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Potential applications of full inversion tillage to increase soil carbon storage during pasture renewal in New Zealand

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December 2015















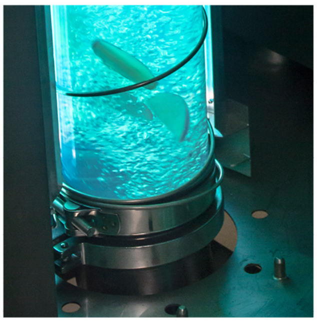


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EXECUTIVE SUMMARY

Potential applications of full inversion tillage to increase soil carbon storage during pasture renewal in New Zealand

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This report reviews the potential to use full inversion tillage (FIT) during pasture renewal to increase the soil organic carbon (SOC) stocks of New Zealand's High Producing Grasslands.

Key findings:

- There is no direct experimental evidence of the effects of FIT on soil C stocks during pasture renewal in New Zealand (or elsewhere). This warrants further investigation.
- We have arrived at the following conclusions based on indirect evidence that includes a critical analysis of published research, modelled projections from available data and professional knowledge and experience.
- Soil inversion during pasture renewal represents a significant opportunity to sequester soil C to offset New Zealand's greenhouse emissions.
- We estimate that an additional 3 megatonnes (Mt) (1 Mt = 10^6 t) of C could be stored over a 30 year period in high producing grassland (HPG) soils following a 'one-off' pasture renewal with FIT (i.e. mouldboard ploughing to 30 cm). The estimate assumes 10% farmer adoption (i.e. 367,000 ha, or 6% of New Zealand HPG) and 10% annual pasture renewal.
- This increase in stored soil C is significant in relation to New Zealand's agricultural greenhouse gas (methane and nitrous oxide) emissions which have increased by the equivalent of 1.1 Mt CO_2-C per annum (relative to 1990).
- Further research is needed to verify the potential soil C gains and evaluate any possible adverse impacts or complimentary benefits from applying this practice in farm systems.

This report includes:

- An overview of literature on soil C storage and stabilisation
- Current and recommended rates of pasture renewal and the projected farm gate value
- A review of literature on the effects of tillage and pasture renewal on changes in SOC
- The land area that is estimated to be suitable for pasture renewal by FIT
- A framework for modelling the effects of FIT on soil C stocks following pasture renewal
- Modelled estimates of soil C stock changes on a per hectare basis for different soil Orders
- National estimates of soil C sequestration under different scenarios of C accumulation efficiencies, farmer adoption and pasture renewal rates
- A discussion of the practical implications for management of pastures renewed by FIT
- Recommendations for future work to confirm the impacts and evaluate associated benefits and limitations.

Research summary:

- Soil C is concentrated near the surface of pastoral soils and decreases rapidly with depth.
- Subsurface soil (e.g., 15–30 cm depth) typically has a greater soil C saturation deficit than topsoil because plant C inputs (roots and root exudates) are lower.
- Implementing management practices that expose under-saturated soil to higher C inputs could result in increased soil C storage and stabilisation.
- Full inversion tillage (FIT) could increase soil C storage via two potential pathways:
  - burial of C-enriched topsoil in closer proximity to under-saturated subsoil is expected to increase storage and stabilisation of C through formation of organo-mineral complexes. Stabilisation of C may be promoted by a slower rate of buried-C decomposition due to cooler temperatures and more anoxic conditions,
  - growing high-producing pasture on inverted low-C subsoil is expected to increase storage and stabilisation of C from root turnover and animal excreta (dung)
- There is a lack of experimental data to directly address the effect of FIT on soil C stocks in pastoral soils of New Zealand.
- We present a model for predicting changes in soil C stocks following FIT to 30 cm. The model accounts for the decomposition of SOC in buried topsoil and the accumulation of C in the new topsoil (inverted subsoil).
- The model was used to provide national estimates of soil C sequestration under different scenarios of C accumulation efficiency, farmer adoption of FIT and annual pasture renewal rates.
- While the calculations are exploratory, we estimate that 5.1 Mt C could be sequestered following soil inversion of 367,000 ha of HPG to 30 cm. This estimate assumes topsoil C stocks will be returned to pre-inversion levels within 20 years following inversion (i.e. 100% accumulation efficiency) and is based on 10% farmer adoption of FIT and a 10% annual rate of pasture renewal (therefore 30 years is required for all paddocks to reach new equilibrium soil C stocks).
- In the absence of any quantitative data, we think a more conservative estimate is warranted, where topsoil C stocks may only return to 80% of pre-inversion levels, thus sequestering 3 Mt C (Table I).

Table I. Predicted soil C stock change in High Producing Grasslands following full inversion tillage (i.e. mouldboard ploughing to 30 cm) during pasture renewal.

	Pre-inversion C stock	Net increase in C stock*		Projected increase in New Zealand soil C stock**
		100% efficiency**	80% efficiency**	
Soil order	t C/ha	t C/ha	t C/ha	Mt C
Allophanic	135	16.4	9.6	0.27
Brown	99	14.3	8.5	1.58
Gley	102	13.7	8.1	0.17
Pallic	99	12.3	7.3	0.56
Recent	79	12.9	7.8	0.43
Total				3.02

* Over 20 years following inversion
** Based on 80% C accumulation efficiency, 10% farmer adoption, and a 10% annual pasture renewal rate.

- Our estimates of C sequestration following FIT during pasture renewal are supported by the following evidence:
  - high C saturation deficits in New Zealand subsoils,
  - rapid rates of SOC accumulation when mineral soils with low C contents are converted to pasture,
  - a single FIT event during pasture renewal does not result in significant losses of soil C compared with alternative pasture renewal tillage methods,
  - burying organic matter in deeper soil layers with ploughing (FIT) can help to stabilise soil C.
- Our estimates are constrained by an imperfect mechanistic understanding of C stabilisation in soils. Our estimates of C sequestration under FIT may be conservative because:
  - the rate and extent of organo-mineral complex formation is unknown and therefore not accounted for in the estimates,
  - allowance is not made for the possibility that environmental conditions at 15–30 cm following burial of topsoil are less favourable for decomposition than at 0–15 cm, owing to lower temperature and moisture, and more anoxic conditions,
  - our model does not include an inert C pool and therefore may slightly overestimate the rate and extent of C decline after burial.
- There is uncertainty around the estimates and any potential adverse effects of FIT. Our estimates may be considered optimistic as they assume:
  - pasture productivity will be unchanged following FIT compared to other tillage practices (i.e. FIT will not alter the length of time a paddock is unable to be grazed, or the total grazable yield),
  - a less structured surface soil (following inversion) will not impact pasture performance although it is possible the surface soil may be more susceptible to compaction from stock treading, and drainage properties may be altered,
  - FIT will not result in any priming effects (we conclude priming is unlikely),
  - While the decomposition of soil organic matter (SOM) buried by FIT may contribute to an increased risk of nitrate leaching, this may be offset by an increased demand for N by the new pasture (given new SOM-depleted topsoil); increased risk of leaching is not accounted for in our estimations.
- Sequestration of 3 Mt C will require additional nutrients (e.g. nitrogen, phosphorus and sulphur) in order to meet the stoichiometric requirements of soil organic matter formation. These nutrients may be supplied from various sources including from existing soil pools; the application of effluent or manure, N fixation from legume/grass swards, and/or from mineral fertilisers. In a worst-case scenario, where all the nutrients (N, P, S) were supplied as mineral fertiliser, the estimated cost per t C stored is ~$160.
- Increased N_2O emissions are expected to result from increased inputs of N. However, these emissions are estimated to be small in relation to the C sequestered by pasture renewal with FIT.
- All estimates of C stock change following inversion tillage are exploratory.
  We recommend a combination of field trials and simulation modelling to experimentally validate and refine the predictions.

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1 INTRODUCTION

Problem/opportunity

The global atmospheric concentration of CO_2 and other greenhouse gases (GHG) is steadily increasing. Sequestration of C in soil organic matter (SOM) is considered one of the more promising GHG mitigation options for agriculture (Lal 2004). It is estimated that, worldwide, soil C sequestration could offset emissions from fossil fuels by 400–1200 Mt C per annum (equivalent to 5%–15% of global fossil fuel emissions) (Goglio et al. 2015).

Relative to 1990, New Zealand's methane emissions in 2013 had increased by 7% and nitrous emissions by 23%, which translates to an annual emission of 1.09 Mt C above the 1990 base (Ministry for the Environment 2015). These emission increases could be offset by an increase in soil C stocks of approximately 1 million tonnes per annum. Recent research (Beare et al. 2014) has shown that many New Zealand pastoral soils are under-saturated with C and thus have potential to stabilise additional C. Soil C is concentrated near the surface of pastoral soils and decreases rapidly with depth (Kelliher et al. 2012). The C saturation deficit is therefore likely to be far greater in subsoil than in topsoil, which is supported by recent projections based on estimates of current soil organic carbon (SOC) stocks and the stabilisation capacity of different soils (Beare et al. 2014). The large C deficit in subsoil layers is a reflection of low C inputs (i.e. C from plant residues and animal excreta). Developing and deploying management practices that expose more of this under-saturated soil to higher C inputs could potentially result in a significant increase in the amount of stored and, ultimately stabilised, soil C.

This report discusses the potential to use full inversion tillage (FIT) as a one-off event during pasture renewal to achieve this objective. We hypothesise that the benefits of FIT for soil C storage would be realised through two potential pathways:

- First, the burial of C-enriched topsoil in closer proximity to under-saturated subsoil is expected to result in enhanced stabilisation of C through the formation of organo-mineral complexes.
  The stabilisation of C may be promoted by a somewhat slower rate of decomposition of the buried C at a depth where soil temperatures are generally cooler and less variable than at the soil surface and where the soil environment is typically more anoxic.
- Second, FIT would also bring some under-saturated subsoil to the surface where the establishment of high-producing pasture would be expected to result in increased storage and stabilisation of C from root turnover and animal excreta (dung), again through the enhanced formation of organo-mineral complexes.

In practice, FIT could be used as an alternative to current methods of pasture destruction and re-establishment (including direct drilling). Inversion tillage could also have benefits for soil C storage in mixed cropping systems, particularly where the original topsoil organic matter contents are reasonably high. Unfortunately, there is little or no research that has directly addressed the effect of FIT on soil C stocks in pastoral soils of New Zealand. Therefore, our assessment of the potential for C sequestration from FIT will, of necessity, be partly underpinned by theoretical knowledge of the nature of SOM, including biogeochemical processes that control the turnover of soil C.

Our review includes:

- An overview of literature on soil C storage and stabilisation
- Current and recommended rates of pasture renewal and the projected farm gate value
- A review of literature on the effects of tillage and pasture renewal on changes in SOC
- The land area that is estimated to be suitable for pasture renewal by FIT
- A framework for modelling the effects of FIT on soil C stocks following pasture renewal
- Modelled estimates of soil C stock changes on a per hectare basis
- National estimates of soil C sequestration under different scenarios of C accumulation efficiencies, farmer adoption and pasture renewal rates
- A discussion of the practical implications for management of pastures renewed by FIT
- Recommendations for future work to confirm the impacts and evaluate associated benefits and limitations.

2 LITERATURE REVIEW

2.1 C stocks in New Zealand pastoral and cropping soils

Organic C stocks in the top 30 cm of New Zealand pasture soils are typically ~100 t C ha^{-1} or more (Figure 1), although stocks differ between soil orders (Beare et al. 2013). Soil C stocks under high producing grasslands (HPG) are typically greater than those under arable cropping (~85 t ha^{-1}). This is largely due to the smaller C inputs under cropland compared to pastures (Baker et al. 2007; Francis et al. 1999). The largest stocks of soil C occur in Allophanic soils and the least in Recent soils. The relative proportion of SOC in surface and subsurface soils (0–15 and 15–30 cm, respectively) is dependent on land use (HPG or Annual Cropland), but is relatively consistent across soil orders.

Soil C stocks in pastoral soils exhibit strong vertical stratification with greatest concentrations at the soil surface and exponential declines with depth (Kelliher et al. 2012) (Figure 2). This is a consequence of C inputs from uneaten herbage and animal urine and dung occurring at the soil surface as well as the majority of plant roots being located near the soil surface. Therefore, subsurface soils, which have lower C stocks, have the potential to store additional C. Interrogation of the LMI dataset (Beare et al. 2013; Lawrence-Smith et al. 2010a) indicates ~two-thirds of the C in the top 30 cm of HPG is located in the top 15 cm of soil. Because of the strong vertical stratification of C with depth, opportunities to enhance C stocks using FIT may be particularly large in pastoral soils.

Vertical stratification of SOC also occurs in cropping soils, however the type and frequency of tillage used can alter the placement and depth-distribution of C rich organic residues near the soil surface. As such, the differential between surface (0–15 cm) and subsurface (15–30 cm) C stocks is smaller for annual cropping than pastoral systems, with slightly more than half (~53%) of the C stored in the top 15 cm. The annual cropland data reported here include a range of management histories and crop rotations. The differential in SOC stocks was greater for sites where arable crops were predominately grown, compared to those predominately sown to vegetable crops (data not shown). This is likely attributable to differences in cultivation depth and intensity of tillage used with the different crops grown in these systems. Arable crops such as wheat and barley are often cultivated to ~15 cm, while cultivation for potatoes and onions is often much deeper (~30 cm) as a finer and less dense seedbed is required. As such, cultivation of annual cropland alters the distribution of organic residues, and mixes residues within the soil matrix at both 0–15 and 15–30 cm depth increments.

Due to these differences in the vertical stratification of SOC, the opportunity for soil inversion (to 30 cm) to enhance C storage will likely be much less for cropland than for grasslands systems.

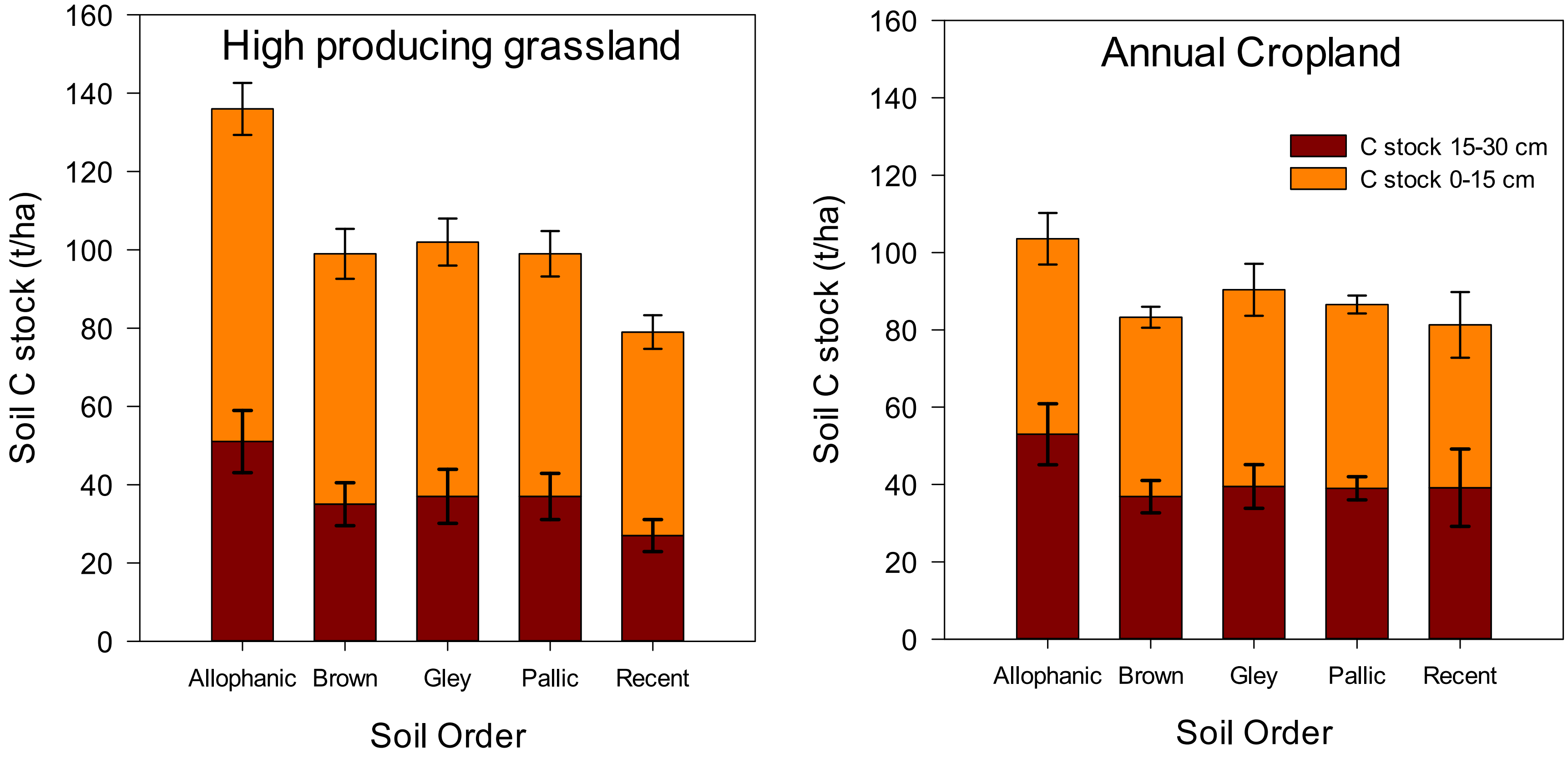

Figure 1. Mean soil carbon stocks in New Zealand's high producing grasslands and annual croplands by soil order. Source: Land Management Index dataset (Beare et al. 2013). Bars represent +/- one standard deviation from the mean.

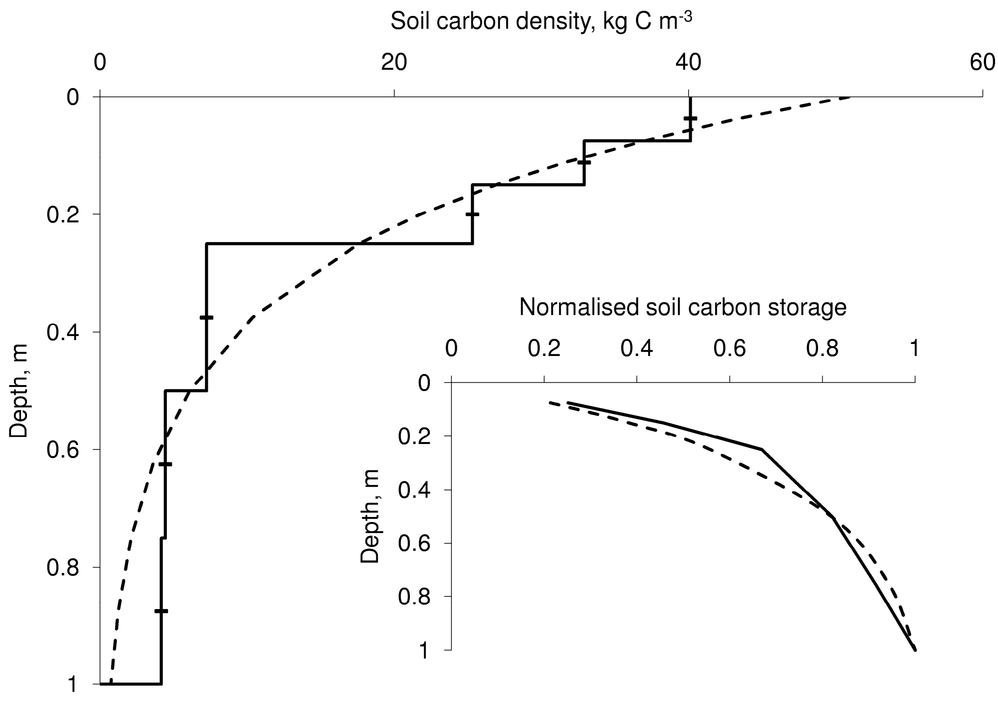

Figure 2. Soil C storage with depth for a long-term (60 years) pasture site in Canterbury. Solid lines are measured soil C stocks using a fixed depth sampling regime, with the short horizontal lines depicting the midpoint of each sampling interval. Dashed lines were fitted using an exponential decay function to allow a continuous vertical distribution to be visualised (Adapted from Kelliher et al. (2012)).

2.2 SOC storage and stabilisation

Soil organic matter (SOM) comprises a heterogeneous mix of components including crop and animal residues, microbial biomass and its metabolites, and stable humic substances adsorbed to soil particles.

The quantity or stock of SOC at any one point in time is a product of C deposition less decomposition. The primary input of C to agricultural soils is from roots (including their exudates), animal excreta (e.g. dung), and above-ground plant residues[1]. Decomposition is the process by which organic matter is broken down by soil biota, releasing C (as CO_2) to the atmosphere via respiration. The SOC stock may be increased by 1) increasing the organic matter input, 2) decreasing the rate of SOM decomposition, 3) increasing SOC stabilisation, or by 4) increasing volume of soil exposed to high inputs of C and maximum rates of sequestration (Whitmore et al. 2014). Enhanced stabilisation of SOC is a key process by which we propose that FIT during pasture renewal could increase SOC storage. However, we note that increases in SOC stocks may also result from greater adoption of pasture renewal (increasing pasture production contributing to increase soil C inputs) and by slowing the rate of topsoil SOM decomposition by burying (with FIT) the SOM at depth where conditions may be less favourable for decomposition.

[1] Soil organic matter refers to the whole range of organic materials present in the soil, including living organisms, dead and decaying plant and animal remains, and soil humus. Carbon is the key constituent of soil organic matter, accounting for approximately 58%.

Generally, stabilised organic C is older than labile C. The concept of stabilisation involves decreasing susceptibility of organic C to decomposition, thereby prolonging its residence time in soil. It is generally assumed that stabilised C is older and less biodegradable than “unstable” C, though concrete evidence for this is lacking. There is also considerable discussion in the scientific literature as to what determines the stability of C in soil. The three most commonly cited mechanisms are:

1. Chemical stabilisation via formation of organo-mineral complexes (i.e. the bonding of organic matter with charged soil mineral surfaces)
2. Physical protection of SOM via occlusion within aggregates
3. Biochemical recalcitrance of the OM (i.e. SOM quality which is independent of the soil factors)

Recent literature places greater emphasis on the spatial separation of substrates and decomposers, (i.e. stabilisation via mineral associations and soil environmental constraints) than on biochemical recalcitrance (Dungait et al. 2012). The three stabilisation mechanisms are discussed further below. Each section concludes with a brief comment noting any likely impact that FIT would have on these stabilisation mechanisms.

2.2.1 Chemical stabilisation of OM via organo-mineral complexes

Formation of organo-mineral complexes is widely accepted to be the most important long-term (decades to centuries) SOM stabilisation mechanism (Rumpel et al. 2012). Organo-mineral complexes can be defined as organic matter bound to clay and silt particles (often referred to as the ‘fine fraction’ of soil). The organic material is either passively adsorbed or covalently bound via electron pairs to the mineral particles. This stabilisation mechanism involves more intimate association with soil minerals than does occlusion of OM in aggregates; thus it offers a greater degree of protection, resulting in longer-term stabilisation of SOC (Dungait et al. 2012).

Many studies have shown that the mass of the fine fraction is correlated with a soil’s SOC content. However, the situation is more complex than this, given that soils can contain a range of different clay minerals, each having vastly differing surface areas that are available for the formation of organo-mineral complexes. For example, 1:1 clays have specific surface areas of ~15 m^2g^{-1}, 2:1 clays of ~80 m^2g^{-1} (Beare et al. 2014 and references therein). In addition, allophane and imogolite (aluminium silicate clays, which typically occur in soils formed from volcanic ash or volcanic glass) have very high specific surface areas ranging from 700–1500 m^2 g^{-1} (Parfitt 2009). In a study of 256 New Zealand soils (which included 31 Allophanic soils), Beare et al. (2014) found the surface area of mineral particles was more closely correlated with the SOC content of the fine fraction than the amount (mass) of fine fraction soil. Iron and aluminium colloids are also important binding materials as they have large charged surface areas (Dungait et al. 2012).

Full Inversion tillage will bring under-saturated mineral soil particles from depth into closer association with C inputs at the soil surface. It will also result in the burial of topsoil organic matter, bringing it in close association with under-saturated subsoil mineral. The best available data (Beare et al 2014) suggest that these mineral subsoils have a greater C saturation deficit than mineral particles in the original topsoil (prior to inversion), and hence it is likely that formation of organo-mineral complexes will be facilitated. There is no evidence in the literature to suggest that inversion tillage would disrupt pre-existing organo-mineral complexes, leading to increased soil C losses.

2.2.2 Physical protection of OM via occlusion within aggregates

Occlusion of organic carbon in aggregates may give protection against decomposition due to the SOM being inaccessible to microbes or because conditions within aggregates are unfavourable to microbial decomposition (Dungait et al. 2012). The latter includes the potential for aggregate formation to result in the development of occluded pores that may restrict oxygen diffusion and thereby limit microbial decomposition of intra-aggregate organic matter.

Macro-aggregate (i.e. aggregates >250 µm diameter) formation could be enhanced by inversion tillage whereby plant residues are embedded within the mineral matrix of the soil and mixed throughout the entire plough layer, as opposed to formation under no-till systems where residues are exposed to a smaller volume of soil (Olchin et al. 2008). Evidence for greater occlusion of organic matter near the bottom of the plough layer was provided by a study in Eastern Canada (Gregorich et al. 2009), details of which are provided in Section 2.5 of this report.

2.2.3 Biochemical recalcitrance

Recent literature suggests that biochemical recalcitrance is exhibited when the energy required to decompose the organic material is greater than the energy supplied via decomposition (Fontaine et al. 2007). As such, providing a fresh C supply may result in microbes decomposing the fresh C and antecedent 'recalcitrant' C simultaneously. This is known as the "priming" effect. Evidence for a priming effect has been shown to be highly variable between experiments, which is likely due to several factors (e.g., the quantity and quality of fresh C inputs; availability of antecedent C in the soil; the microbial community present; and interactions between these factors), and consequently is still a subject of considerable debate within the scientific community.

With respect to soil inversion for enhanced C storage, we considered whether burial of C-rich topsoil in close proximity to subsoil C (mainly recalcitrant C), may result in a priming effect. Despite the uncertainties around priming effects, we highlight three observations of particular note:

- Fontaine et al. (2007) observed that increased decomposition of antecedent stabilised C was not maintained in the absence of a permanent fresh organic C supply. As such, Fontaine et al. (2007) concluded that burial of recalcitrant SOC below/away from inputs of fresh C should protect it from decomposition allowing long-term storage of C.
- Priming effects have mainly been observed at short time scales (a few days to a year) and in incubation experiments. Analysis of a long-term field modelling experiment (>50 years) suggested no long-term impact of priming (Cardinael et al. 2015).
- Several authors (e.g. Fontaine et al. (2004); Kirkby et al. (2013); Richardson et al. (2014)) noted that any priming effects appear to be minimised when nutrient availability was high (i.e. the stoichiometric requirements of microbes for N, P, and S are met or exceeded).

We conclude that soil inversion is unlikely to have a direct effect on the biochemical recalcitrance of SOC as C inputs will be similar (in terms of magnitude) regardless of whether or not FIT is practised. Furthermore, while the concept of organic matter priming is widely debated and relatively unproven, we conclude this is unlikely to be a significant factor when assessing the merits of soil inversion for enhanced carbon storage, given that: (1) no large or ongoing amounts of fresh organic matter will be introduced to the buried topsoil following inversion, and (2) the antecedent C content at the burial zone will be low.

2.3 Modelling soil organic matter dynamics

Understanding the dynamics of SOM requires that it be subdivided into fractions that differ in their turnover rate. Typically, SOM is divided into two to five pools that are characterised by increasing resistance to biological decomposition. One commonly used fractionation scheme is shown in Figure 3.

Organic matter associated with fine soil particles (clay and fine silt) is generally regarded as highly stable, with a long turnover time (Balesdent et al. 1998; Buyanonovsky et al. 1994) and slow response to management changes (Campbell et al. 1991; Chung et al. 2008; Skjemstad et al. 2004). Clay particles have large surface areas onto which organic matter may adsorb and this association with mineral surfaces is considered the primary stabilisation mechanism for clay-bound organic matter (Dungait et al. 2012). A large proportion (typically >50%) of SOM resides in the clay fraction, which is usually highly enriched in organic matter compared with soil as a whole (Christensen 1992). The carbon stabilised by adsorption onto clay and silt particles is designated "humus" C in Figure 3.

Particulate organic matter (POM, i.e., macro-organic matter particles >50 μm) comprises a relatively small (10–25% of soil C) but dynamic fraction of the SOM. The POM comprises less decomposed organic matter with a wide C:N ratio (Gregorich et al. 2006). Due at least in part to the absence of a stabilising influence of mineral surfaces, POM is highly labile and can respond rapidly to changes in land management (Baldock et al. 2010; Gregorich & Beare 2008; Gregorich et al. 2006). In pastoral soils, the proportion of soil C in the POM fraction decreases rapidly with depth; typically 15–25% in surface (0–15 cm) soil v. ~10% in subsoil (15–30 cm).

Some soil organic matter models also include a recalcitrant C pool, which comprises biologically inert material that is not actively cycling. This may include charcoal particles derived from historic burning of vegetation. Soil organisms, mainly microbial biomass, make up a small (3–5 % of soil C) but a very important SOM fraction, as they are responsible for the decomposition and turnover of non-living SOM.

Increasing the amount of clay-associated C is particularly desirable from a C sequestration perspective as it offers the possibility of long-term C storage. In the short term, land-use effects of soil C are usually most apparent in C pools where organo-mineral stabilisation is weak. For example, the loss of POM-C accounts for a disproportionately large part of the soil C decline following conversion of long-term pasture to arable cropping (Baldock et al. 2011). The stabilisation of C through the formation of organo-mineral complexes (including clay-bound C) is generally believed to be a slower process.

Associated with each of the biologically active SOM fractions is a decomposition rate constant, *k*, which can be determined experimentally. Working with Australian soils, Skjemstad et al. (2004) derived *k* values of 0.02 y^{-1} for humus-C and 0.15 y^{-1} for POM-C. We used the SOM model pools given in Figure 3, with locally optimised rate constants, to estimate losses of topsoil C following burial by soil inversion (i.e. FIT).

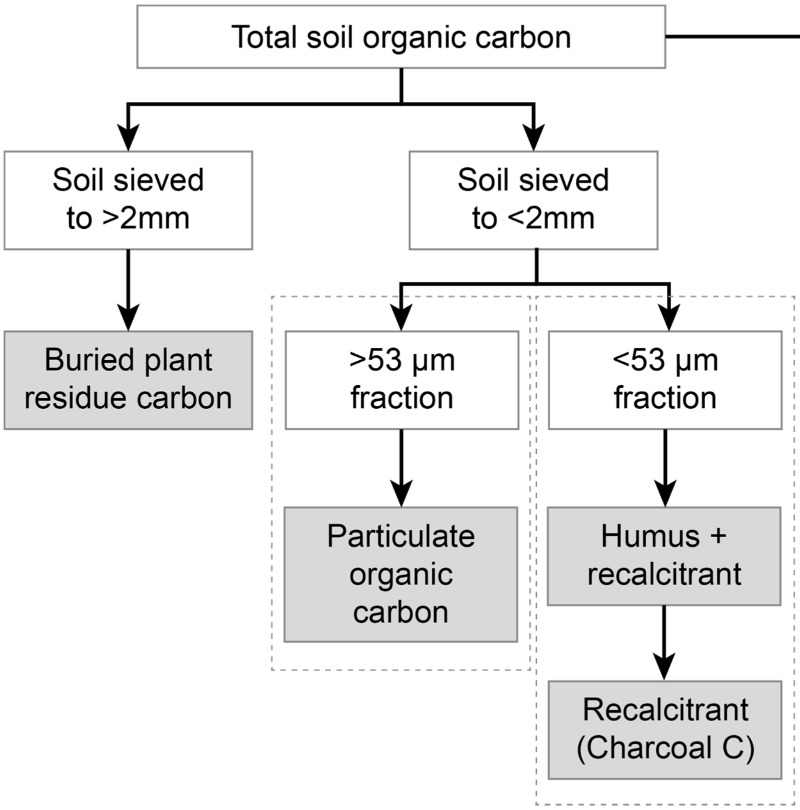

Figure 3. Example fractionation scheme used to divide soil organic C into biologically meaningful fractions (shaded in grey). The fractions given in the dashed boxes are those in the Rothamsted Carbon model (Roth-C). (Adapted from Skjemstad et al (2004)).

2.4 Pasture renewal rates in New Zealand

Pasture renewal represents a key opportunity to deploy FIT to enhance soil C storage. It involves the destruction and replacement of existing pasture to change the sward composition or vigour, usually with the aim of increasing the quality or rate of pasture production. Pasture renewal is often recommended to address the gradual deterioration in pasture performance that has been attributed to a number of factors including weed invasion, soil-borne diseases, soil compaction, and/or the development of hydrophobic conditions associated with drought.

There is still considerable uncertainty regarding the current rate of pasture renewal in New Zealand. The Pasture Renewal Charitable Trust (PRCT) commissioned a report on pasture renewal rates based on a telephone survey of 1000 farmers representing the dairy (53%), sheep/beef (41%) and cropping (6%) sectors in 2008. The results of the survey showed that farmers renewed an average of 8% (+/- 0.7%, 95% CI) of their paddocks annually or about 11% of the area under improved pasture (Bewsell et al. 2008). Dairy farms had the highest rates of pasture renewal (10%) which were about twice that of drystock (sheep/beef/deer) farms. Pasture renewal rates varied from a low of 4% in Taranaki to as high as 12% in Canterbury and tended to be higher on the South Island than the North Island under both dairy and drystock farming (Table 1).

Rates of pasture renewal were also reported by Beare et al. (2012) based on a survey of pastoral sector experts. The survey included a total of 31 respondents (leading farmers, farm management consultants, pasture agronomists and farm systems researchers) with an average of 21.8 years' experience covering six major agricultural regions. Based on the survey results, Beare et al. (2012) reported that the average annual rate of renewal on dairy farms across the six regions increased from 5.6 to 7.2% of the total area under pasture between 1990 and 2008 (Table 2). Regional rates of dairy pasture renewal ranged from a low of 3.0% in Taranaki/ Manawatu in 1990 to a high of 9.3% in Canterbury in 2008. An increase in the average rate of renewal between 1990 and 2008 was reported for all regions except Northland, where there was a slight decline. The high rates of renewal reported for Northland, especially in 1990, were most likely influenced by the common practice of over-sowing pastures (in the absence of pasture destruction) and, therefore, may be an overestimate of the true renewal rates. The survey results indicate that the largest relative increases in rates of dairy pasture renewal occurred in the Waikato and Canterbury regions.

Table 1. Rates of Pasture renewal across regions (Source: Bewsell et al. (2008)).

Region	Number of respondents	Hectares Mean ± 95% CI[1]	Mean % Renewal (Actual)	Mean % Renewal (Recommended)
Northland/Auckland	44	22 (10)	11	14
Waikato	90	8 (2)	7	10
East Coast	89	47 (56)	5	9
Taranaki	88	9 (4)	4	8
Lower North Island	92	18 (6)	5	9
West Coast/Nelson	42	23 (8)	9	9
Canterbury	171	43 (4)	12	13
Otago/Southland	177	29 (11)	9	11
Total	793			

[1] Values in parentheses are ± 95% confidence interval

Overall, the average rates of dairy pasture renewal reported by Beare et al. (2012) were slightly lower than the actual rates of renewal reported by Bewsell et al. (2008) but, in general, they followed the same trend; being highest in Canterbury and lowest in Taranaki/Manawatu. There is a significant gap in the data on pasture renewal rates for the south and east coast of the North Island.

Table 2. The number of respondents, their average years of experience, and the average rates (% of farm area) of pasture renewal reported for dairy and sheep/beef/deer farms in 1990 and 2008 based on a survey of farm experts (Source: Beare et al 2012).

Region	Number of respondents	Experience (Years)[1]	Pasture renewed annually (% of total area)[2]			
			Dairy		Sheep/beef/deer	
			1990	2008	1990	2008
Northland	5	26.2	8.5 (2.7)	7.3 (2.0)	1.0 (0.0)	2.1 (0.7)
Waikato	5	21.4	4.3 (0.9)	7.4 (2.5)	ND	3.0 (0.7)
Taranaki/Manawatu	5	25.8	3.0 (2.1)	4.8 (1.3)	1.0 (0.8)	3.0 (1.6)
West Coast	4	24.6	5.1 (2.1)	8.0 (1.0)	3.0 (1.1)	3.0 (1.1)
Canterbury	6	17.7	6.2 (1.9)	9.3 (1.9)	1.0 (0.0)	3.3 (0.5)
Otago/Southland	6	17.5	6.4 (2.7)	7.2 (1.6)	3.2 (0.8)	3.4 (0.9)
Total	31	21.8	5.6	7.4	1.5	3.0

[1] Values are average years' experience in the pastoral sector.
[2] Values are mean (± 1 standard deviation)

Sanderson and Webster (2009) reported estimates of pasture renewal rates based on data from Meat and Wool New Zealand's annual survey, the AgResearch market research report (Bewsell et al. 2008) and projections made from grass seed production data (pers. comm. Murray Wilcox, New Zealand Agriseeds Ltd.). They concluded that a slightly more conservative estimate of pasture renewal was warranted, estimating that the annual rates for 2006/07 were about 2% of the sheep/beef land area and an average of 6.1% for land under dairying.

Sanderson and Webster (2009) also compiled data on the dry matter production responses to pasture renewal based on studies from both sheep/beef and dairy systems. Their summary of the available data showed that pasture renewal resulted in a 10–30% increase in pasture production on sheep/beef farms and 7–27% increase on dairy farms. Using data on the estimated value of pasture-based products, the authors modelled the impact of pasture renewal on the farm gate values assuming targeted rates of renewal of 8% and 12% for the sheep/beef and dairy sectors, respectively. Depending on the size of the (modelled) pasture renewal response, the farm gate value for sheep/beef farms was projected to increase from 8% to 27% and from 6 to 25% for dairy farms. They estimated that this would result in a direct GDP increase of about 15%, from $5.2 billion to $6.0 billion.

These estimates of farm gate value provide a strong economic driver for pasture renewal that would help to underpin the potential value of FIT for enhancing soil C storage. This assumes that the direct (e.g. tillage) and indirect (e.g. capital fertiliser) costs of using FIT for pasture renewal would be offset by the realised benefits of enhanced pasture production and enhanced soil C storage. These issues are discussed below.

2.5 Potential effects of FIT on soil C stocks following pasture renewal

As discussed above, pasture renewal represents a key opportunity to use FIT (e.g. mouldboard ploughing) to both improve pasture production and enhance soil C storage. The increases in soil C storage are proposed to occur through a combination of burying topsoil OM and growing high-producing pasture on the under-saturated subsoil brought to the soil surface during inversion tillage, both leading to enhanced stabilisation of SOC. There are several key assumptions that may be important to achieving enhanced SOC storage from the use of FIT during pasture renewal. These include that:

- A single, full inversion tillage (FIT) event during pasture renewal will not result in significant losses of soil C from the breakdown of buried topsoil organic matter.
- Burying C-rich topsoil in close proximity with under-saturated subsoil minerals increases the potential to stabilise SOC at or below the depth of tillage.
- Growing high-producing pasture on inverted subsoil with a high soil C saturation deficit (i.e. depleted in SOC) will enhance the rate of soil C stabilisation.

The first two of these hypotheses are addressed below, while the third hypothesis is addressed in section 2.6.

Does tillage increase losses of SOC?

Many previous studies have reported adverse effects of tillage on soil C concentrations (Baker et al. 2007; West & Post 2002; Lal et al. 1998). However the vast majority of studies are based on the repeated use of tillage in continuous cropping systems. Under these conditions, the effects of repeated disturbance with tillage and the tendency for crops to produce less dry matter and return less C to soils are two important factors contributing to soil C losses over time. Furthermore, there has been a tendency in the international literature to report effects of tillage (compared to no-tillage) on changes in topsoil C concentrations without properly accounting for the redistribution of soil C through the soil profile (to below the depth of tillage) and changes in soil bulk density that are important to properly quantify effects on soil C stocks.

Continuous no-tillage (NT) management (soils not tilled, crops direct drilled) of arable crops has received much attention as a possible method to either reduce the rate of carbon loss or to sequester additional carbon under long-term cropping (Lal et al. 2003). Based on a meta-analysis of data from 23 published studies (soil sampling depth ≥30 cm), Angers and Eriksen-Hamel (2008) reported that SOC stocks were an average of 4.9 t ha^{-1} greater under crops managed with continuous NT compared to FIT (average ploughing depth = 23 cm, most in North America). Sequestration rates of ~0.3 t C/ha/yr (Baker et al. 2007) to 0.57 ± 0.14 t C/ha/yr (West & Post 2002) have been reported for continuous NT management systems. However, it is important to recognise that all of these studies are based on continuous cropping and the repeated use of either FIT or NT management, often on soils that are relatively depleted in soil organic matter. These conditions are likely to accentuate the relative effects of FIT and NT management on SOC stocks with time.

In contrast to the findings reported above, a number of recent studies suggest that in many environments SOC stocks are comparable under continuous no-till and tilled systems, particularly when the measurements account for the re-distribution of SOM through the soil profile and are expressed on an equivalent soil mass basis. Whereas SOC tends to accumulate near the soil surface (top 5–10 cm) under NT, it tends to be more evenly distributed through the plough layer under FIT (Baker et al. 2007; Gregorich et al. 2009). As such, sampling depth can introduce a bias when interpreting the effects of tillage on SOC stocks. Whereas shallower sampling tends to suggest (often incorrectly) greater SOC storage under no-till, deeper sampling (e.g. below 15 cm) tends to indicate little or no difference in SOC stocks under FIT and NT systems (Baker et al. 2007). Indeed, some studies have actually reported higher SOC stocks under crops established with FIT than under NT (Baker et al. 2007; VandenBygaart et al. 2003).

Although very few studies have reported longer-term effects of tillage on soil C stocks following pasture renewal or re-grassing, a few studies have reported short-term effects. Short-term (hours to days), rapid losses of CO_2 following tillage events have been reported in several studies and attributed to degassing of CO_2 held in the soil profile, rather than enhanced decomposition of soil organic matter (Quincke et al. 2007). Rutledge et al. (2014) compiled data from several studies that showed that soil respiration rates during the first few weeks following the ploughing of pastures ranged from about 1.4 to 4.3 g C m^{-2} d^{-1}. However these rates of respiration range from about 85% higher to 44% lower than those of undisturbed pastures. Rutledge et al. (2014) also reported the short-term (39–43 days) effects of mouldboard ploughing on C losses from three New Zealand pasture renewal sites. In this case the authors reported that the ‘net impact of cultivation’ (accounting for both direct respiratory losses and lack of C inputs from photosynthesis) ranged from about 1.9 to 9.9 g C m^{-2} d^{-1}. The highest losses were associated with spring cultivation, which amounted to about 2–3% of the SOC in the top 30 cm of soil, whereas losses following autumn tillage were much lower. However, we cannot assume that short-term losses of C following cultivation of pasture reflect the longer-term net effects of pasture renewal on the C balance. In fact, a subsequent study in New Zealand based on net ecosystem flux measurements using eddy covariance methods suggests that the losses of C following cultivation during pasture renewal can be replaced by the C fixed by new pasture within one year of regrassing (L Schipper, pers. comm.). Despite the fact that pasture renewal (following destruction of the existing pasture) typically involves a short period of limited C-fixation as the new pasture is establishing, the longer-term enhanced rates of pasture production following renewal (see section 2.5) may be sufficient to off-set the lower C inputs during pasture re-establishment.

There are very few studies that have reported the effects of different pasture renewal practices on soil C stocks. Linsler et al. (2013) compared the effects of FIT on SOC stocks following the renewal of permanent grasslands to those of undisturbed grassland in Germany. Although the authors reported a difference in the vertical stratification of SOC stocks, there were no significant differences in the stocks of C (0–40 cm) under permanent grassland and grassland re-established following FIT in the five years immediately following grassland renewal. In a similar context, Wortmann et al (2010) evaluated the effects of applying a one-off FIT event to long-term NT soils at two sites in Nebraska. They reported that a single application of mouldboard ploughing (20 cm depth) resulted in no significant differences in SOC stocks (0–30 cm) compared to continuous NT management five years after the event.

Collectively these studies indicate that employing a single FIT event during pasture renewal is unlikely to lead to significant losses of SOC in the short-term.

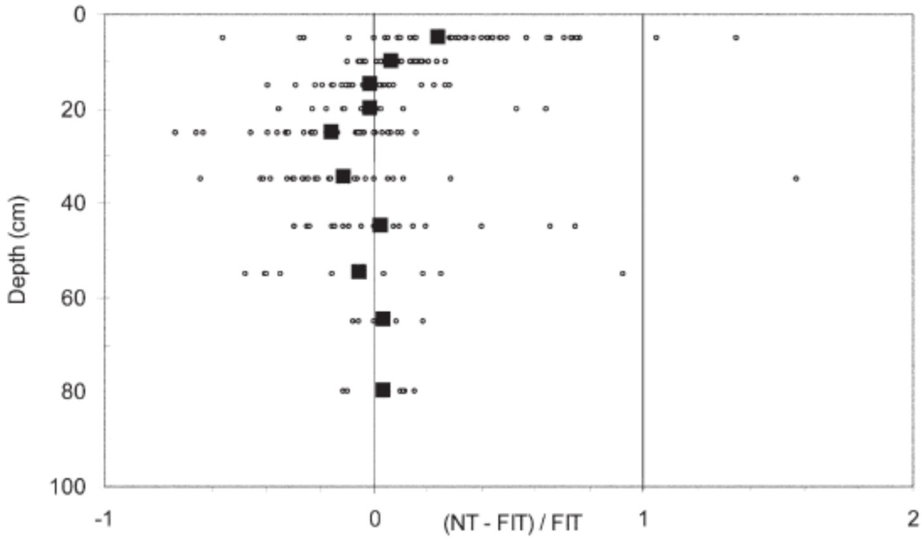

Figure 4. Relative change in soil organic C stocks under No-till (NT) compared with Full Inversion tillage (FIT) as a function of soil depth (Source: Angers and Eriksen-Hamel (2008)).

Does burying SOM at depth increase soil C stabilisation?

Several previous studies have suggested that incorporation of SOM with tillage increases the physical contact between OM and the soil mineral matrix (Gregorich et al. 2009; Olchin et al. 2008). The closer contact between under-saturated minerals and organic matter-rich topsoil is expected to provide a greater opportunity for the formation of organo-mineral complexes and the physical occlusion of organic matter in aggregates, ultimately leading to enhanced SOC stabilisation over time.

A study of four cropped soils in eastern Canada provided evidence that FIT can promote the stabilisation and storage of soil C, particularly in the subsurface soils (Gregorich et al. 2009). The authors showed that annually tilled soils (mouldboard ploughed to 15–20 cm) had greater quantities of SOC protected within aggregates (protected light fraction) and more SOC associated with the fine mineral fraction (i.e. stable fraction) than continuous NT soils.
The effects of physical protection were particularly evident at or near the bottom of the plough layer. Although the effects of tillage on aggregate protected OM were highly significant, the aggregate protected OM made up a relatively small portion (2–14%) of the overall soil C stock. However, the SOC associated with the fine mineral fraction, which accounted for the largest proportion of the total SOC (85–97% of total SOC), was also strongly affected by tillage. In this case, the mineral associated organic matter was about 40–50% higher in tilled v. no-tilled soils at three of the four sites. Again, most of the differences were associated with fine fraction minerals at or near the depth of ploughing.

Angers and Eriksen-Hamel (2008) presented results of their meta-analysis (data from 23 studies) as the ratio of SOC stocks under NT and FIT management (i.e. [NT-FIT]/FIT) to emphasise the effects tillage on the vertical stratification of soil organic matter (Figure 4). Although SOC stocks were significantly greater near the soil surface (0–10 cm) under no-till compared to FIT, the difference was reversed at a depth of approximately 20–35 cm. This depth range aligned well with the average depth of ploughing (23 cm), indicating that SOC tended to accumulate at or just below the plough depth. Similar findings were reported by (Gregorich et al. 2009). Angers and Eriksen-Hamel (2008) concluded that the relative accumulation of SOC at depth (near the plough layer) under FIT could not be attributed to specific soil or climatic variables, and as such could be considered a general characteristic of FIT systems.

Above-ground dry matter and roots represent one source of the C that may be stabilised by burying the topsoil with FIT. Olchin et al. (2008) carried out controlled field experiments which showed that stabilisation of C from crop residues incorporated in C-depleted subsoil was greater than that for topsoils. They also compared the C stabilisation efficiency of tilled and no-tilled soils and reported that the negative effects of tillage on aggregate protected C appeared to be counterbalanced by the enhanced stabilisation of residue-C in the cultivated layer of tilled soils. In a similar study, Wingeyer et al. (2012) reported evidence that the incorporation of maize residues with deep tillage enhanced soil organic matter stabilisation compared to continuous NT management. The activity and biomass of soil microbes is typically greater in subsurface soils (e.g.15–30 cm) under FIT than NT (Doran, 1987; Doran et al., 1998), which may account for the greater humification of SOM (Horáček et al., 2001; Murage and Voroney, 2008) in subsurface soils under FIT management.

A recent study by Don et al. (2013) found that the turnover of compost-C was lower in C-depleted soils than in soils with high C concentrations. This finding is consistent with our hypothesis that burying topsoil organic matter in close association with low C subsoil (i.e. with FIT) will result in greater net storage of the buried SOC.

Alcantara et al. (2014) investigated the long-term effects of ploughing on soil C storage based on a survey of sites in Germany and Denmark where a single deep ploughing event (50 to 120 cm) had been used to improve water infiltration and drainage. They reported that the one-off deep ploughing events resulted in soil C stocks over the entire soil profile that were 3–25% higher than reference sites (ploughing to 30 cm) where similar management was applied over a 35- to 50-year period.

A German study reported increased soil C contents following a deepening of the plough depth from <25 to > 35 cm (study included 120 plots on 16 farms, soil C measured between 1970 and 1998) (Nieder & Richter, 2000) (Figure 5). A cumulative increase of up to 16 t C ha^{-1} was observed for loess soils used for cash crop production, and up to 26 t C ha^{-1} in sandy soils under livestock production. During this time, increased production was also observed, and fertiliser application rates exceeded the amount of nutrients removed in harvested crops.

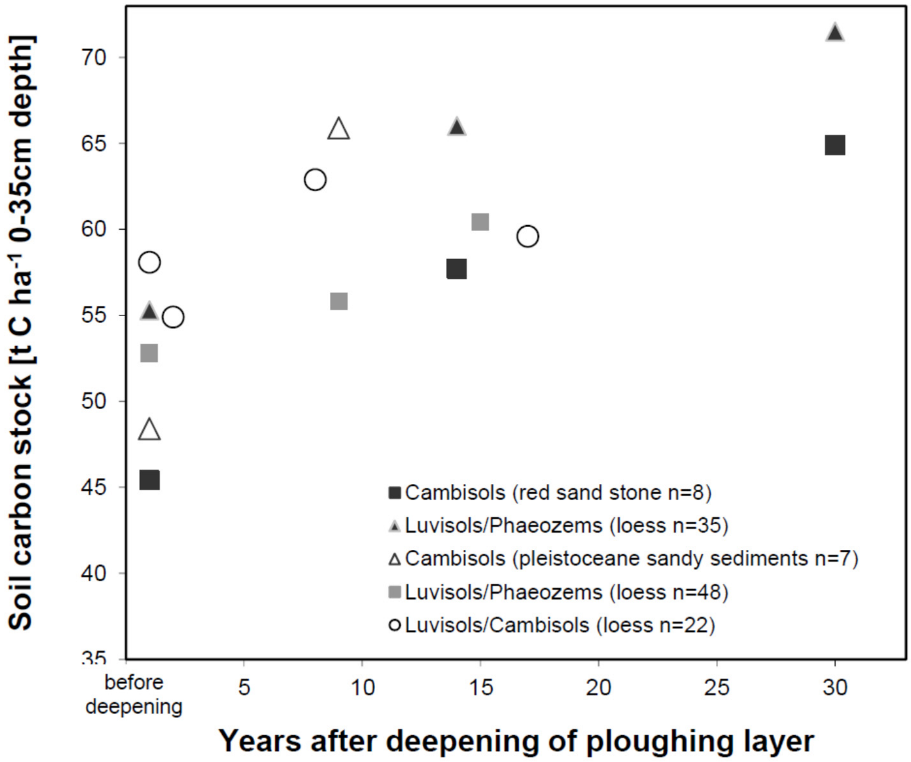

Figure 5. Soil C stock following deepening of the plough layer (<25 to >35 cm, 120 plots across 16 farms) in Germany. Data from Nieder & Richter (2000).

2.6 Accumulation of SOM after grassing C-depleted soils

2.6.1 Rates of SOM accumulation

Soils under long-term pasture are generally considered to be at or near "steady state" with respect to C, and offer relatively little potential to store additional C. However there is evidence that when mineral soil with low C content is converted to pasture, SOC can accumulate very rapidly (>3.5 t C/ha/yr) (Horrocks et al. 2010; Thomas et al. 2007).

Thomas et al. (2007) reported a five-fold increase in soil C over an 8-year period after establishment of grazed pasture on a sandy Pakihi[2] soil on the West Coast of New Zealand. Prior to pasture establishment, the soil was "flipped", bringing C-depleted subsoil material to the surface and burying the original topsoil (as would occur with inversion tillage by ploughing). The 'newly created topsoil' had a very low SOC concentration of ~0.6 % (14.3 t/ha, 0–15 cm), which increased to ~3.1% (58 t/ha) over an 8- to 10-year period. Average SOC accumulation during the eight years following inversion was ~0.36%/yr, which equates to >5 t C/ha/yr. High rates of SOC accumulation (3.5 t C/ha/yr) on the Pakihi soils were also reported following humping and hollowing[3] (Thomas et al 2007). SOC of the more productive humps increased from ~10 to ~45 t C/ha in the 10 years after modification (0–15 cm).

[2] Podzolised and gley podzolised brown soils.
[3] Large machinery is used to excavate "hollows" by removing topsoil and breaking up iron pans, creating surface drains. The excavated soil is then deposited on to neighbouring soil surface to create "humps".

Rapid accumulation of organic matter on slip scars has been documented in a study of Wairarapa siltstone hill country (Rosser & Ross 2011) where the soil C concentration (0–10 cm) increased from ~0.2% in fresh slip scars to 3–4% within 20–30 years.

Very rapid rates of C accumulation (8.0±0.85 t/ha/yr for 0–30 cm depth) have also been reported in a Georgia, USA following conversion of degraded cropland (~0.5% C in surface layers) to intensively grazed dairy pastures (Machmuller et al. 2015).

These rates of C accumulation are significantly greater than those reported for two New Zealand pasture studies where the C concentration at the time of pasture establishment was moderately high. At Winchmore in Canterbury, where pasture was established on land previously under continuous arable cropping (initial C concentrations of ~2.7%), the accumulation rate in the following 15 years averaged 0.9 t C/ha/yr (Metherell 2003). This SOC accumulation rate is comparable with those reported by Schipper and Sparling (2011) following establishment of pastures on reverted scrubland, between 1.07 and 0.09 t C/ha/y (depending on number of years post pasture establishment).

The rates of C accumulation on highly C-depleted soils (Machmuller et al. 2015; Rosser & Ross 2011; Horrocks et al. 2010; Thomas et al. 2007) are approximately one order of magnitude greater than rates reported for adoption of a range of best management practices (e.g. improved grazing, nutrient, and water management, adoption of no-till or reduced tillage, elimination of fallow) under grassland and cropland management reported by Stockmann et al. (2013) and Freibauer et al. (2004).

2.6.2 Timeframe for SOC to reach a new steady state following establishment of pasture

Previous research in New Zealand (Nguyen & Goh 1990; Schipper & Sparling 2011)) and overseas (Freibauer et al. 2004; Smith 2004) indicates the rate of SOC change is greatest immediately following adoption of a new management practice, with the accumulation rate decreasing as soil C approaches a new steady state or equilibrium (Freibauer et al. 2004; Smith 2004). On this basis, it is assumed that the soil C sequestration rate will be greatest when the SOC saturation deficit is large, though direct evidence for (or against) this effect is lacking. This concept can be extrapolated to conclude the use of FIT during pasture renewal, which brings soil with a high C saturation deficit to the surface, would provide a greater opportunity for carbon sequestration than renewal of pasture on undisturbed topsoil (e.g. via direct drilling), where SOC concentrations are closer to the stabilisation capacity (i.e. SOC saturation).

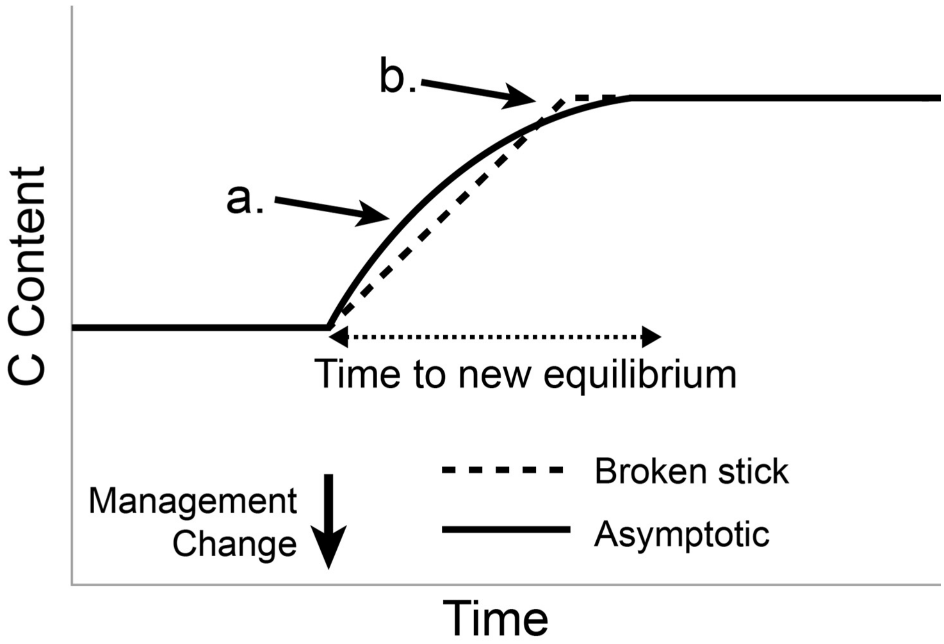

Figure 6. Schematic of soil C stock change following adoption of land management change leading to C sequestration, where (a) represents the maximum rate of C sequestration and (b) represents the new equilibrium stock. Two C stock trajectories are provided, a broken stick and asymptotic trajectory. (Adapted from IPCC, 2014).

The time taken to reach a new equilibrium following a management change is likely to be variable depending on the C saturation deficit, the quantity and quality of C inputs, and climatic factors. The Intergovernmental Panel on Climate Change (IPCC) uses a default value of 20 years for establishment of a new steady state following land use change (IPCC 2014) (Figure 6). This timeframe is consistent with New Zealand experimental data. Nguyen and Goh (1990) reported that soil C reached steady state 15–16 years following pasture establishment on arable land at Winchmore in Canterbury, while Rosser and Ross (2011) showed that after very rapid initial increases in soil C stocks on erosion slip scars, there was little further increase between ~30 and 70 years.

3 PREDICTING CHANGES IN SOIL C STOCKS FOLLOWING SOIL INVERSION

The following sections outline the methods and results obtained from modelling the changes in soil C stocks that are projected to occur following from the adoption of FIT during pasture renewal in New Zealand.

3.1 Dataset

Two important sources of SOC data for New Zealand's High Producing Grasslands (HPG) are the Land Management Index (LMI) data set (275 sites; Lawrence-Smith et al 2010b, Beare et al 2013) and the National Soils Database Resampling Sites (NSDrs) (123 sites; Schipper et al 2007, 2010). Both of these datasets form part of the Ministry for the Environment's Soil C Monitoring System dataset that is used in calculating the National soil C inventory. A recent report by Beare et al (2013) showed that the soil C stocks reported in these two datasets for dairy and drystock systems compared very well except for Allophanic soils. For these soils the overall average stock of soil C (0–30 cm) in the NSDrs dataset was about 30 t C/ha greater than that of the LMI dataset. Much of the difference in soil C stocks between datasets was attributed to differences in soil C concentrations rather than any differences in soil mass. Geographic differences in the distribution of sites on Allophanic soils may have contributed to the differences in soil C stocks between the datasets

Relevant soil C stock data from the Land Management Index (LMI) dataset were used to derive estimates of soil C change following full soil inversion. The full LMI dataset contains data for 748 sites. Some 257 of these sites meet the IPCC criteria for HPG (Beare et al. 2013) and were included in the Ministry for the Environment Soil Carbon Monitoring System in 2010 (Lawrence-Smith et al. 2010b). These HPG sites comprised dairy (61%), intensive bull/beef (7%) and extensive sheep/beef (32%) pastures. The paddocks are spread across seven New Zealand regions (Auckland, Waikato, Gisborne, Hawke's Bay, Manawatu, Canterbury and Southland), and represent a range of important agricultural soil types (Allophanic (66), Brown (34), Gley (51), Pallic (64), and Recent (32)). The LMI data are based on fixed depth samples (0–15, 15–30 cm) where the entire sample was used to measure the bulk density, and to calculate the soil C stocks. Details on the sample collection and analysis methods have been described previously (Kirschbaum et al. 2009; Lawrence-Smith et al. 2010a; Lawrence et al. 2008).

To account for the uncertainly of C stocks for Allophanic soils, a second estimate is provided for these soils based on data from the NSDrs dataset. The NSDrs dataset contains horizon-based measurements of soil C concentration and bulk density which were used to calculate the soil C stock for each horizon in the soil profile at each site. The individual measurements of horizon depth were used to convert the horizon-based estimates of soil C concentrations (mg C/g soil), soil mass (t soil/ha) and soil C stocks (t C/ha) to fixed-depth (0–15 and 15–30 cm) estimates of these properties to allow a direct comparison to the LMI data. Details on the sample collection methods and analyses can be found in Schipper et al. (2007) and Schipper et al. (2010). The NSDrs data were also used to predict SOC increases following soil inversion to 45 cm.

3.2 Estimating SOC change following soil inversion

We modelled the effect of FIT (i.e. mouldboard ploughing to 30 cm) of HPG on soil C stocks across a range of soil orders. The distribution of C in a hypothetical pasture soil before and immediately after ploughing is shown in Figure 7. To estimate how C stocks may change post inversion, we divided the plough layer into two sub-layers (0–15 and 15–30 cm depth intervals).

We assumed that the high post-inversion C concentration in the 15–30 cm layer would not be sustainable by the small C input and that C concentrations in this layer would decline over time. Carbon accumulation in the 0–15 cm layer (with low initial C) was estimated by assuming that a new steady state C concentration would be achieved 20 years post inversion (following the IPCC guideline, section 2.6.2). Resultant changes in soil C stocks to 30 cm were scaled across New Zealand land areas to estimate the total change in SOC stock following soil inversion. Several scenarios were considered including: different rates of SOC accumulation, different levels of farmer adoption of soil inversion, and different pasture renewal frequencies.
Our estimates assume no change in C stock over time beyond 20 years after inversion.

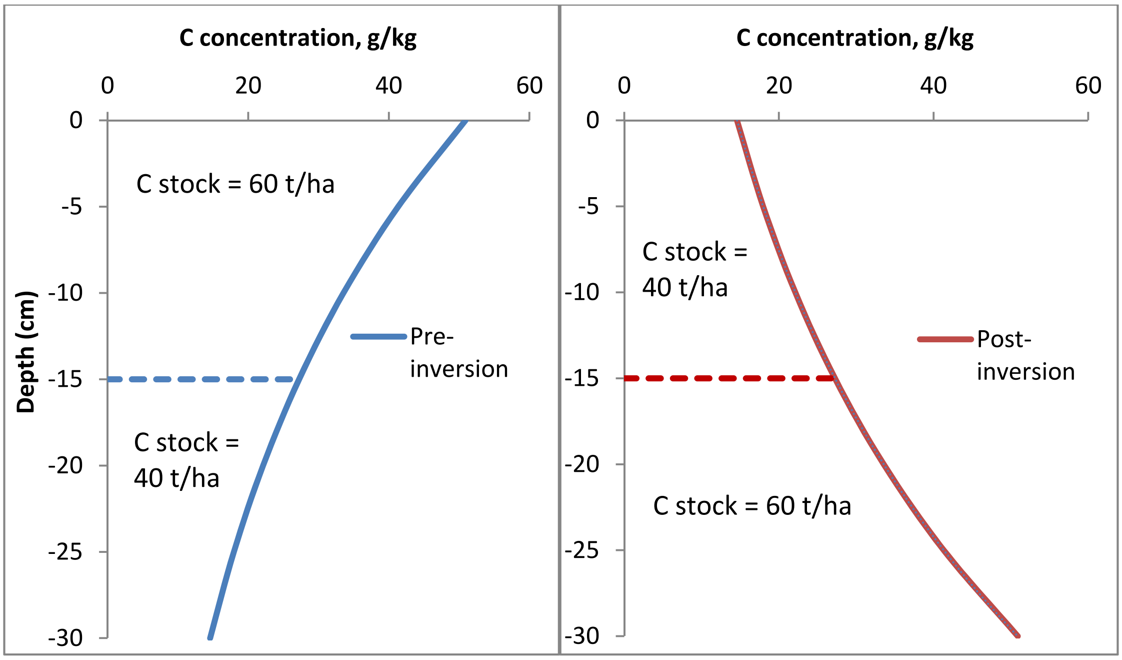

Figure 7. Distribution of C in a hypothetical pasture soil before and immediately after inversion cultivation to 30 cm (C stocks are shown for the 0–15 and 15–30 cm layers)

3.2.1 C changes in 15–30 cm layer (former topsoil) post-inversion

In estimating post-inversion soil C stock changes, we assumed that inputs of C to the soil will not be altered as a result of pasture renewal. Further, we assume that C inputs to the 15–30 cm layer will be sufficient to maintain the same C stock as was present pre-inversion. For example, if the C stock in the 15–30 cm layer increases from 40 to 60 t/ha when the soil is inverted, the additional 20 t/ha will not be sustainable and will gradually decrease over time (eventually to a minimum of 40 t/ha). This represents a relatively conservative estimate of the C inputs following pasture renewal given that several studies have shown that rates of dry matter production are 10–30% higher in renewed pastures compared to original “old” pastures (Sanderson & Webster 2009).

We used a simple two-pool model to simulate the time-course of C decline in the 15–30 cm layer, i.e., SOC was divided into a labile pool (POM-C) and stable C (estimated as total soil C minus POM-C) (Figure 3). [Note: This model may slightly overestimate the rate and extent of C decline because an inert C pool is not included, i.e., all of the C is assumed to be biodegradable]. Decomposition rate constants, *k*, of 0.1 and 0.02 y^{-1} were used for POM-C and stable- C, respectively. With these values, the decline in POM-C and stable-C was adequately simulated when C inputs were eliminated (using herbicides to keep plots plant free) in a trial at Lincoln, Canterbury (Figure 8). These decomposition rate values are also consistent with previously published values (Skjemstad et al. 2004).

Stable-C and POM-C generally comprise approximately 80 and 20%, respectively, of soil C in pasture topsoil (0–15 cm) (Baldock et al. 2010). The proportion of POM-C decreases with depth in pasture soils; we assumed that POM-C comprises 10% of C in the 15–30 cm layer. Using these values, the *additional* C in the 15–30 cm layer after inversion (20 t/ha in the example above) was partitioned into POM-C and stable-C fractions. The amounts of these fractions remaining in the soil were calculated (using the rate constants) for the 20-year period after inversion.

This approach may underestimate the quantity of C remaining in the 15–30 cm layer (after 20 years) for two reasons: (1) allowance is not made for the possibility that environmental conditions (temperature, moisture, oxygen availability) in that layer may be less favourable for decomposition than in topsoil (i.e. the *k* values above were derived from data for topsoils); (2) burial of C-rich topsoil in close association with low-C subsoil may result in formation of stable organo-mineral complexes between the buried C and the mineral component of subsoil. The extent and rate at which these complexes may form is not known.

3.2.2 C accumulation in the new 0–15 cm layer

Our literature review suggests that SOC can accumulate rapidly when pasture is established on soil with low starting SOC content. We assumed that SOC would reach a new steady state in the top 15 cm within 20 years of inversion cultivation (mouldboard ploughing). This is the accepted time frame for management-induced SOC changes, according to IPCC guidelines (IPCC 2014). It is also consistent with timeframes for attainment of steady state SOC following land management change in New Zealand (Nguyen & Goh 1990; Rosser & Ross 2011).

Post-inversion, SOC in the 0–15 cm layer could, potentially, return to the pre-inversion level. The underpinning assumption here is that low C stocks in the 15–30 cm layer prior to inversion were entirely due to low C inputs. This assumption may be valid in many/most situations as soil physico-chemical characteristics affecting C stabilisation (texture, mineralogy, free Al and Fe, pH) generally do not change greatly with depth.

The maximum potential increase in SOC to 15 cm can be estimated as:

Pre-inversion Soil C stock (0–15 cm) – Post-inversion Soil C stock (0–15 cm)

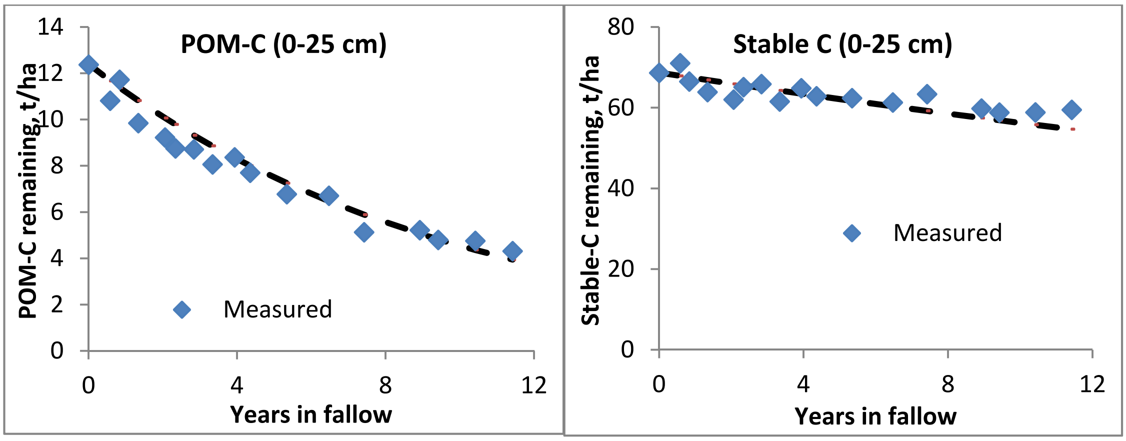

Figure 8. Measured and simulated changes in stable C and POM-C when plots on a Wakanui silt loam (at Lincoln, Canterbury) were maintained plant-free using herbicides (chemical fallow).

The maximum potential increase in SOC (referred to as “100% efficiency scenario”) can be calculated for any soil as long as C stocks in the 0–15 and 15–30 cm layers pre-inversion are known.

We also estimated C stock increases assuming that, in the 20 years after inversion, only 80 or 60% of the maximum potential increase in the 0–15 cm layer was achieved (80 and 60% efficiency scenarios).

The rate at which C will accumulate in the 0–15 cm layer post-inversion cannot be predicted with certainty. IPCC guidelines allow for a linear (i.e. broken stick) rate of C accumulation in the absence of experimental evidence for rates of change. We applied two different accumulation scenarios: a linear, and an asymptotic trajectory. The asymptotic accumulation trajectory includes a lag phase with no increase in C for some time after inversion (C inputs may be low while the new pasture is establishing; tillage disturbance may cause some loss of soil C). Thereafter, C accumulation is likely to increase rapidly, before slowing as the new steady state nears. Our asymptotic curve is in reasonable agreement with the C accumulation pattern following pasture establishment on a low-C arable soil at Winchmore (Nguyen & Goh 1990).

3.2.3 Scaling C stock changes across New Zealand land areas

Based on a geographic information system (GIS) overlay, the land area of high-producing grassland (as mapped 1 January 2008) for each of New Zealand’s 15 soil Orders was estimated (Dr Andrew Manderson, personal communication) (Table 3). These estimates were then modified as described below:

- Land areas were reduced by 30% to provide area estimates for HPG on flat land (70% of grasslands occur on slopes <20 degrees). This area reduction was applied equally across all soil Orders, however we acknowledge the vast majority of hill country is likely to be under low-producing grasslands rather than HPG. Thus our estimates of the SOC increases following modelled FIT are likely to be conservative.
- Land areas were then reduced further by applying a ‘farmer adoption’ factor. This factor in effect reduced the area of HPG on flat land to 5, 10, and 20% of their original areas. Land areas based on 5% farmer adoption refer to 184,000 ha or 3% of mineral soils under HPG. Farmer adoption rates of 10 and 20% refer to land areas of 367,000 ha (6 %) and 734,000 ha (11%), respectively.

- A pasture renewal rate of 10% per year was applied. This assumes that farmers are renewing different pastures each year, thereby ultimately renewing all of their pastures over a 10-year timeframe. As such, there is a cumulative effect, where each year includes added SOC that has been caused by pasture renewal occurring in previous years, resulting in total SOC increases from inversion tillage occurring 30 years following the first paddock subjected to this management.
- The land areas (ha) were then multiplied by the estimated change in SOC stocks (t/ha) following simulated FIT. This was completed for the Allophanic, Brown, Gley, Pallic and Recent soils Orders, which account for 80% of the total area of HPG on mineral soils.
- Land areas which could be considered too stony for deep inversion tillage were not explicitly removed from calculations. We however propose that these areas would have been discounted via the land area reductions associated with the low farmer adoption levels presented.

3.2.4 Calculation of New Zealand's methane and nitrous oxide emissions

New Zealand's annual agricultural CH_4 and N_2O emissions for the period between 1990–2013 have been tabulated in Appendix I according to the Ministry for the Environment (2015).
We added calculations of these emissions with respect to emissions in 1990. Thus, for each gas expressed in units of Mt CO_2-equivalents and Mt C-eq (Mt C-eq = (12/44) x Mt CO_2-eq), we calculated the difference between the emissions in a given year and those in 1990. In total, for the years 1991–2013 inclusive, CH_4 emissions above the 1990 level (emissions base) were 12.7 Mt C-eq, while the N_2O emissions were 7.3 Mt C-eq greater. Consequently, soils would need to sequester 20.0 Mt C (=12.7 + 7.3 Mt C-eq) to offset all emissions above the 1990 level. Alternatively, sequestering 4.5 Mt C would offset the additional (above 1990 levels) agricultural CH_4 and N_2O emissions for the five years between 2008 and 2012. Finally, sequestering 1.1 Mt C would offset the additional (above 1990 levels) emissions from 2013 alone.

Table 3. Estimated land areas under high producing grasslands by soil Order for non-organic soils. Areas are rounded to the nearest 1000 ha.

Soil Order	Land area (ha)	Area with slope <20 degrees (ha)
Allophanic	406,000	284,000
Anthropic	1,000	1,000
Brown	2,651,000	1,856,000
Gley	304,000	213,000
Granular	85,000	59,000
Melanic	110,000	77,000
Oxidic	13,000	9,000
Pallic	1,103,000	772,000
Podzols	393,000	275,000
Pumice	273,000	191,000
Raw	136,000	95,000
Recent	783,000	548,000
Semi-arid	71,000	50,000
Ultic	202,000	142,000
Total	6,530,000	4,570,000

4 PREDICTED C STOCK CHANGE WITH INVERSION

Predictions of SOC change following full soil inversion are reported on a t/ha basis (section 5.1), and are scaled across New Zealand HPG land areas (section 5.2). Predictions of SOC change following inversion to 30 cm are based on C stocks from the LMI database. Predictions based on full inversion to 45 cm are based on soil C stocks data from the NSDrs dataset.

As noted above, several scenarios are reported including effects of different SOC accumulation efficiencies (100, 80 and 60% recovery of pre-inversion topsoil C stocks), SOC accumulation trajectories (linear accumulation or asymptotic), levels of farmer adoption of soil inversion (5, 10 and 20%), and depths of inversion tillage (30 and 45 cm).

Figure 9 illustrates one example of how soil C stocks may change in the 20 years after full inversion (to 30 cm) of a Brown soil with (pre-inversion) C stocks of 64 and 35 t C ha^{-1} in 0–15 and 15–30 cm layers, respectively. In this example, it was assumed that after 20 years C stocks in the top 15 cm would fully recover to the pre-inversion level. Carbon loss from the 15–30 cm layer will offset part of C gain in the topsoil, but there is a net increase in C stock to 30 cm of 14 t/ha. The timing of the C gain will vary depending on whether a linear (A) or asymptotic (B) rate of C increase in the 0–15 cm layer is assumed. Regardless of the accumulation trajectory, the net position at 20 years after inversion is comparable.

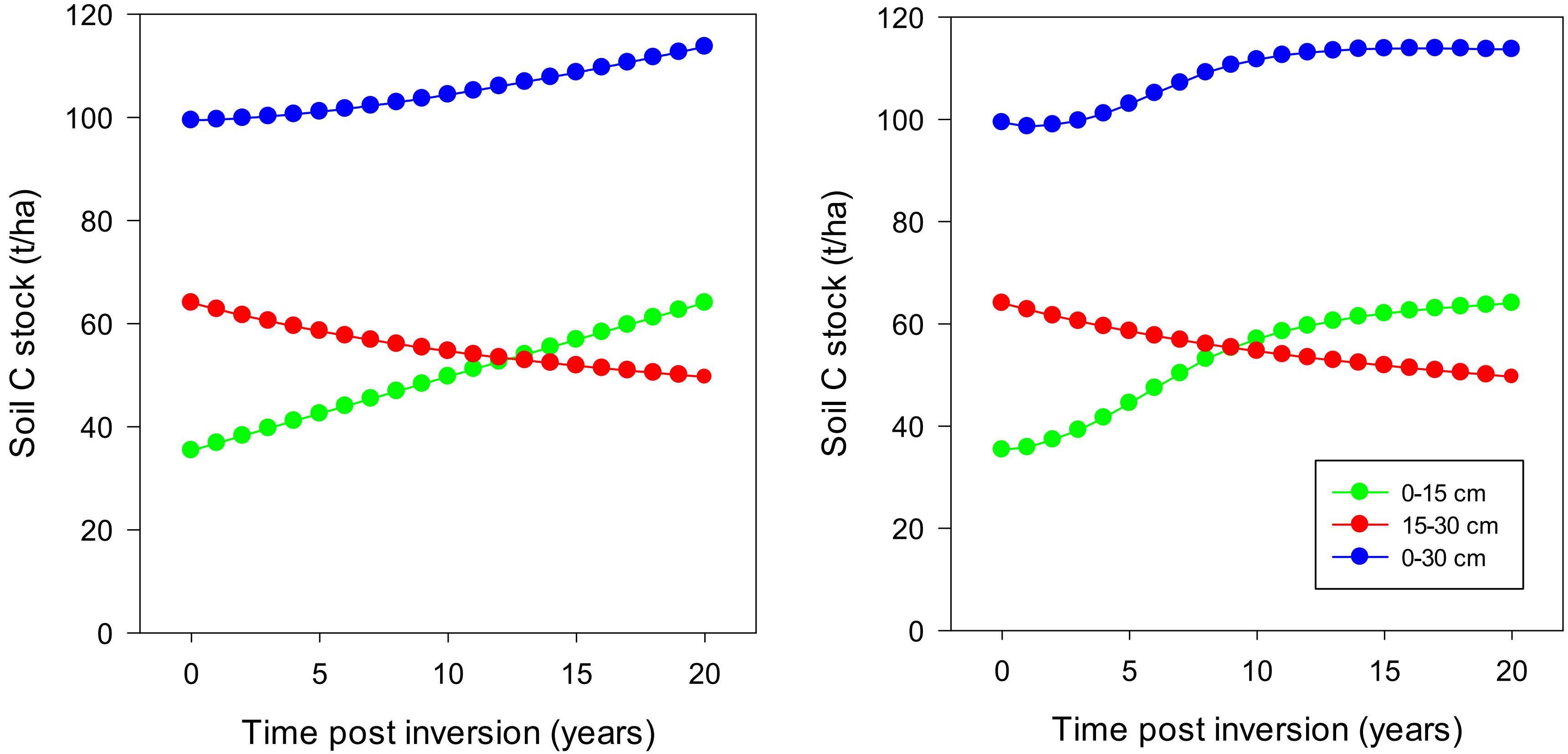

Figure 9. Estimated soil organic carbon (SOC) stock change following soil inversion (30 cm) for the Brown soil where accumulation efficiency is 100% and the accumulation of 0–15 cm SOC is calculated using a linear (left) and asymptotic (right) accumulation function.

4.1 Predictions of SOC change following inversion (t/ha)

Our model predicts an additional 12 to 16 t C/ha could be stored in the 20 years after a one-off soil inversion event (to 30 cm) if topsoil (0–15 cm) SOC stocks were to return to pre-inversion levels (i.e. 100% accumulation efficiency) (Table 4). This represents a stock increase of ~12–16% above pre-inversion levels depending on soil Order. If Allophanic soils under HPG have SOC stocks of 165 t/ha as suggested by the NSDrs dataset, then these soils may be able to store an additional 24 t C/ha following inversion (i.e. ~8 t/ha more than predicted for Allophanic soils using the LMI database).

However in the absence of any direct experimental evidence to support these predictions, we recommend a more conservative approach. As such, we propose SOC stocks following inversion may only recover to ~80% of the pre-inversion levels within the 20-year timeframe applied. Predictions of SOC change for an accumulation efficiency of 80% suggest net C stocks following soil inversion will increase by ~7–10 t/ha dependent on soil Order. This would require a mean annual soil C stock increase of 1.7 t/ha, or peak C stock accumulation rates of 2.5–3 t/ha/yr in years 5–10 post-inversion (i.e. based on an asymptotic model).

If topsoil SOC stocks return to only 60% of the total pre-inversion level, the effect of soil inversion on C stocks would be greatly reduced; total stock changes after 20 years are predicted to be <3 t/ha greater than pre-inversion stocks. Given the considerable spatial variability of SOC, increases of this size may not be measureable at a paddock scale.

If soil inversion tillage is undertaken to a depth of 45 cm, the predicted effect on SOC stocks (if measured to 45 cm and compared to shallower non-inversion tillage) would be greater (Table 5). After inversion of pasture to 45 cm, we predict, assuming that within 20 years topsoil SOC stocks would return to 80% of pre-inversion levels, SOC would increase by ~15–25 t/ha (dependent on soil order) or around 20% above pre-inversion levels. While these predictions are encouraging, inverting soil to this depth may present increased barriers to successful pasture production, including greater risk of nutrient leaching (see section 5). Furthermore, to achieve these net soil C stock increases, sequestration rates of ~5 t C/ha/yr would be required for several years, or an average of 3 t/ha/yr over the 20 years. While sequestration rates of these magnitudes have been reported (Machmuller et al. 2015; Thomas et al. 2007) they are certainly ambitious.

Our model predicts soil C stocks could increase by ~6–10 t C/ha following soil inversion to 45 cm if accumulation efficiency was only 60%.

Table 4. Hypothetical increases to soil C stock (tonnes/ha to 30 cm) following inversion, when C is accumulated using an asymptotic accumulation model.

			Soil C stock change at 5, 10, 15 and 20 years post inversion			
			----------------------------t/ha----------------------------			
Soil Order	Accumulation efficiency	Pre Inversion C stock[a] (t/ha)	5	10	15	20
Allophanic	1	135	1.5	10.9	15.6	16.4 (+12% [b])
	0.8		-0.2[c]	6.5	9.5	9.6 (+7%)
	0.6		-1.8	2.0	3.4	2.8 (+2%)
Allophanic (NSDrs)	1	165	2.5	16.2	22.9	24.2 (+15%)
	0.8		0.2	9.8	14.2	14.5 (+9%)
	0.6		-2.2	3.4	5.5	4.8 (+3%)
Brown	1	99	1.5	9.6	13.6	14.3 (+14%)
	0.8		0.1	5.8	8.4	8.5 (+9%)
	0.6		-1.3	2.0	3.2	2.8 (+3%)
Gley	1	102	1.3	9.2	13.0	13.7 (+13%)
	0.8		0.0	5.5	8.0	8.1 (+8%)
	0.6		-1.4	1.8	3.0	2.6 (+2%)
Pallic	1	99	1.1	8.2	11.7	12.3 (+13%)
	0.8		-0.1	4.9	7.1	7.3 (+7%)
	0.6		-1.3	1.5	2.6	2.2 +2%)
Recent	1	79	1.4	8.7	12.3	12.9 (+16%)
	0.8		0.2	5.3	7.7	7.8 (+10%)
	0.6		-1.0	2.0	3.1	2.7 (+3%)

[a] All pre-inversion carbon stock values are from the Land Management Index data set (Lawrence-Smith et al. 2010b) except for Allophanic (NSDrs) values which are from Schipper et al. (2007, 2010).

[b] Values in parenthesis are % change relative to pre-inversion stocks.

[c] Negative numbers indicate a net loss of soil organic carbon (SOC) compared to pre inversion SOC stocks.

Table 5. Hypothetical increases to soil C stock (tonnes/ha) following inversion to 45 cm, when C is accumulated using an asymptotic accumulation model. Soil organic carbon (SOC) stock data from National Soils Database resampling dataset (Schipper et al. 2007, 2010).

			Soil C stock change at 5, 10, 15 and 20 years post inversion			
			---------------------------t/ha---------------------------			
Soil Order	Accumulation efficiency	Pre Inversion C stock (t/ha)	5	10	15	20
Allophanic (n=29)	1	196	5.7	27.9	38.8	40.8 (+30% [a])
	0.8		2.1	18.0	25.2	25.7 (+19%)
	0.6		-1.6[b]	8.0	11.7	10.6 (+8%)
Brown (n=17)	1	131	4.1	19.7	27.3	28.7 (+32%)
	0.8		1.5	12.7	17.8	18.2 (+20%)
	0.6		-1.0	5.8	8.4	7.6 (+9%)
Gley (n=25)	1	106	4.3	20.1	27.8	29.2 (+37%)
	0.8		1.7	13.1	18.2	18.6 (+24%)
	0.6		-0.9	6.0	8.7	8.0 (+10%)
Pallic (n=60)	1	112	3.4	16.5	22.9	24.1 (+31%)
	0.8		1.3	10.7	15.0	15.2 (+20%)
	0.6		-0.9	4.8	7.0	6.4 (+8%)
Recent (n=16)	1	106	3.4	16.2	22.4	23.5 (+32%)
	0.8		1.3	10.4	14.6	14.9 (+20%)
	0.6		-0.8	4.7	6.8	6.3 (+8%)

[a] Values in parenthesis are % change relative to pre-inversion stocks.

[b] Negative numbers indicate a net loss of SOC compared to pre inversion SOC stocks.

4.2 Estimates of SOC gain following inversion (t/ha) scaled across New Zealand

Predicted SOC stock changes (t/ha) following soil inversion were scaled up for different levels of farmer adoption. Farmer adoption rates (5, 10, 20%) refer to the proportion of grassland that will be renewed by inversion cultivation. Predictions for 5% farmer adoption refer to 184,000 ha or 3% of mineral soils under HPG. Farmer adoption rates of 10 and 20% refer to land areas of 367,000 ha (6 %) and 734,000 ha (11%) respectively.

Predicted net SOC stock change following inversion tillage to 30 cm is reported for the following scenarios:

- Scenario 1: accumulation efficiency = 100%, farmer adoption = 10%, pasture renewal rate = 10%/year.
- Scenario 2: accumulation efficiency = 80%, farmer adoption = 10%, pasture renewal rate = 10%/year.
- Scenario 3: as for scenario 1, except with 5% farmer adoption.
- Scenario 4: as for scenario 1, except with 20% farmer adoption.

Inversion tillage of HPG to 30 cm has the potential to offset a significant proportion of New Zealand's Methane and Nitrous Oxide emissions since 1990. Nationally, an increase in SOC stocks of between 2.5 and 10 Mt C is predicted, depending on which of the four scenarios is considered. Net C stock change was negative for all scenarios at year 1 (Table 6, Table 7, Table 8, and Table 9). However, due to the cumulative effect of pasture renewal and an asymptotic C accumulation trajectory, while only ~20% of the total gain in soil C is realised at 10 years, >90 % of the total gain is realised by 20 years.

Our calculations predict 5.1 Mt C could be sequestered following soil inversion to 30 cm where soil C stocks are returned to 100% of the pre-inversion level, farmer adoption is 10% and 10% of pastures are renewed each year until all pastures had been renewed. However, in the absence of any quantitative data, we propose a cautious approach, where topsoil C stocks may return to only 80% of the pre-inversion level. Under this scenario, our calculations predict net C sequestration of 3 Mt may be achievable from employing soil inversion tillage to renew pastures across 367,000 ha. This represents a significant opportunity to mitigate greenhouse gas emissions; 1.09 Mt C would offset New Zealand's annual methane and nitrous oxide emissions above the 1990 base in 2013, while 4.5 Mt C of sequestered C would offset emissions for the five years 2008–2012 above the 1990 level.

Table 6. Predicted SOC stock change (kilotonnes, kt = 1000 t) following inversion tillage. Specified model parameters were: accumulation efficiency = 100%, accumulation rate = asymptotic, farmer adoption = 10% of the available land area, and 10% of pastures are renewed each year until the entire farm area has been subjected to soil inversion. Total values include data for Allophanic soils from the Land Management Index data set only.

	Soil C stock[a] changes (kt) at 1, 10, 20 and 30 years post soil inversion			
Soil order	**1**	**10**	**20**	**30**
Allophanic	-3[a]	98	431	466
Allophanic (NSDrs)	-4	151	634	686
Brown	-15	582	2,450	2,649
Gley	-2	63	269	291
Pallic	-6	201	879	952
Recent	-4	159	654	707
Total	-29	1,102	4,683	5,066

[a] Underpinning soil C stock data are from the Land Management Index data set (Lawrence-Smith et al. 2010b) except for Allophanic (NSDrs) values which are from Schipper et al. (2007, 2010).

Table 7. Predicted SOC stock change (kilotonnes) following inversion tillage. Specified model parameters were: accumulation efficiency = 80%, accumulation rate is asymptotic, farmer adoption is 10% of the available land area, and 10% of pastures are renewed each year until the entire farm area has been subjected to soil inversion. Total values include data for Allophanic soils from the Land Management Index data set only.

	Soil C stock[a] changes (kt) at 1, 10, 20 and 30 years post soil inversion			
Soil order	**1**	**10**	**20**	**30**
Allophanic (LMI)	-3	38	259	274
Allophanic (NSDrs)	-4	67	389	411
Brown	-16	253	1,500	1,584
Gley	-2	26	164	173
Pallic	-6	81	530	560
Recent	-4	73	405	428
Total	-32	472	2,858	3,019

[a] Underpinning soil C stock data are from the Land Management Index data set (Lawrence-Smith et al. 2010b) except for Allophanic (NSDrs) values which are from Schipper et al. (2007, 2010).

Table 8. Predicted SOC stock change (kilotonnes) following inversion tillage. Specified model parameters were: accumulation efficiency = 100%, accumulation rate is asymptotic, farmer adoption is 5% of the available land area, and 10% of pastures are renewed each year until the entire farm area has been subjected to soil inversion. Total values include data for Allophanic soils from the Land Management Index data set only.

	Soil C stock[a] changes (kt) at 1, 10, 20 and 30 years post soil inversion			
Soil order	1	10	20	30
Allophanic (LMI)	-1	49	215	233
Allophanic (NSDrs)	-2	76	317	343
Brown	-7	290	1,225	1,325
Gley	-1	31	135	146
Pallic	-3	101	440	476
Recent	-2	80	327	353
Total	-14	550	2,341	2,533

[a] Underpinning soil C stock data are from the Land Management Index data set (Lawrence-Smith et al. 2010b) except for Allophanic (NSDrs) values which are from Schipper et al. (2007, 2010).

Table 9. Predicted SOC stock change (kilotonnes) following inversion tillage. Specified model parameters were: accumulation efficiency = 100%, accumulation rate is asymptotic, farmer adoption is 20% of the available land area, and 10% of pastures are renewed each year until the entire farm area has been subjected to soil inversion. Total values include data for Allophanic soils from the Land Management Index data set only.

	Soil C stock[a] increase achieved at each time step (year) post implementation of soil inversion (kt)			
Soil order	1	10	20	30
Allophanic (LMI)	-6	196	861	933
Allophanic (NSDrs)	-8	302	1,268	1,372
Brown	-29	1,161	4,899	5,299
Gley	-3	125	538	582
Pallic	-11	402	1,759	1,904
Recent	-7	318	1,308	1,414
Total	-57	2,203	9,365	10,131

[a] Underpinning soil C stock data are from the Land Management Index data set (Lawrence-Smith et al. 2010b) except for Allophanic (NSDrs) values which are from Schipper et al. (2007, 2010).

5 OTHER PRACTICAL, ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

There are several important practical issues that will need to be considered in applying FIT to enhance soil C storage during pasture renewal. Based on the scenarios outlined above, we estimate that applying a relatively shallow depth of FIT (30 cm) could have a large effect on New Zealand's soil C stocks and offset a large proportion of the agricultural greenhouse gas emissions above 1990 levels. Full inversion tillage to a depth of 30 cm is easily within the practical limits of conventional mouldboard ploughs and modern tractors. On average the cost to FIT is about $395/ha, which is composed of $145/ha for ploughing and $250/ha for secondary cultivation and drilling. This compares to about $135/ha for direct drilling, but does not account for the additional costs of chemical weed control and pesticides that are commonly used under NT management. Compared to direct drilling, FIT may require slightly greater care (i.e. to avoid excessively wet conditions) and time (i.e. to allow soil drying between tillage events) to ensure that optimal conditions are achieved for sowing new pasture. Pasture renewal is commonly undertaken in the autumn when rainfall and soil moisture conditions are less likely to constrain the timing of cultivation and sowing of new pasture. Any additional time required to re-establish pasture with FIT is unlikely have a significant detrimental effects on pasture production.

The use of FIT to renew pastures may also have effects on the soil water storage and drainage, soil structure, nutrient availability and the risk of N losses to the environment, including both from nitrate leaching and N_2O emissions. These potential effects are briefly discussed below.

5.1 Water storage and drainage

Soil organic matter can affect water retention because of its hydrophilic character and its influence on soil structure (Kern 1995). The effect of SOM on plant-available water holding capacity can be significant and may have important implications for improving the water use efficiency of intensive production systems and reducing the reliance on irrigation to supplement rainfall. Plant available water capacity is typically estimated as the difference between water content at -30 and -1500 kPa. It is interesting to note that the benefits of increasing SOM content on plant-available water holding capacity are relatively consistent across a broad range of soil textural classes (Figure 10). The potential benefits of FIT for improving plant-available water capacity would be expected to gradually increase over time (e.g. a 20-year frame) as soil organic matter levels in the topsoil gradually approach pre-inversion levels in the original topsoil. The benefits of FIT would be further enhanced by water retention in the buried topsoil, which is enriched in SOM and assumed to decay at a relatively slow rate. Consequently, FIT would be expected to increase the plant-available water capacity as soil C is sequestered and increase the overall size of the water storage "bucket".

In contrast to the potential benefits of FIT for improving the water holding capacity of soil in the longer term (i.e. as SOM accumulates), inversion tillage is also likely to result in changes to the drainage characteristics of soils, possibly increasing the risk of macropore flow and nitrate leaching. Whereas the SOM buried by FIT may contribute to an increased risk of nitrate leaching during its decomposition, this may be offset by an increased demand for mineral N by the new pasture in the new, SOM depleted topsoil. The extent to which this may encourage the roots from new pasture to scavenge for N (and other nutrients) deeper in the soil profile is not known. It is interesting to note that a New Zealand based study (Fraser et al 2013), which compared the effects of continuous cropping on nitrate leaching losses over a 7-year period, found no significant differences in losses under crops managed with NT and FIT (to 20 cm depth), both in the presence and absence of winter-grazed (sheep) cover crops. Although repeated use of FIT is different to the one-off use of FIT we propose for pasture renewal, we would expect the regular use of FIT to accentuate the effects of tillage relative to continuous NT management.

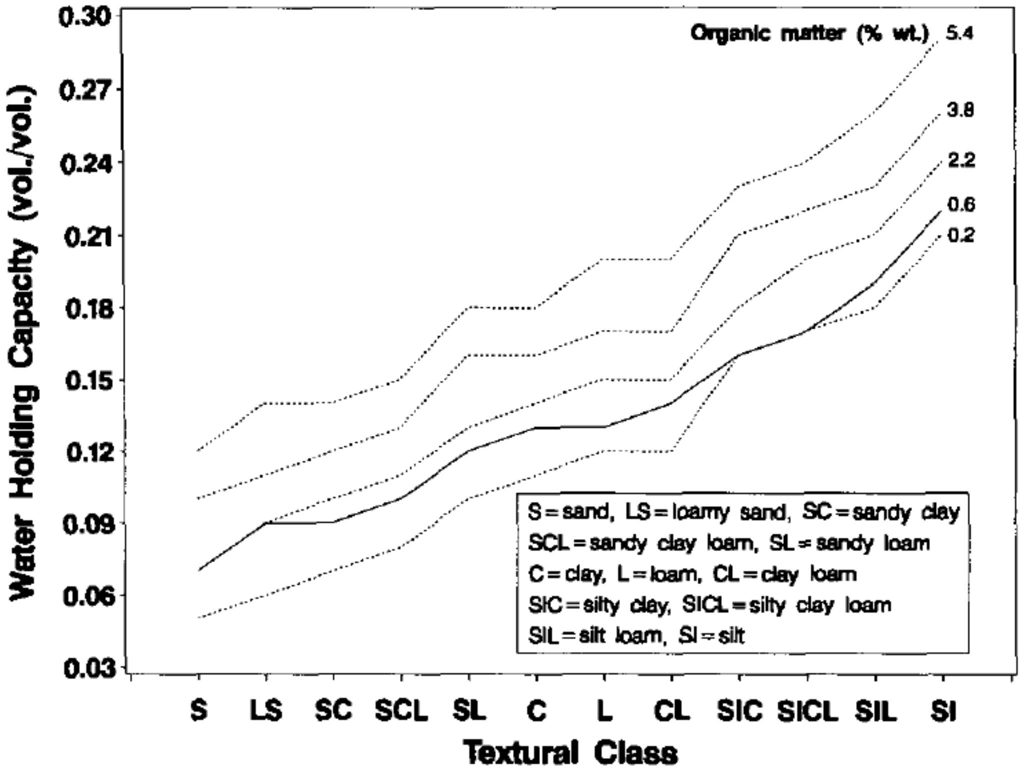

Figure 10. Effect of soil organic matter and texture on water holding capacity, estimated as the difference between water content at -30 and -1500 kPa (Kern 1995).

5.2 Soil structure changes

The use of FIT would result in the placement of relatively unstructured (low C, poor aggregation) subsoil at the soil surface, which creates a new soil surface that may be more susceptible to compaction from stock treading and sediment runoff, due to a lower physical integrity (i.e. less water-stable aggregates with a greater risk of dispersion). Given that FIT to a shallower depth of 20–25 cm is still practised on some soils, both for pasture renewal and for intensive arable and vegetable cropping, it seems unlikely that this will be a major impediment to more widespread adoption of FIT for pasture renewal at a depth of 30 cm. Some additional care may be needed to avoid the adverse effects of stock treading during the early stages of pasture re-establishment, which may include a longer stand-down period prior to imposing the first grazings and avoiding grazing of the new pasture under wet soil conditions. Any field evaluation of FIT for pasture renewal should include an assessment of the risks associated with change in soil physical integrity at the soil surface. This should include potential effects of soil compaction on pasture production and nitrous oxide emissions (Thomas et al. 2008).

5.3 Nutrient availability

In pastures, plant-available P accumulates close to the soil surface because of its low mobility. Inversion cultivation will cause major changes in the vertical distribution of available P by bringing soil with low P content to the surface and burying the P-rich surface soil. Whether this "re-stratification" of soil P will result in decreased availability to pasture plants is not clear. Roots of pasture species are usually particularly abundant near the soil surface. However, it has been shown that roots will proliferate into soil zones that are enriched in P (Drew and Saker, 1978) and it is possible that pasture P acquisition may not be greatly affected by changes in P distribution resulting from inversion tillage (to 30 cm).

We recognise that for each tonne of C stored as SOM, simultaneous sequestration of significant amounts of inorganic nutrients will also be necessary in order to meet the stoichiometric requirements of SOM (Richardson et al. 2014). Consequently, any increases in SOM after inversion tillage will result in some sequestration of P (as organic P). Assuming the C:P ratio of SOM is ~100:1, a soil C increase of 10 t/ha would be matched by about ~100 kg P/ha in organic P, which could require an additional fertiliser P input to offset organic P formation.

It is assumed that pasture production will not be impacted by inversion tillage (relative to alternative tillage methods used for pasture renewal). If this assumption is correct, pasture N *demand* should not change appreciably.

After inversion, most of the mineralisable organic matter will be buried and the N mineralisation rate may change if environmental conditions that affect microbial activity (particularly soil moisture, temperature, and aeration) are less favourable in "subsoil" than in "topsoil". There may also be greater potential for nitrate leaching following deep inversion because (1) mineralisation of N occurs deep in the soil so that the travel distance to move nitrate and dissolved organic N beyond the root zone is relatively small, and (2) low root abundance at depth may result in less efficient plant N acquisition. We know of no studies that have directly addressed this potential adverse effect from using FIT during pasture renewal. However, it should be noted that a shallower form (typically 20–25 cm) of FIT is still practised, in some cases, for pasture renewal and in arable cropping rotations. For reference, the effects of FIT and NT management on nitrate leaching losses under continuous arable cropping in New Zealand are briefly discussed in section 5.1.

As in the case of P, additional N inputs may be required if SOM is increased by inversion tillage. For each 1 t/ha increase in C sequestered in SOM, there will be an increase in soil organic N of about 100 kg/ha of N (C:N ratio of ~10:1). Given the inevitability of some loss of N to the environment, the N requirement per tonne of C sequestered in organic matter would be expected to exceed 100 kg.

These nutrients may be supplied from various sources including from existing soil pools, the application of effluent or manure, N fixation from legume/grass swards, and/or from fertilisers. If all the nutrients were to be met from fertiliser, the estimated cost would be ~$160 per tonne of C. We highlight that this cost is not specific to the practice of FIT, but to all circumstance of SOM accumulation.

A complete life cycle analysis of FIT as it may be applied to pasture renewal is beyond the scope of this review and probably premature, given the assumptions and uncertainties outlined in the discussion above.

5.4 Effects of N fertilisation on N_2O emissions

Any extra input of N required to build the additional soil organic matter (and thereby sequester C) that would follow from the use of FIT would be expected to contribute to some increase in N_2O emissions. Assuming an additional 100 kg of fertiliser N (as urea) would be needed per tonne of C sequestered as a result of inversion (worst-case scenario), we estimated the associated N_2O emissions using emission factors recommended for pastoral soils in New Zealand (Kelliher et al. 2014).The total emissions of N_2O (direct and indirect) were estimated at 0.8 kg per 100 kg of urea-N (Table 11). This translates to a global warming potential (GWP) equivalent to 250 kg of CO_2 or 68 kg CO_2-C (assuming the GWP of N_2O is 298).

This analysis suggests that emissions of N_2O (in CO_2-C equivalents) from any additional fertiliser inputs will be small in relation to amount of C sequestered from FIT. Some additional N_2O emissions may accrue from mineralisation of organic matter in the buried topsoil; however, these are more difficult to predict. Overall, it seems reasonable to suggest that increases in N_2O would offset only a small part of the CO_2 mitigation potential of FIT, however, this needs to be experimentally confirmed.

Table 11. Estimated emissions of N_2O associated with additional urea-N input required to sequester 1 tonne of C in soil organic matter.

N required (kg) (worst-case scenario)	100
Direct emission factor for urea	0.48%
Direct emission of N_2O (kg)	0.75
Fraction of urea that volatilises (as ammonia) and is re-deposited onto soil	10%
Emission factor for volatilised N that is re-deposited	1%
Indirect emissions of N_2O from volatilised/re-deposited ammonia (kg)	0.001
Fraction of urea N leached beyond root zone	7%
N_2O emission factor for leached N	0.75%
N_2O emissions from leached N (kg)	0.08
Total N_20 emissions (kg)	0.84
Global warming potential; CO_2 equivalents (kg CO_2)	250

6 RECOMMENDATIONS FOR FURTHER WORK

Our review has provided evidence that the use of FIT during pasture renewal may represent a significant opportunity to sequester soil C to offset New Zealand's greenhouse emissions. This represents a novel approach to increasing soil C that is based on some assumptions that may not necessarily align with some conventional wisdom (although justified above) and will require careful verification and field validation to ensure the concept is viable and can be applied on farm. We outline below a series of phased research steps that would be needed to verify the concept and demonstrate its potential impact and application to on-farm systems.

In the first phase of the research, we recommend conducting controlled isotope labelling experiments with grass sown on to soil inverted to 30 and 45 cm to quantify the rate of C losses from inverted (buried) topsoil and the rate of C accumulation from new grass grown on surface of inverted (low-C) subsoil. These experiments would include measurements of the fixation (by pasture) and below-ground deposition of C and its transfer into stable and unstable fractions of soil organic matter. These experiments would provide an initial proof-of-concept for the proposed application of FIT to increase soil C storage and stabilisation during pasture renewal. The resulting data would be used to test and adapt an existing soil C model (e.g. Cen-W) to account for the effects of FIT and the stabilisation of C in under-saturated mineral soils.

Simultaneously we recommend conducting short-term small plot trials to determine the optimum rates of fertiliser and water needed to achieve acceptable rates of dry matter production from pastures renewed with FIT to depth of 30 and 45 cm. These trials would include measurements of above- and below-ground dry matter production and rooting depth as well as the storage and supply of plant available water and nutrients. These trials would help to establish the optimum management of pastures established with FIT that would be applied to larger, paddock-scale validation and demonstration trials.

In second phase of the research we recommend conducting a multi-year field trial to quantify the effects of FIT on soil C stocks following renewal of permanent high-producing pasture on a suitable soil. Given the longer time frames needed to achieve the projected increases in SOC, field validation of the concept would be best conducted by comparing the net ecosystem fluxes of C from pastures renewed with FIT and direct drilling (NT) to those of undisturbed, continuous pasture. This would be achieved by combining measurements of net C exchange using eddy co-variance methods with data on other potential C input (e.g. supplementary feed) and export pathways (e.g. leaching of dissolved organic C). In addition to standard measurements of pasture performance, these large paddock-scale experiments should also include measurement of pasture water use efficiency, nitrate leaching and N_2O emissions (among others) to account for any potential benefits or unintended consequences of pasture renewal with FIT. These data would also be used to parameterise and validate the modelled projection of soil C stock change as a result of different pasture renewal practices, including FIT.

If the above research is successful in providing evidence to verify the concept, then we would recommend establishing paddock-scale trials on pastoral farms (dairy and drystock) on different soils and in different climate regions across New Zealand to demonstrate the approach and monitor the longer-term effects of pasture renewal with FIT on soil C stocks and pasture performance relative to permanent pasture and/or pasture renewed with direct drilling.

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APPENDIX I: ANNUAL METHANE AND NITROUS OXIDE EMISSIONS FOR NEW ZEALAND BETWEEN 1990 AND 2013

Table 12. New Zealand annual Methane and Nitrous Oxide emissions between 1990 and 2013 (Adapted from Ministry for the Environment, 2015).

	Methane			Nitrous Oxide		
Year	Emissions (with CH_4 from LULUCF) CO_2 equivalent, kt	Annual emissions above 1990 levels (CO_2 equivalent, kt)	Annual emissions above 1990 levels (C equivalent, kt)	Emissions (with N_2O from LULUCF) CO_2 equivalent, kt	Annual emissions above 1990 levels (CO_2 equivalent, kt)	Annual emissions above 1990 levels (C equivalent, kt)
1990	33,381	-	-	7,471	-	-
1991	33,600	219	60	7,537	66	18
1992	33,288	-93	-25	7,488	17	5
1993	33,404	23	6	7,665	194	53
1994	34,070	689	188	7,948	477	130
1995	34,393	1,012	276	8,155	684	186
1996	35,088	1,708	466	8,250	780	213
1997	35,781	2,400	655	8,419	948	259
1998	35,000	1,619	442	8,256	785	214
1999	35,370	1,989	542	8,291	820	224
2000	36,305	2,924	797	8,647	1,176	321
2001	36,484	3,103	846	8,876	1,405	383
2002	36,431	3,050	832	9,089	1,618	441
2003	36,655	3,274	893	9,312	1,842	502
2004	36,609	3,229	881	9,347	1,876	512
2005	36,970	3,590	979	9,452	1,982	540

Year	Methane			Nitrous Oxide		
	Emissions (with CH_4 from LULUCF) CO_2 equivalent, kt	Annual emissions above 1990 levels (CO_2 equivalent, kt)	Annual emissions above 1990 levels (C equivalent, kt)	Emissions (with N_2O from LULUCF) CO_2 equivalent, kt	Annual emissions above 1990 levels (CO_2 equivalent, kt)	Annual emissions above 1990 levels (C equivalent, kt)
2006	37,095	3,714	1,013	9,376	1,905	519
2007	35,833	2,452	669	8,959	1,488	406
2008	34,647	1,266	345	8,774	1,303	355
2009	35,190	1,809	493	8,699	1,228	335
2010	35,158	1,777	485	8,840	1,369	373
2011	35,308	1,927	526	9,005	1,534	418
2012	35,862	2,481	677	9,202	1,731	472
2013	35,688	2,307	629	9,182	1,712	467
Total	847,610	46,469	12,673	206,239	26,939	7,347

C accumulation required to ‘offset’ all Methane and Nitrous Oxide emissions above 1990 levels for the period between 1991 and 2013 is estimated at 20,020 kt.

C accumulation required to ‘offset’ all Methane and Nitrous Oxide emissions above 1990 levels for the period between 2008 and 2012 is estimated at 4480 kt.

C accumulation required to ‘offset’ all Methane and Nitrous Oxide emissions above 1990 levels for 2013 is estimated at 1096 kt.

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