel Identification System (LPIS) (Zimmermann et al., 2016a). The LPIS is a support dataset which helps farmers and authorities with subsidy claims under the European Union Common Agricultural Policy. It provides annual updates with a high spatial accuracy (agricultural landuse in Ireland is reported on a field basis, where a field is defined as a land unit on a single farm under a single crop). Using the LPIS, a land use history from 2000 to 2016 was created (data from subsequent years not available) (Zimmermann et al., 2016b). Within this history suitable grassland was defined as following:

(1) Any land area never subject to tillage practice (i.e. used for cropland or horticulture).
(2) Any area that was either grassland or unreported from 2000 to 2015 (the assumption is that unreported land is fallow/setaside and therefore still suitable for FIT).
(3) Any area that has never been reported as anything other than grassland in 2016 (to avoid areas that have been set aside for non-agricultural land uses such as housing or forestry).

From an initial estimate of the total grassland area in Ireland the area not meeting the following criteria was subsequently removed:

(1) Grassland parcels which exceeded a maximum slope of 16 degrees (Lynn et al., 2009). This was considered unsuitable for FIT due to inaccessibility to farm machinery and increased risk of soil erosion. The slope was calculated from a 20 m Digital Terrain Model (produced by the Irish Environmental Protection Agency) using ArcGIS Pro (ESRI, Redlands, CA, USA).
(2) Grassland parcels on organic soils (peats and soils with organic horizons) or on shallow soils which were identified using the Teagasc Irish Forest Soils (IFS) indicative soils map (Fealy et al., 2009). Organic soils were considered unsuitable for FIT as disturbance will likely lead to increased loss of organic matter (Morris et al., 2004; Renou-Wilson et al., 2014; Renou-Wilson et al., 2015). Following the definition in the IFS map, shallow soils are all soils that overlay a subsoil class considered to be providing a shallow soil-forming environment, including eskers, gravels and rock outcrop (Fealy et al., 2009). While this does not provide a clear cut-off with regards to the depth to which a soil can be ploughed, these soils were excluded as there is a strong likelihood that such soils are too shallow to apply FIT. The resulting exclusion of soils can be considered conservative as suitable soils will likely be excluded. However, since there is no spatially explicit data on soil depth available for Ireland it was decided to exclude all shallow soils.
(3) Additionally, areas of commonage were removed. Commonages are large areas utilised by multiple farmers and therefore not suitable for FIT. Furthermore commonage is generally linked to upland areas with shallow and stony soils which are not suitable for FIT.
(4) Finally, any grassland situated in Special Areas of Conservation (SAC) and Special Protection Areas (SPA) was removed as FIT may cause conflict with wildlife conservation. Outlines for SACs and SPAs were acquired from the Irish National Parks and Wildlife Service (NPWS, 2020).

In all cases, the exclusion was carried out using ArcGIS Pro (ESRI, Redlands, CA, USA). Each grassland parcel resulting from the creation of land use histories was considered the minimum mapping unit and was not further modified as part of the exclusion, as LPIS is the highest resolution of the available datasets. Therefore, each parcel spatially coinciding with an exclusion criterion was fully removed from the final selection of suitable grasslands, rather than removing parts of grasslands that overlap with exclusion datasets.

Applying all exclusions, the remaining grassland potentially suitable for FIT is 9975.6 km^2 or 24.5% of the total estimated area of grassland in Ireland. Fig. 3 shows the distribution of areas considered to be suitable for FIT across the Republic of Ireland.

Based upon the limited amount of research that has estimated the long-term carbon sequestration resulting from FIT during pasture renewal and presented in Table 3, we suggest that the sequestration rates expected in Ireland would be in the range of 1-2 t C ha^{-1} yr^{-1} and similar to those recently modelled in New Zealand (Lawrence-Smith et al., 2021) The sequestration rates reported by Calvelo Pereira et al. (2017) and Schiedung et al. (2019) are higher but they are obtained from locations with particularly high levels of rainfall and are on deep, sandy soils. These are conditions which would appear to maximise carbon sequestration rates (Schiedung et al., 2019). We also suggest that FIT could have a net beneficial effect of enhancing SOC stock levels in soils over a prolonged period (> 20 years). The application of FIT across suitable Irish grasslands (9976 km^2) therefore offers a sequestration potential averaging 1-2 $\times$ 10^5 t C yr^{-1} which is equivalent to 2.1 - 4.2% of the current GHGs emitted by Irish agriculture each year (Khalil and Osborne, 2018).

As previously indicated, numerous factors affect the long-term capability of a soil to sequester carbon (Lal, 2013; IPCC, 2019). Therefore, it is difficult to estimate with a high degree of confidence the possible sequestration potential of FIT during pasture renewal in Irish grasslands based upon data from other countries and land uses post-FIT. However, the Irish climate is conducive to the accumulation of SOC levels (Byrne et al., 2007; Soussana et al., 2007), and coupled with a carbon-deficient 'new' topsoil resulting from FIT, there is a strong potential for long-term accumulation of carbon in Irish grassland soils (Creamer and O' Sullivan, 2018).

5. Conclusions and research directions

The Irish Climate Change Advisory Council (CCAC, 2019) has identified a need for additional research covering both new and existing mitigation measures for agriculture which will evaluate the development and refinement of national inventory accounting in terms of emission factors and activity data collection. Because of the significance of grasslands for agricultural land, accounting for ~61% of land cover and 53% of terrestrial carbon stocks in Ireland (Haughey, 2021), all management strategies to increase these stocks and sequester carbon need to be maximised. In support of these recommendations, this review has highlighted the need for further experimental evidence not only to assess potential soil C stock development during pasture renewal, post FIT, in Ireland but to do this while recognising the importance of maximising the contribution of a number of other management practices illustrated in Table 1. We therefore recommend conducting short- to medium-term trials (e.g. 10 years) on representative grassland sites on a range of soils throughout Ireland. In relation to the use of FIT during pasture renewal there will be a need to monitor the establishment of soil aggregate formations throughout the soil profile in order to assess how FIT alters the stability of fractions in Irish grassland soils. Multi-year trials assessing above- and below-ground dry matter production as well as measuring changes in various soil parameters including structure, pH, and levels of N, P and K will provide valuable information regarding optimum pasture management strategies post FIT (e.g. Beare et al., 2020; Calvelo Pereira et al., 2020). This includes assessing appropriate fertiliser application to ensure nutrient availability alongside carbon stock accumulation. In turn, further investigations are required to assess the financial costs to farmers to replenish the nutrient-poor 'new' topsoil by additional fertiliser inputs.

The response of a soil to the alteration of pH is complex and may result in potentially beneficial or destructive effects on the development of soil aggregates. Therefore, it is also important to explore the climatic and soil physiochemical conditions most conducive to the advantageous application of liming in association with FIT. There are currently numerous potential methods for assessing soil fractions (Poeplau et al., 2018), making it difficult to directly compare data across various studies. A robust, reproducible and cost-effective standardised soil fractionation analysis would allow for greater knowledge acquisition across the scientific community and in turn a more comprehensive understanding of the dynamics involved in SOC development post FIT.

For FIT to be considered a feasible future management practice in agriculture, it is essential that the environmental benefits from reducing atmospheric CO_2 levels are not counteracted by increases in emissions of other GHG's, particularly N_2O, as well as any increased risk of nitrate leaching (Velthof et al., 2010). Therefore, it is important to assess if deep soil disturbance either directly (physically) or indirectly (altered soil microbial activity) affects the release of N_2O and nitrates. Further research is required to evaluate the effects of FIT on soil microbial community structures as well as the primary productivity and C sequestration functions they help to deliver. As soil microbes are central for healthy plant production and nutrient supply, understanding soil microbial responses to deep ploughing, especially in the 'new' topsoil, is critical in determining the potential of FIT as part of an atmospheric CO_2 mitigation management strategy for Ireland.

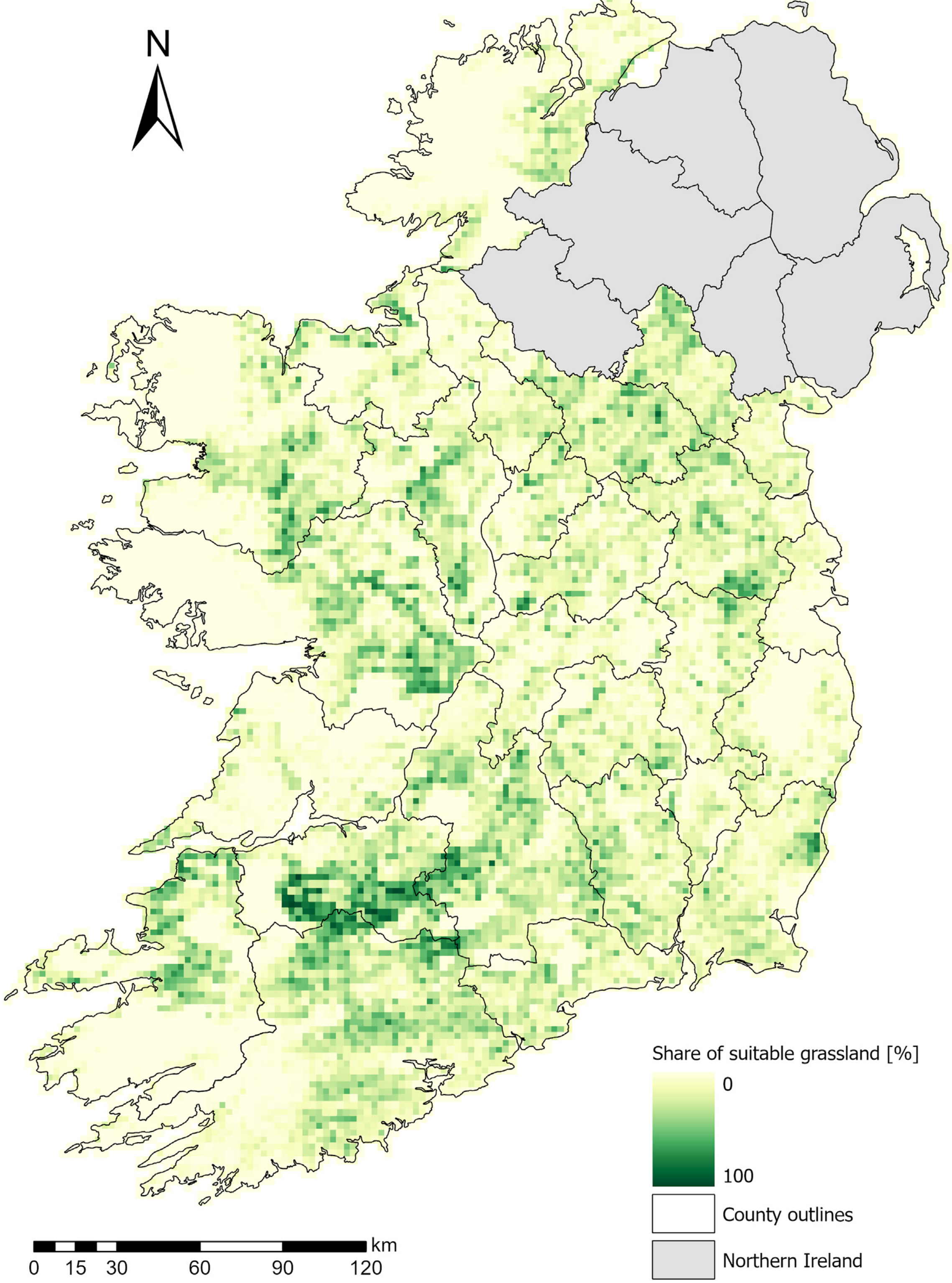


Fig. 3. Map of areas assessed to be most suitable for FIT across the Republic of Ireland

Although we suggest that, based on our current knowledge of soil carbon in Irish grasslands, the adoption of full inversion tillage during pasture renewal could make a significant contribution to increasing carbon sequestration in grasslands, further research is needed to verify the amount of sequestration that could be achieved over the next two or three decades. This is particularly important for Irish agriculture as there is a need to maximise any offsets to the very high current levels of GHG emissions from this sector. Furthermore, we need to verify that these benefits are achieved without environmental costs and that there are no significant barriers to its adoption.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the New Zealand Government to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases and the New Zealand Agricultural Greenhouse Gas Research Centre.

References

Aksoy, E., Yigini, Y., Montanarella, L., 2016. Combining soil databases for topsoil organic carbon mapping in Europe. PLoS ONE 11 (3), e0152098. https://doi.org/10.1371/journal.pone.0152098.

Alcantara, V., Don, A., Vesterdal, L., Well, R., Nieder, R., 2017. Stability of buried carbon in deep-ploughed forest and cropland soils - implications for carbon stocks. Sci. Rep. 7, 5511. https://doi.org/10.1038/s41598-017-05501-y.

Alcántara, V., Don, A., Well, R., Nieder, R., 2016. Deep ploughing increases agricultural soil organic matter stocks. Glob. Chang. Biol. 22 (8), 2939–2956. https://doi.org/10.1111/gcb.13289.

Mitigation of the greenhouse effect. In: Arrouays, D., Balesdent, J., Germon, J.C., Jayet, P.A., Soussana, J.-F., Stengel, P. (Eds.), Increasing Carbon Stocks in French Agricultural Soils? An Assessment Report Compiled by the French Institute for Agricultural Research (INRA) on the Request of the French Ministry for Ecology and Sustainable Development 32 pp.

Azevedo, S.G., Sequeira, T., Santos, M., Nikuma, D., 2020. Climate change and sustainable development: the case of Amazonia and policy implications. Environ. Sci. Pollut. Res. 27 (8), 7745–7756. https://doi.org/10.1007/s11356-020-07725-4.

Bailey, V.L., Pries, C.H., Lajtha, K., 2019. What do we know about soil carbon destabilization? Environ. Res. Lett. 14 (8), 083004. https://doi.org/10.1088/1748-9326/ab2c11.

Baldock, J.A., Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Org. Geochem. 31 (7–8), 697–710. https://doi.org/10.1016/S0146-6380(00)00049-8.

Baveye, P.C., Berthelin, J., Tessier, D., Lemaire, G., 2018. The "4 per 1000" initiative: a credibility issue for the soil science community? Geoderma 309, 118–123.

Beare, M.H., SR, McNally, Calvelo Pereira, R., Tregurtha, C.S., Gillespie, R.N., Van der Klei, G.R., Hedley, M.J., 2020. The agronomic and Environmental benefits and risks of autumn pasture renewal with full inversion tillage. In: Christensen, C.L., Horne, D.J., Singh, R. (Eds.), Nutrient Management in Farmed Landscapes. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand 7 pages http://flrc.massey.ac.nz/publications.html.

Beare, M.H., McNeill, S.J., Curtin, D., et al., 2014. Estimating the organic carbon stabilisation capacity and saturation deficit of soils: a New Zealand case study. Biogeochemistry 120 (1–3), 71–87. https://doi.org/10.1007/s10533-014-9982-1.

Brady, N., Weil, R., 2002. The Nature and Properties of Soils. 13th ed. Prentice Hall, Upper Saddle River, NJ.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124 (1–2), 3–22. https://doi.org/10.1016/j.geoderma.2004.03.005.

Byrne, K.A., Kiely, G., Leahy, P., 2007. Carbon sequestration determined using farm scale carbon balance and eddy covariance. Agric. Ecosys. Environ. 121 (4), 357–364. https://doi.org/10.1016/j.agee.2006.11.015.

Cai, H., Ma, W., Zhang, X., et al., 2014. Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. Crop J. 2 (5), 297–307. https://doi.org/10.1016/j.cj.2014.04.006.

Calvelo Pereira, R., Hedley, M.J., Camps Abertain, M., Bishop, P., Enongene, K.E., Otene, I.J.J., 2017. Evidence for soil carbon enhancement through deeper mouldboard ploughing at pasture renovation on a typic fragiaqualf. Soil Res. 56, 182–191. https://doi.org/10.1071/SR17039.

Calvelo Pereira, R., Hedley, M.J., Hanly, J., Osborne, M., SR, McNally, Beare, M.H., 2020. The agronomic and environmental benefits and risks of spring pasture renewal with full inversion tillage. In: Christensen, C.L., Horne, D.J., Singh, R. (Eds.), Nutrient Management in Farmed Landscapes. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand 9 pages http://flrc.massey.ac.nz/publications.html.

Carolan, R., Fornara, D.A., 2016. Soil carbon cycling and storage along a chronosequence of re-seeded grasslands: do soil carbon stocks increase with grassland age? Agric. Ecosyst. Environ. 218, 126–132.

CCAC, 2019. Annual review 2019. Available online:CCAC, Dublin. https://tinyurl.com/CCAC-IE-Review-2019.

Chan, K.Y., Conyers, M.K., Li, G.D., et al., 2011. Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments. Soil Res. 49 (4), 320–328. https://doi.org/10.1071/SR10185.

Chaopricha, N.T., Marin-Spiotta, E., 2014. Soil burial contributes to deep soil organic carbon storage. Soil Biol. Biochem. 69, 251–264.

Chenu, C., Angers, D.A., Barré, P., Dervien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil Till. Res. 188, 41–52. https://doi.org/10.1016/j.still.2018.04.011.

Chung, H., Ngo, K.J., Plante, A., Six, J., 2010. Evidence for carbon saturation in a highly structured and organic-matter-rich soil. Soil Sci. Soc. Am. J. 74 (1), 130–138. https://doi.org/10.2136/sssaj2009.0097.

Creamer, R., O' Sullivan, L., 2018. The Soils of Ireland. Springer, Yew York, NY, USA.

Creamer, R., Simo, I., Reidy, B., Carvalho, J., Fealy, R.M., Hallett, S., Jones, R., Holden, A., Holden, N., Hannam, J., Massey, P., Mayr, T., McDonald, E., O'Rourke, S., Sills, P., Truckell, I., Zawadzka, J., Schulte, R., 2014. Irish Soil Information System. Synthesis Report (2007-S-CD-1-SQ). Report 130. Environmental Protection Agency, Wexford. Ireland.

Crow, S.E., Lajtha, K., Filley, T.R., Swanston, C.W., Bowden, R.D., Caldwell, B.A., 2009. Sources of plant-derived carbon and stability of organic matter in soil: implications for global change. Glob. Chang. Biol. 15 (8), 2003–2019. https://doi.org/10.1111/j.1365-2486.2009.01850.x.

DAFM, 2015. Information on the LULUCF Actions to Limit or Reduce Emissions and Maintain or Increase Removals From Activities Defined Under Decision 529/2013/EU. Department of Agriculture, Food and the Marine, Dublin.

Denef, K., Six, J., Merckx, R., Paustian, K., 2004. Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Sci. Soc. Am. J. 68 (6), 1935–1944. https://doi.org/10.2136/sssaj2004.1935.

Don, A., Rödenbeck, C., Gleixner, G., 2013. Unexpected control of soil carbon turnover by soil carbon concentration. Environ. Chem. Lett. 11 (4), 407–413. https://doi.org/10.1007/s10311-013-0433-3.

Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob. Chang. Biol. 18 (6), 1781–1796. https://doi.org/10.1111/j.1365-2486.2012.02665.x.

EASAC, 2018. Negative emission technologies: what role in meeting Paris agreement targets? Policy report 35. Retrieved from www.easac.eu.

Fatichi, S., Pappas, C., Zscheischler, J., Leuzinger, S., 2019. Modelling carbon sources and sinks in terrestrial vegetation. New Phytol. 221 (2), 652–668. https://doi.org/10.1111/nph.15451.

Fealy, R.M., Green, S., Loftus, M., et al., 2009. Teagasc EPA Soil and Subsoils Mapping Project-final Report. vol. I. Teagasc, Dublin.

Flessa, H., Amelung, W., Helfrich, M., et al., 2008. Storage and stability of organic matter and fossil carbon in a Luvisol and Phaeozem with continuous maize cropping: a synthesis. J. Plant Nutr. Soil Sci. 171 (1), 36–51. https://doi.org/10.1002/jpln.200700050.

Fornara, D.A., Steinbeiss, S., Mcnamara, N.P., et al., 2011. Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland. J. Ecol. 17 (5), 1925–1934. https://doi.org/10.1111/j.1365-2486.2010.02328.x.

Fornara, D.A., Tilman, D., 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. J. Ecol. 96 (2), 314–322. https://doi.org/10.1111/j.1365-2745.2007.01345.x.

Franzluebbers, A.J., 2018. Short-term C mineralization (aka the flush of CO2) as an indicator of soil biological health. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 13, 017. https://doi.org/10.1079/PAVSNNR201813017.

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23.

Gaiser, T., Abdel-Razek, M., Bakara, H., 2009. Modeling carbon sequestration under zero-tillage at the regional scale. II. The influence of crop rotation and soil type. Ecol. Model. 220 (23), 3372–3379. https://doi.org/10.1016/j.ecolmodel.2009.08.001.

Ghafoor, A., Poeplau, C., Katterer, T., 2017. Fate of straw- and root-derived carbon in a Swedish agricultural soil. Biol. Fertil. Soils 53 (2), 257–267. https://doi.org/10.1007/s00374-016-1168-7.

Gleixner, G., 2013. Soil organic matter dynamics: a biological perspective derived from the use of compound-specific isotopes studies. Ecol. Res. 28 (5), 683–695. https://doi.org/10.1007/s11284-012-1022-9.

Hamilton, S.K., Kurzman, A.L., Arango, C., Jin, L., Robertson, G.P., 2007. Evidence for carbon sequestration by agricultural liming. Glob. Biogeochem. Cycles 21 (2), GB2021. https://doi.org/10.1029/2006GB002738.

Haughey, E., 2021. Climate Change and Land Use in Ireland. EPA Research Report N0. 371. Environmental Protection Agency, Johnstown Castle, Wexford, Ireland.

Hedley, M.J., Beare, M.H., Calvelo Pereira, C., McNally, S.R., Lawrance-Smith, E.J., Tregurtha, C.S., Osborne, M.A., Gillespie, R.N., Van der Klei, G., Thomas, S.M., 2020. Where, when and how – practise guidelines for successful introduction of full inversion tillage to increase soil carbon stocks under pasture. In: Christensen, C.L., Horne, D.J., Singh, R. (Eds.), Nutrient Management in Farmed Landscapes. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand 9 pages http://flrc.massey.ac.nz/publications.html.

Hegerl, G.C., Brönnimann, S., Cowan, T., et al., 2019. Causes of climate change over the historical record. Environ. Res. Lett. 14 (12), 0123006. https://doi.org/10.1088/1748-9326/ab4557.

Humphreys, J., Casey, I.A., 2002. Grassland renovation in Ireland. In: Conijn, J.G., Velthof, G.L., Taube, F. (Eds.), Grassland Resowing and Grass-arable Crop Rotations. Report 47. Plant Research International BV, Wageningen, The Netherlands.

Hussein, M.A., Muche, H., Schmitter, P., et al., 2019. Deep tillage improves degraded soils in the (sub) humid ethiopian highlands. Land 8 (11), 15. https://doi.org/10.3390/land8110159.

IPCC, 2019. In press In: Shukla, P.R., Skea, J., Buendia, E. Calvo, Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J. Portugal, Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems . http:/www.ipcc.ch/reports/sr2/.

Jastrow, J.D., Amonette, J.E., Bailey, V.L., 2007. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. Clim. Chang. 80 (1–2), 5–23. https://doi.org/10.1007/s10584-006-9178-3.
Jokubauskaite, I., Karcauskiene, D., Slepetiene, A., Repsiene, R., Amaleviciute, K., 2016. Effect of different fertilization modes on soil organic carbon sequestration in acid soils. Acta Agric. Scand. B Soil Plant Sci. 66 (8), 647–652. https://doi.org/10.1080/09064710.2016.1181200.
Jones, M.B., Donnelly, A., 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO2. New Phytol. 164, 423–439. https://doi.org/10.1111/j.1469-8137.2004.01201.x.
Jones, S.K., Rees, R.M., Kosman, D., Ball, B.C., Skiba, U.M., 2006. Carbon sequestration in a temperate grassland; management and climate controls. Soil Use Manag. 22, 132–142. https://doi.org/10.1111/j.1475-2743.2006.00036.x.
Keane, T., Collins, J.F., (Eds.), 2004. Climate, weather and irish agriculture. (2nd, Edition). AGMET Group, Met Eireann, Ireland.
Khalil, M.I., Kiely, G., O'Brien, P., Mueller, C., 2013. Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches. Geoderma 193, 222–235. https://doi.org/10.1016/j.geoderma.2012.10.005.
Khalil, M.I., Osborne, B.A., 2018. Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland. Geoderma 322, 172–183. https://doi.org/10.1016/j.geoderma.2018.02.038.
Kiely, G., Leahy, P., Lewis, C., Xu, X., Sottocornola, M., 2017. SoilC - Feasability of Grassland Soil Carbon Survey. EPA, Wexford, Ireland 978-1-84095-737-2.
Koncz, P., Pintér, K., Balogh, J., et al., 2017. Extensive grazing in contrast to mowing is climate-friendly based on the farm-scale greenhouse gas balance. Agric. Ecosyst. Environ. 240, 121–134. https://doi.org/10.1016/j.agee.2017.02.022.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677), 1623–1627. https://doi.org/10.1126/science.1097396.
Lal, R., 2013. Soil carbon management and climate change. Carbon Manag. 4 (4), 439–462. https://doi.org/10.4155/cmt.13.31.
Lal, R., 2017. Digging deeper: a holistic perspective of factors affecting soil organic carbon sequestrationin agroecosystems. Glob. Chang. Biol. 24, 3285–3301. https://doi.org/10.1111/gcb.14054.
Lawrence-Smith, E.J., Curtin, D., Beare, M.H., McNally, S.R., Kelliher, F.M., Calvelo Pereira, R., Hedley, M.J., 2021. Full inversion tillage during pasture renwal to increase soil carbon storage: New Zealand as a case study. Glob. Chang. Biol. 27, 1998–2010.
Leisner, C.P., 2020. Review: climate change impacts on food security- focus on perennial cropping systems and nutritional value. Plant Sci. 293, 110412. https://doi.org/10.1016/j.plantsci.2020.110412.
Li, Q., Zhou, D., Denton, M.D., Cong, S., 2019. Alfalfa monocultures promote soil organic carbon accumulation to a greater extent than perennial grass monocultures or grass-alfalfa mixtures. Ecol. Eng. 131, 53–62. https://doi.org/10.1016/j.ecoleng.2019.03.002.
Linsler, D., Geisseler, D., Loges, R., Taube, F., Ludwig, B., 2013. Temporal dynamics of soil organic matter composition and aggregate distribution in permanent grassland after a single tillage event in a temperate climate. Soil Tillage Res. 126, 90–99. https://doi.org/10.1016/j.still.2012.07.017.
Lynn, I.H., Manderson, A.K., Page, M., et al., 2009. Land Use Survey Handbook - A New Zealand Handbook for the Classification of Land. 3rd ed. AgResearch: Lincoln, Landcare Research; Lower Hutt, GNS Science, Hamilton 163p.
Martin, M.P., Dimassi, B., Roman Dobarco, M., Guenet, B., Arrouays, D., et al., 2021. Feasability of the 4 per 1000 aspirational target for soil carbon: a case study for France. Glob. Chang. Biol. 27, 2458–2477.
Minasny, B., Malone, B.P., McBratney, A.B., et al., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.
Minasny, B., Arrouays, D., McBratney, A.B., et al., 2018. Letter to editor. Rejoiner to comments on Minasny et al., 2017, soil carbon 4 per mille. Geoderma, 292, 59–86. Geoderma 309, 124–129.
Miyazawa, M., Takahashi, T., Sato, T., Kanno, H., Nanzyo, M., 2013. Factors controlling accumulation and decomposition of organic carbon in humus horizons of andosols: a case study for distinctive non-allophanic andosols in northeastern Japan. Biol. Fertil. Soils 49 (7), 929–938. https://doi.org/10.1007/s00374-013-0792-8.
Morris, D.R., Gilbert, R.A., Reicosky, D.C., Gesch, R.W., 2004. Oxidation potentials of soil organic matter in histosols under different tillage methods. Soil Sci. Soc. Am. J. 68 (3), 817–826. https://doi.org/10.2136/sssaj2004.8170.
Necpalova, M., Caset, I., Humphreys, J., 2013. Effects of ploughing and reseeding of permanent grassland on soil N, N leaching and nitrous oxide emissions from a clay-loam soil. Nutr. Cycl. Agroecosyst. 95, 305–317.
Assoc, N.Z.GNobilly, F., Bryant, R.H., Mckenzie, B.A., Edwards, G.R., 2013. Productivity of rotationally grazed simple and diverse pasture mixtures under irrigation in Canterbury. Proceedings of the New Zealand Grassland Association, 2013, pp. 165–171 (Proceedings of the New Zealand Grassland Association; vol. 75.).
NPWS, 2020. National Parks and Wildlife Service Boundary Datasets. https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data. (Accessed July 2020).
Pan, G., Smith, P., Pan, W., 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. Agric. Ecosyst. Environ. 129 (1–3), 344–348. https://doi.org/10.1016/j.agee.2008.10.008.
Paradelo, R., Virto, I., Chenu, C., 2015. Net effect of liming on soil organic carbon stocks: a review. Agric. Ecosyst. Environ. 202, 98–107. https://doi.org/10.1016/j.agee.2015.01.005.
Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57. https://doi.org/10.1038/nature17174.
Poeplau, C., Don, A., Six, J., et al., 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils - a comprehensive method comparison. Soil Biol. Biochem. 125, 10–26. https://doi.org/10.1016/j.soilbio.2018.06.025.
Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Chang. Biol. 6, 317–327.
Poulton, P., Johnston, J., Macdonald, A., White, R., 2017. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob. Chang. Biol. 24, 2563–2584.
Pugh, T.A.M., Mueller, C., Arneth, A., Haverd, V., Smith, B., 2016. Key knowledge and data gaps in modelling the influence of CO2 concentration on the terrestrial carbon sink. J. Plant Physiol. 203, 3–15. https://doi.org/10.1016/j.jplph.2016.05.001.
Renou-Wilson, F., Barry, C., Müller, C., Wilson, D., 2014. The impacts of drainage, nutrient status and management practice on the full carbon balance of grasslands on organic soils in a maritime temperate zone. Biogeosciences 11 (16), 4361–4379. https://doi.org/10.5194/bg-11-4361-2014.
Renou-Wilson, F., Wilson, D., Barry, C., Foy, B., Müller, C., 2015. Carbon Loss From Drained Organic Soils Under Grassland - CALISTO. EPA Research Report No 141. Environmental Protection Agency, Wexford, Ireland.
Rogelj, J., Geden, O., Cowie, A., Reisinger, A., 2021. Three ways to improve net-zero emission targets. Nature 591, 365–368.
Rutledge, S., Mudge, P.L., Campbell, D.I., Woodward, S.L., Goodrich, J.P., Wall, A.M., Kirschbaum, M.U.F., Schipper, L.A., 2015. Carbon balance of an intensively grazed temperate diry pasture over four years. Agric. Ecosyst. Environ. 206, 10–20.
Rutledge, S., Wall, A.M., Mudge, P.L., Troughton, B., Campbell, D.I., Pronger, J., Joshi, C., Schipper, L.A., 2017. The carbon balance of temperate grasslands part II: the impact of pasture renewal via direct drilling. Agric. Ecosyst. Environ. https://doi.org/10.1016/j.agee.2017.01.013 239-142.
Schiedung, M., Tregurtha, C.S., Beare, M.H., Thomas, S.M., Don, A., 2019. Deep soil flipping increases carbon stocks of New Zealand grasslands. Glob. Chang. Biol. 25 (7), 2296–2309. https://doi.org/10.1111/gcb.14588.
Schipper, L.A., Parfitt, R.L., Fraser, S., Littler, R.A., Baisden, W.T., Ross, C., 2014. Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. Agric. Ecosyst. Environ. 184, 67–75. https://doi.org/10.1016/j.agee.2013.11.012.
Schlesinger, W.H., 2000. Carbon sequestration in soils: some caution amidst optimism. Agric. Ecosyst. Environ. 82, 121–127. https://doi.org/10.1016/S0167-8809(00)00221-8.
Schlesinger, W.H., Amundson, R., 2019. Managing for soil carbon sequestration: let's get realistic. Glob. Chang. Biol. 25 (2), 386–389. https://doi.org/10.1111/gcb.14478.
Shehzadi, S., Shah, Z., Mohammad, W., 2017. Impact of organic amendments on soil carbon sequestration, water use efficiency and yield of irrigated wheat. Biotechnol. Agron. Soc. Environ. 21 (1), 36–49. https://doi.org/10.25518/1780-4507.13435.
Simo, I., Schulte, R., O'Sullivan, L., Creamer, R., 2019. Digging deeper: understanding the contribution of subsoil carbon for climate mitigation, a case study of Ireland. Environ. Sci. Policy 98, 61–69. https://doi.org/10.1016/j.envsci.2019.05.004.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002a. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil Sc. 241 (2), 155–176. https://doi.org/10.1023/A:1016125726789.
Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32 (14), 2099–2103. https://doi.org/10.1016/s0038-0717(00)00179-6.
Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62 (5), 1367–1377. https://doi.org/10.2136/sssaj1998.03615995006200050032x.
Six, J., Feller, C., Denef, K., Ogle, S.M., De Moraes, S.J.C., Albrecht, A., 2002b. Soil organic matter, biota and aggregation in temperate and tropical soils - effects of no-tillage. Agronomie 22 (7–8), 755–775. https://doi.org/10.1051/agro:2002043.
Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 68, A4–A9. https://doi.org/10.1016/j.soilbio.2013.06.014.
Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agric. Syst. 98 (3), 208–219. https://doi.org/10.1016/j.agsy.2008.07.004.
Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Glob. Chang. Biol. 22 (3), 1315–1324. https://doi.org/10.1111/gcb.13178.
Smith, P., Rowlson, D., Glendining, M., Smith, J.O., 1997. Potential for carbon sequestration in european soils: preliminary estimates for five scenarios using results from long-term experiments. Glob. Chang. Biol. 3 (1), 67–79. https://doi.org/10.1046/j.1365-2486.1997.00055.x.
Soussana, J.-F., Allard, V., Pilegaard, K., et al., 2007. Full accounting of the greenhouse gas (CO2, N2O, CH4) budget of nine European grassland sites. Agric. Ecosyst. Environ. 121 (1), 121–134. https://doi.org/10.1016/j.agee.2006.12.022.
Soussana, J.-F., Loiseau, P., Vuichard, N., et al., 2004. Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Manag. 20, 219–230. https://doi.org/10.1079/SUM2003234.
Soussana, J.-F., Lutfalla, S., Ehrhardt, F., rosenstock Lamanna, T., et al., 2019. Matching policy and science: rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil and Tillage Research 188, 3–15.
Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86 (1), 19–31. https://doi.org/10.1007/s10533-007-9140-0.
Strassmann, K.M., Joos, F., Fischer, G., 2008. Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric CO2 increases and future commitments due to losses of terrestrial sink capacity. Tellus Ser. B Chem. Phys. Meteorol. 60 (4), 583–603. https://doi.org/10.1111/j.1600-0889.2008.00340.x.
Sykes, A.J., Macleod, M., Eory, V., et al., 2020. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Glob. Chang. Biol. 26 (3), 1085–1108. https://doi.org/10.1111/gcb.14844.

Tefs, C., Gleixner, G., 2012. Importance of root derived carbon for soil organic matter storage in a temperate old-growth beech forest - evidence from C, N and 14C content. For. Ecol. Manag. 263, 131–137. https://doi.org/10.1016/j.foreco.2011.09.010.

Teagasc, 2017. Pocket Manual for Reseeding. Series 33. Moorepark Animal and Grassland Research and Innovation Centre. Teagasc, Fermoy, Co. Cork, Ireland 35 p.

Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral control of soil organic carbon storage and turnover. Nature 389 (6647), 170–173. https://doi.org/10.1038/38260.

Torres-Sallan, G., Creamer, R.E., Lanigan, G.J., Reidy, B., Byrne, K.A., 2018. Effects of soil type and depth on carbon distribution within soil macroaggregates from temperate grassland systems. Geoderma 313, 52–56. https://doi.org/10.1016/j.geoderma.2017.10.012.

Torres-Sallan, G., Schulte, R.P.O., Lanigan, G.J., et al., 2017. Clay illuviation provides a longterm sink for C sequestration in subsoils. Sci. Rep. 7, 45635. https://doi.org/10.1038/srep45635.

Tu, C., He, T., Lu, X., Luo, Y., Smith, P., 2018. Extent to which pH and topographic factors control soil organic carbon level in dry farming cropland soils of the mountainous region of Southwest China. Catena 163, 204–209. https://doi.org/10.1016/j.catena.2017.12.028.

UNFCCC, 2015. Adoption of the Paris agreement. FCCC/CP/2015/L.9/Rev. 1.

Velthof, G.L., Hoving, I.E., Dolfing, J., Smit, A., Kuikman, P.J., Oenema, O., 2010. Method and timing of grassland renovation affects herbage yield, nitrate leaching, and nitrous oxide emissions in intensively managed grasslands. Nutr. Cycl. Agroecosyst. 86, 401–412.

Vleeshouwers, L.M., Verhagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Glob. Chang. Biol. 8 (6), 519–530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

Von Lützow, M.V., Kögel-Knabner, I., Ekschmitt, K., et al., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. Eur. J. Soil Sci. 57 (4), 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x.

Wang, J., Chen, Y., Tett, S.F.B., et al., 2020. Anthropogenically-driven increases in the risks of summertime compound hot extremes. Nat. Commun. 11 (1), 528. https://doi.org/10.1038/s41467-019-14233-8.

Wang, Y., Wang, Z.L., Zhang, Q., et al., 2018. Long-term effects of nitrogen fertilization on aggregation and localization of carbon, nitrogen and microbial activities in soil. Sci. Total Environ. 624, 1131–1139. https://doi.org/10.1016/j.scitotenv.2017.12.113.

Wang, Z., Van Oost, K., Lang, A., et al., 2014. The fate of buried organic carbon in colluvial soils: a long-term perspective. Biogeosciences 11 (3), 873–883. https://doi.org/10.5194/bg-11-873-2014.

Watson, C.J., Jordan, C., Kilpatrick, D., McCarney, B., Stewart, R., 2007. Impact of grazed grassland management on total N accumulation in soil receiving different levels of N inputs. Soil Use Manag. 23 (2), 121–128. https://doi.org/10.1111/j.1475-2743.2006.00081.x.

West, T.O., Marland, G., King, A.W., Post, W.M., Jain, A.K., Andrasko, K., 2004. Carbon management response curves: estimates of temporal soil carbon dynamics. Environ. Manag. 33, 507–518. https://doi.org/10.1007/s00267-003-9108-3.

Whitehead, D., Schipper, L.A., Pronger, J., et al., 2018. Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. Agric. Ecosyst. Environ. 265, 432–443. https://doi.org/10.1016/j.agee.2018.06.022.

Wiesmeier, M., Urbanski, L., Hobley, E., et al., 2019. Soil organic carbon storage as a key function of soils - a review of drivers and indicators at various scales. Geoderma 333, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026.

Zimmermann, J., Fealy, R.M., Lydon, K., et al., 2016a. The Irish Land-Parcels Identification System (LPIS) - experiences in ongoing and recent environmental research and land cover mapping. Biol. Environ.: Proc. R. Ir. Acad. 116B (1), 53–62. https://doi.org/10.3318/bioe.2016.04.

Zimmermann, J., González, A., Jones, M.B., O'Brien, P., Stout, J.C., Green, S., 2016b. Assessing land-use history for reporting on cropland dynamics—a comparison between the land-parcel identification system and traditional inter-annual approaches. Land Use Policy 52, 30–40. https://doi.org/10.1016/j.landusepol.2015.11.027.