Lawrence-Smith, E.J., et al. 2020. The potential for full inversion tillage pasture renewal to build soil carbon in permanent pastures. In: *Nutrient Management in Farmed Landscapes.* (Eds. C.L. Christensen, D.J. Horne and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand. 7 pages.

THE POTENTIAL FOR FULL INVERSION TILLAGE RENEWAL TO BUILD SOIL CARBON IN PERMANENT PASTURES

EJ Lawrence-Smith[1], D Curtin[1], MH Beare[1], SR McNally[1], FM Kelliher[2], R Calvelo Pereira[3], MJ Hedley[3]

[1] New Zealand Institute for Plant and Food Research Limited, Canterbury Agriculture and Science Centre, Private Bag 4704, Christchurch 8140, New Zealand
[2] Retired, Formerly AgResearch, Lincoln, New Zealand
[3] Environmental Sciences Group, School of Agriculture & Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand

Abstract
This paper outlines a methodology and the first national estimates of the soil carbon (C) sequestration potential of full inversion tillage (FIT) pasture renewal in New Zealand.

Soils under long term permanent pastures have large topsoil C stocks. As such, the scope to accumulate additional C in surface soil is limited. However, because C in pastoral soils declines with depth, there may be potential for subsoil to sequester additional C. Grazed pastures in New Zealand often require periodic renewal (re-seeding following shallow cultivation) to maintain productivity.

To derive the first national estimates of the soil C sequestration potential of FIT pasture renewal in New Zealand, we conducted a case study using soil C data obtained from 247 continuously grazed pasture sites (five major soil Orders representing ~80% of the country's improved grassland area), a soil C accumulation and decomposition model and a geographic overlay of land use, slope and soils information.

On average, prior to FIT the C concentration in the 0–15 cm layer across all soil Orders was 1.8 to 2.0 times that in the 15–30 cm layer, with the 0–15 cm layer containing around 25–30 t ha^{-1} more C. Predicted changes in C stocks following (hypothetical) FIT pasture renewal were considered to be driven by: 1) accumulation of C in the new 0–15 cm layer (inverted subsoil), and 2) decomposition of C in the new 15–30 cm layer. Decomposition was estimated using a two-pool model with decay rate constants (k) of 0.1 y^{-1} for particulate organic C and 0.02 y^{-1} for stable C. In the 20 years following FIT pasture renewal, the stock of soil C was estimated to increase on average by between 12 (Pallic and Recent soils) and 16 t ha^{-1} (Allophanic soils), assuming that C in the surface 15 cm recovered to pre-FIT concentration. Nationally, adoption of FIT for pasture renewal on all ploughable land currently under high producing grasslands could potentially induce soil C sequestration of 36 Mt over 20 years.

Introduction
Global atmospheric concentrations of greenhouse gases are steadily increasing. Soil C sequestration is considered a promising mitigation option to help offset these emissions (Lal, 2004).

New Zealand pastures, dominated by ryegrass and white clover swards, tend to have ~80% of their root mass in the upper 15 cm of the soil profile (Crush et al. 2005). As such, these soils tend to have high topsoil C stocks, which decline rapidly with depth (Kelliher et al., 2012, Schipper et al., 2007) (Figure 1). A recent review on management practices that may increase soil C stocks in New Zealand (NZ) pastoral soils, identified deeper rooting pasture species, biochar incorporation, and manipulation of the soil profile (i.e. FIT) as promising options (Whitehead et al. 2018).

Our aim was to estimate the potential for FIT to sequester C in NZ soils. We hypothesised that FIT would increase C storage by (1) exposing under-saturated subsoil to large inputs of C (i.e., roots, exudates, excreta), and (2) burying C-rich surface soil deeper in the soil profile may slow its decomposition. To achieve our aim, we conducted a case study using soil C data obtained from 247 continuously grazed pasture sites (five major soil Orders representing ~80% of the country's improved grassland area), developed a soil C accumulation and decomposition model and utilised geographic overlays of land use, slope and soils information.

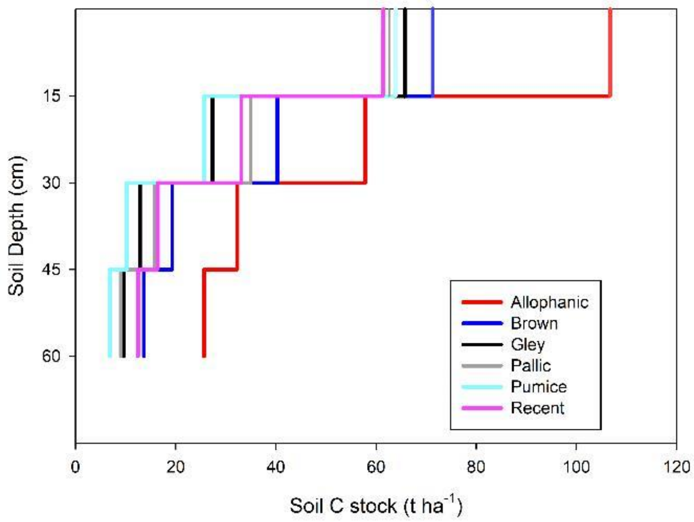

Figure 1. Soil carbon stocks by depth for New Zealand soils. Adapted from Schipper et al. 2010.

Methods

Soil organic carbon stocks and vertical stratification

Soil C stocks and stratification in New Zealand pastoral soils were assessed using a dataset comprised of measurements from 247 long-term pasture sites, representing five soil Orders (Table 1). Within each paddock, samples were collected from two depths (0–15 and 15–30 cm) and analysed to determine soil C content, and bulk density.

Estimating C change following soil inversion

The effect of a one-time FIT event (0–30 cm) on soil C stocks was modelled for each of the 247 paddocks. To estimate how C stocks may change in the 20- year period post inversion, the plough layer (0–30 cm) was divided into two sub-layers (0–15 cm and 15–30 cm depth intervals). We assumed that changes in C stocks would be driven by: 1) accumulation of C in the new 0–15 cm layer, and 2) decomposition of C in the 15–30 cm layer.

C accumulation in the 0–15 cm layer post inversion

Our assumptions were: (1) Soil C in the uppermost 15 cm would reach a new steady state within 20 years of FIT based on the IPCC guideline (IPCC 1997) for attainment of steady state soil C following a change in land management, (2) the maximum C stock achievable in the new surface soil would be the same as that in the pre-inversion surface soil, (3) the rate of soil C accumulation with time is linear, (4) that other nutrients that could influence C cycling were ignored, and (5) any pasture renewal undertaken within 20-years of FIT would not disturb soil below the upper 15 cm.

The maximum potential increase in soil C to 15 cm was estimated as: Pre-inversion soil C stock (0–15 cm) - Post-inversion soil C stock (0–15cm).

C decomposition in the 15–30 cm layer post inversion
Our assumptions were: (1) inputs from pasture production following FIT would be sufficient to maintain pre-FIT soil C stock, (2) decomposition of additional C (that above the pre-FIT soil C stock) can be predicted using a two-pool model with decay rate constants (k) of 0.1 y^{-1} for particulate organic C (labile C) and 0.02 y^{-1} for stable C (Skjemstad et al. 2004; Coleman & Jenkinson, 2014). For example, if the C stock in the 15–30 cm layer increases from 40 to 60 t ha^{-1} when the soil is inverted, the additional 20 t ha^{-1} will not be sustainable and will gradually decrease over time (eventually to a minimum of 40 t ha^{-1}). Prior to, or on reaching the minimum subsoil C stock FIT could be repeated.

Scaling C stock changes across New Zealand
To generate a national estimate of the C sequestration potential following FIT, we estimated the area of ploughable land in each of the five soil orders (Table 1) equivalent to NZ's total land area under high producing exotic grassland from Land Cover Database v 4.1, 2012 land cover time step (Landcare Research NZ Ltd, 2015), with Land Use Capability (LUC) classes 1–3 and slope class A, B or C (i.e. slope of less than 15 degrees) (Landcare Research Ltd, 2010a). These LUC classes were selected as they are considered suitable for grazed pastures and FIT (Lynn et al. 2009), i.e., deep, ploughable soils. These data layers were overlaid with soil Order information obtained from the '*Fundamental soil layer'* database (Landcare Research Ltd, 2010b). Mean net soil C change (0–30 cm) for each Order was multiplied by the ploughable land area, and summed to generate the national estimate.

Table 1. Numbers of long-term pasture sites sampled and ploughable land areas (ha) as estimated from geographic overlays for each soil Order.

Soil Order	Numbers of sites	Ploughable land area (ha)
Allophanic	66	386,000
Brown	34	646,000
Gley	51	518,000
Pallic	64	682,000
Recent	32	397,000

Results & Discussion
Mean C stocks (0–30 cm), ranged between 80 and 135 t ha^{-1} depending on soil Order (Figure 2). Soil C concentration in the uppermost 15 cm of long-term pasture soils was 1.8 to 2.0 times that in the 15–30 cm layer, with the 0–15 cm layer containing about 25–30 t ha^{-1} more C.

Figure 3 shows predicted C changes in C stocks for a hypothetical soil in the 20 years following FIT. For this example, the mean pre-inversion soil C stocks for Brown soils were applied, 65 and 34 t C ha^{-1} for the 0–15 cm and 15–30 cm depths, respectively. Immediately following simulated FIT, the 0–15 cm C stock decreased from 65 to 34 t ha^{-1}. Thus, manipulation of the soil profile via FIT creates the opportunity for 31 t C ha^{-1} to be accumulated in the new topsoil (mean accumulation rate of 1.4 t ha yr^{-1} over the 20 year model simulation). We assume this gain can be realised within a 20 year timeframe, in line with the IPCC guidelines for attainment of steady state soil C following a change in land management (IPCC, 1997). Immediately following FIT, C stocks in the 15–30 cm layer increase from 34 to 65 t ha^{-1}. As per our assumptions, the original 34 t C ha^{-1} can be maintained by inputs of C from the new pasture, while the additional 31 t C ha^{-1} deposited in this layer will decay at a rate dependent on the proportions of particulate and stable C. Twenty years following FIT, we estimate ~85% of the particulate organic carbon added to this depth will have decomposed, as would ~30% of the stable C. Thus, of the additional 31 t C ha^{-1} in the 15–30 cm layer immediately following FIT, 15–16 t will remain after 20 years. Combining C changes estimated for the two depth increments, the net effect of FIT is a gain of 14 t C ha^{-1} (0–30 cm).

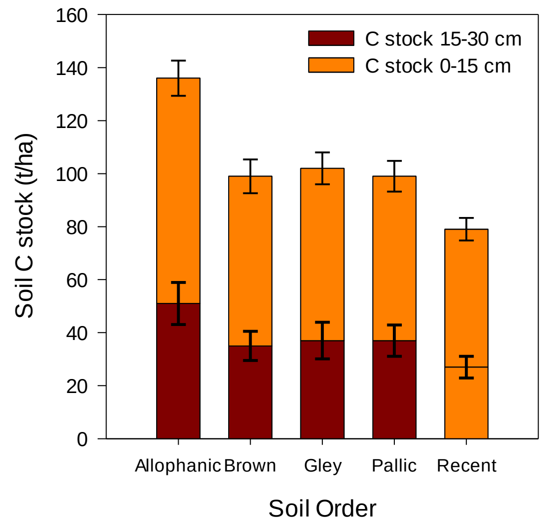

Figure 2. Mean soil carbon stocks in New Zealand's high producing grasslands (n=247). Bars represent +/- one standard deviation from the mean.

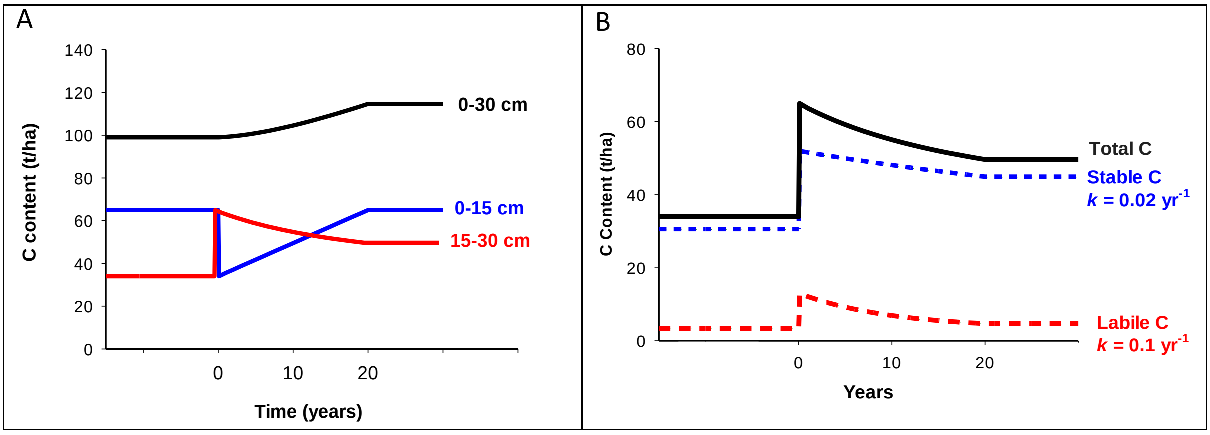

Figure 3. Predicted changes in C stocks in the 0–15 and 15–30 cm layers in 20 years following full inversion tillage (at time point zero) for a hypothetical soil with initial C stocks of 65 and 34 t ha^{-1}, in the 0-15 and 15-30 cm depths, respectively (A); and decay of C added to the 15–30 cm increment (i.e., previous topsoil) by proportion of stable and labile C.

For the pastoral soils dataset (n=247), estimates of net soil C change ranged from -10 t C ha^{-1} to +41 t C ha^{-1} (Figure 4); both extremes of this range occurring in Allophanic soil. Eighty percent of paddocks had a net soil C change ranging between +6 and +22 t C ha^{-1}. Mean net change in soil C varied with soil Order, with average increases of between 12 (Pallic and Recent soils) and 16 t ha^{-1} (Allophanic soils). The greatest absolute increase in soil C stocks (per hectare) was predicted for Allophanic soils; however, the highest proportional increases relative to pre-inversion stocks were predicted for Recent soils. A net loss of C was predicted for a small number of sites with little or no soil C stratification with depth pre-inversion.

Nationally, adoption of FIT for pasture renewal on ploughable grasslands (2.6 million ha) was estimated to induce soil C sequestration by 36 Mt over 20 years (Table 2). During those 20 years it would offset approximately 17% of the total accumulated emissions (39 t CO_2e /y over 20 years) from NZ agriculture. Thus, this potential management strategy to sequester soil C warrants further investigation.

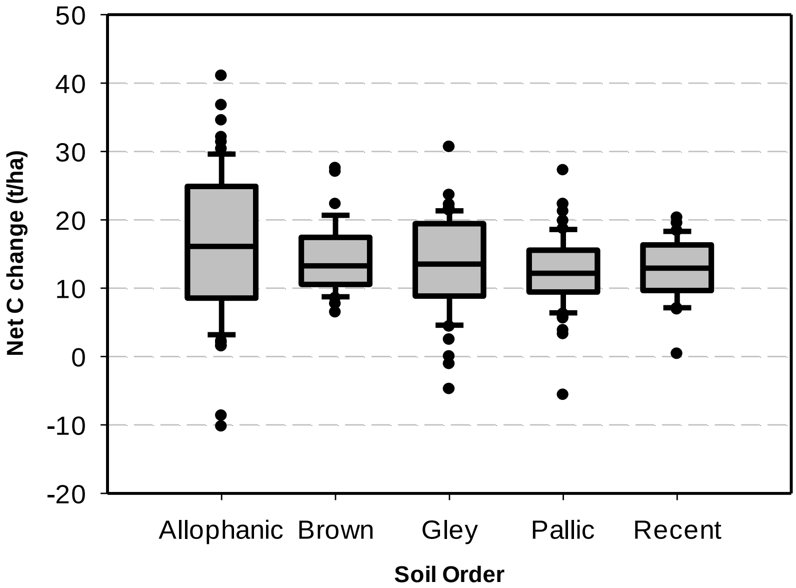

Figure 4. Predicted net soil C change (0–30 cm) for 247 pasture soils, representing five soil orders, 20 years after full inversion tillage (to 30 cm). Boxes represent the middle 50% of values, with whiskers showing the 10th and 90th percentiles.

Table 2. Estimates of net C sequestration 20 years following pasture renewal with full inversion tillage (to 30 cm) on ploughable high-producing grasslands in five soil orders.

Soil Order	Net gain (t C)
Allophanic	6,325,000
Brown	9,243,000
Gley	7,095,000
Pallic	8,385,000
Recent	5,120,000
Total	**36,168,000**

The potential of FIT to sequester C relies on the rate of accumulation in new topsoil occurring faster than the decomposition of the buried topsoil. There is considerable uncertainty regarding the time needed for topsoil C stocks to return to pre-inversion levels. Future estimates of net C change, should consider scenarios where topsoil C stocks do not fully recover to the pre-inversion level. This paper also highlights that significant depth-stratification of C is essential to achieve net soil C gain from FIT; further research is required to develop soil suitability guidelines that address the conditions in which the practice is likely to have the greatest benefit. Additionally, other factors, such as interactions between soils and seasonal climate (e.g. a narrow window of opportunity for tillage, limited by soil moisture conditions, or susceptibility of the seedbed to erosion by wind and intense rain), may limit the area suitable for implementation of FIT pasture renewal for C sequestration. The results of field trials that are investigating the agronomic and environmental benefits and trade-offs of FIT pasture renewal are given by Beare et al. (2020), Calvelo-Pereira et al. (2020) and McNally et al. (2020).

Acknowledgements

Funded by the New Zealand Government to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases and Plant & Food Research – Sustainable Agroecosystems Programme (SSIF).

References

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

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

Coleman K, Jenkinson DS 2014. RothC—A Model for the Turnover of Carbon in Soils. Model Description and User Guide. Rothamsted Research, Harpenden, UK. https://www.rothamsted.ac.uk/sites/default/files/RothC_guide_WIN.pdf

Crush JR, Waller JE, Care DA 2005. Root distribution and nitrate interception in eleven temperate forage grasses. Grass and Forage Science 60: 385-392.

IPCC 1997. IPCC Guidelines for National Greenhouse Gas Inventories Workbook

Kelliher FM, Condron LM, Cook FJ, Black A 2012. Sixty years of seasonal irrigation affects carbon storage in soils beneath pasture grazed by sheep. Agriculture Ecosystems & Environment 148: 29–36.

Lal R, 2004. Carbon emission from farm operations. Environment International 30(7): 981–990.

Landcare Research NZ Ltd 2015. Land Cover Database version 4.1, Mainland New Zealand. Accessed 13 September 2019. lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/ doi:10.7931/L17H3

Landcare Research NZ Ltd 2010. LZLRI Land Use Capability. Accessed 13 September 2019. lris.scinfo.org.nz/layer/48076-nzlri-land-use-capability/

Landcare Research NZ Ltd 2010. LZLRI FSL New Zealand Soil Classification. Accessed 13 September 2019. lris.scinfo.org.nz/layer/ 48079-fsl-new-zealand-soil-classification/ doi:10.7931/L10T0

Lynn IH, Manderson AK, Page MJ, Harmsworth GR, Eyles GO, Douglas GB, Mackay AD, Newsome PJF 2009. Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land 3rd ed. Hamilton, AgResearch; Lincoln, Landcare Research; Lower Hutt, GNS Science. 163p.

McNally SR, Van der Klei G, Calvelo Pereira R, Thomas S, Beare MH, Hedley MJ 2020. Nitrous oxide emissions from fertiliser and urine following full inversion tillage autumn pasture renewal. In: *Nutrient Management in Farmed Landscapes*. (Eds. C.L. Christensen, D.J. Horne and R. Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 33. Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand.

Schipper LA, Baisden WT, Parfitt RL, Ross C, Claydon JJ, Arnold G 2007. Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. Global Change Biology 13: 1138-1144.

Schipper LA, Parfitt RL, Ross C, Baisden WT, Claydon JJ, Fraser S 2010. Grains and losses in C and N stocks of New Zealand pasture soils depend on land use. Agriculture, Ecosystems and Environment 139:611-617.

Skjemstad JO, Spouncer LR, Cowie B, Swift RS 2004. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. Australian Journal of Soil Research 42(1): 79–88.

Whitehead D, Schipper LA, Pronger J, Moinet GYK, Mudge PL, Calvelo Pereira R, Kirschbaum MUF, McNally SR, Beare MH, Camps-Arbestain M 2018. Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. Agriculture, Ecosystems and Environment 265: 432-443. doi:https://doi.org/10.1016/j.agee.2018.06.022