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Comparing deep soil organic carbon stocks under kiwifruit and pasture land uses in New Zealand

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ABSTRACT

Soil organic carbon (SOC) is important natural capital for agricultural production, as it affects soil physical, chemical and biological functions and the provision of ecosystem services. Measures of land-use effects on SOC stocks generally focus on the top 0.3 m of soil, as the topsoil has the highest SOC concentration. However, while subsoil horizons have low SOC concentrations, they contain a greater absolute amount of SOC with longer mean residence times than topsoil layers. Perennial horticultural crops offer potential to store SOC deep in the soil profile because of their long-lived and deep rooting systems. To investigate the hypothesis that kiwifruit (*Actinidia chinensis* Planch.) can increase subsoil SOC stocks, we sampled soils from 19 paired kiwifruit and pasture sites in New Zealand in 2018. Pasture was selected for comparison as it was the antecedent land use before establishment of the kiwifruit orchards. Paired land uses were located within 100 m of each other on the same soil type. Kiwifruit vines were at least 15 years old and the pasture was not cultivated during that time. Total SOC and nitrogen (N), and labile soil SOC stocks were assessed to a depth of 2 m. Kiwifruit production resulted in a modest increase in SOC and N stocks at a depth of 1.5–2.0 m (1.6 Mg C ha^{-1} and 0.52 Mg N ha^{-1}), averaging to increases of 0.06 Mg C ha^{-1} y^{-1} and 0.02 Mg N ha^{-1} y^{-1}. However, cumulative SOC and N stocks to 2-m depth were not different between land uses. The labile water extractable pools of SOC were lower under kiwifruit in the topsoil (0–0.1 m) and corresponded with lower N stocks and a higher soil C:N ratio at this depth. Further work on the dynamics of subsoil SOC pools is needed to understand the contribution of perennial horticulture crops to subsoil SOC storage.

1. Introduction

Soil organic carbon (SOC) is important natural capital for agricultural production, as it affects soil physical, chemical and biological functions and the provision of ecosystem services. As the largest terrestrial pool of organic carbon (C) (Batjes, 1996), SOC is also important in the global C cycle. While subsoil horizons have low SOC concentrations, more than half of the global SOC stocks are located below 0.3 m (Balesdent et al., 2018; Batjes, 1996; Jobbágy and Jackson, 2000). Furthermore, subsoil SOC stocks are characterised by high radiocarbon age and longer turnover times (Balesdent et al., 2018; Rumpel and Kögel-Knabner, 2011; Schrumpf et al., 2013).

Subsoil SOC stocks may be increased by increasing C inputs to subsoil layers and/or decreasing the rate of subsoil SOC mineralisation. Subsoil C inputs include plant roots and root exudates, incorporation of surface litter, and transport of dissolved or particulate organic C from surface layers (Kaiser and Kalbitz, 2012; Ota et al., 2013; Rumpel and Kögel-Knabner, 2011). Root inputs are thought to be the dominant source of C in subsoils due to the similarity of depth distributions between roots and SOC profiles (Jobbágy and Jackson, 2000) and the preferential stabilisation of root C in soil (Kong and Six, 2010; Rasse et al., 2005). Thus increasing subsoil root C inputs is proposed as a potential strategy for greenhouse gas mitigation and SOC storage (Paustian et al., 2016).

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Perennial horticulture crops have potential to increase subsoil SOC stocks because they develop and maintain deep rooting systems, and stand undisturbed for decades (Li et al., 2019; Scandellari et al., 2016). In New Zealand, perennial horticulture systems predominantly maintain permanent vegetative understory along the alleyways (e.g., mixed grass sward) and are small-scale, intensively managed systems. Kiwifruit (*Actinidia chinensis* Planch.) production covers more than 12,000 ha in New Zealand (New Zealand Horticulture, 2018). Deurer et al. (2010) conducted an initial experiment to assess the rate of SOC storage under kiwifruit production, by comparing SOC stocks to 1-m depth in adjacent 10- and 25-year-old orchard blocks. The 25-year-old block had 6 Mg C ha^{-1} more soil SOC, with the difference occurring at the 0.5–1 m depth, equating to a storage rate of 0.4 Mg C ha^{-1} y^{-1} in the top 1 m of soil. A second single paired-site comparison sampling down to 9-m depth found 6.3 Mg C ha^{-1} y^{-1} more SOC under a 30-year-old kiwifruit orchard than the adjacent pasture (Holmes et al., 2015).

Water extractable C is a dynamic and important bioavailable SOC fraction as microbial C uptake requires an aqueous environment (Kemmitt et al., 2008; Marschner and Kalbitz, 2003). The solubility of SOC fractions increases exponentially with temperature (Chantigny et al., 2012; Curtin et al., 2011), and two operational pools of water extractable C are often measured: cold (room temperature, 20 °C) water extractable C (CWEC), which is proxy measurement for in-situ dissolved organic C (Zsolnay, 2003), and hot (80 °C) water extractable C (HWEC). HWEC has been found to be well correlated with soil microbial biomass and mineralisable nitrogen (N), and is a sensitive indicator of land use and management impacts on biological activity and soil fertility (Ghani et al., 2003; Leinweber et al., 1995; Sparling et al., 1998). It is the SOC fraction that explained most of the change in decadal losses of SOC in New Zealand pasture soils (Lambie et al., 2019), and thus may be an indicator of SOC changes in the soil profile with perennial horticulture management.

To investigate the hypothesis that kiwifruit production can increase subsoil SOC stocks, we sampled soils from multiple paired sites of kiwifruit production and pasture land use in the Bay of Plenty and Waikato regions of New Zealand. We measured total SOC and N stocks to 2-m depth and pools of labile water extractable C as sensitive indicators of change through the soil profile. Pasture was selected for comparison as it was the antecedent land use before kiwifruit production, and allows for a space-for-time analysis of the effect of kiwifruit production. An underlying assumption of this approach is that both sites in a pair had similar soil properties and SOC stocks before kiwifruit production began.

2. Materials and methods

2.1. Site selection

We sampled soils under kiwifruit and pasture land uses at 19 paired sites in the Waikato and western Bay of Plenty regions of New Zealand (Fig. 1). Before locating sites an ad hoc power analysis was completed to estimate the number of paired sites needed to detect a difference in soil C stocks (Kravchenko and Robertson, 2011). The power analysis assumed that a paired site sampling approach would have similar variability to the kiwifruit SOC stock assessment by Holmes et al. (2012), and we estimated a change in SOC stock of 1.2 Mg C ha^{-1} y^{-1} to 2-m depth based on the preliminary findings of Deurer et al. (2010) and Holmes et al. (2015). We determined that sampling of 18 paired sites would be needed to detect a difference in SOC of 18 Mg C ha^{-1}, 80 % of the time at $P < 0.05$. We targeted a selection of 20 pairs and successfully sampled 19 paired sites.

Criteria for the paired site selection was that the land uses were as follows: (i) adjacent to each other with sampling sites within 100 m of each other, (ii) sampling sites had the same soil type according to S-map (Manaaki Whenua - Landcare Research, 2019), (iii) kiwifruit blocks were at least 15 years old, and (iv) the pasture had no cultivation during period since kiwifruit establishment. Further, during field sampling, field texturing was used to confirm soil profiles of each paired land use were comparable in texture.

Suitable paired sites were identified by local knowledge from industry contacts and horticulture consultants. The western Bay of Plenty region is the main kiwifruit growing region in New Zealand and is characterised by deep, well drained allophanic and buried-allophanic pumice soils according to the New Zealand soil classification (Hewitt, 1998) or Andosols according to the World Reference Base (FAO, 2015).

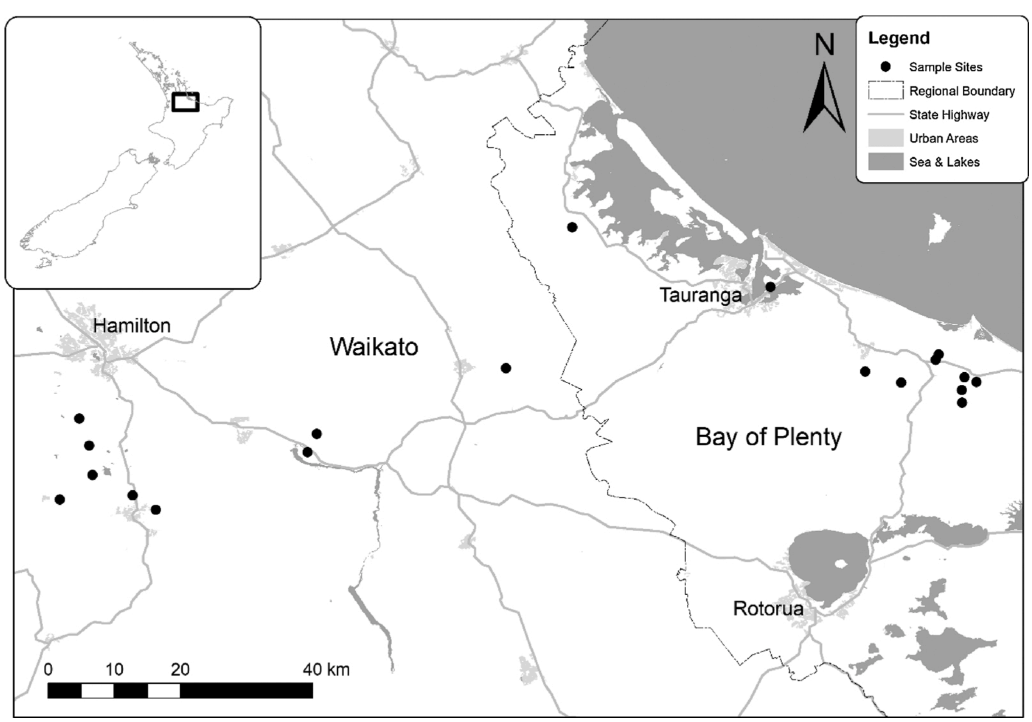

Fig. 1. Location of the 19 paired kiwifruit/pasture sites in the Waikato and Western Bay of Plenty regions of New Zealand.

However, because of the dominance of kiwifruit production it was difficult to locate enough sites of undisturbed pasture in the main growing region. Therefore, the Waikato region was included. In this region deep, well drained allophanic soil (Hewitt, 1998) or Andosols (FAO, 2015) predominate with SOC stocks to 1 m depth similar to the Bay of Plenty region (Holmes et al., 2012). We located 10 paired sites in the Bay of Plenty and nine sites in the Waikato regions. Soil texture profiles for the sites included silt, loam and clay and pH of the topsoil (0–0.1 m) ranged from 6.1 to 7.1 (Manaaki Whenua - Landcare Research, 2019). Information on kiwifruit orchard age, cultivar grown and main use of pasture were collected from the growers at the time of sampling (Table 1).

2.2. *Soil sampling*

Soil samples were collected between June and September 2018 during the winter period. At each paired site, the two selected sampling areas were located within 100 m of each other and at least 15 m away from any boundary such as a hedgerow or fence line. The soil sampling scheme was based on the protocol developed by Holmes et al. (2012) to assess SOC stocks in kiwifruit orchards. Soil samples were collected from eight points within each land use.

In the kiwifruit orchards, we sampled the allocated area around one female kiwifruit vine (Fig. 2). Four sampling points were located along the vine row, half-way between the selected vine and the neighbouring vines in the north and south directions, and half-way again between the selected vine and these mid-way points. Four corresponding sampling points were collected from the middle of the alleyways beside the selected vine alternating between the eastern and western alleyway as we sampled from north to south. The kiwifruit orchards had varying planting densities and patterns and the spacing of the eight sampling points varied with each orchard to accommodate the sampling design. Row spacing ranged from 2 to 5.5 m and vine spacing ranged from 2 to 6 m. In the pasture land use, a simplified sampling pattern was used where two parallel rows of four sampling points were located in a grid pattern with 2 m spacing running in a north to south direction (Fig. 2).

At each of the sampling locations, an intact soil core sample was collected to determine both bulk density and SOC concentration. To sample the top 1 m of soil, a motorised drill soil corer as described by Périé (2015) was used to collect a core with a diameter of 0.0512 m. Beyond this depth, a 0.025-m diameter manual soil sampler was used to collect core samples to a depth of 2 m where possible. At some sites the high soil moisture prohibited the collection of soil samples to 2 m. Soil core samples from each sampling point were divided into depth increments of 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, 0.7–1.0, 1.0–1.5, and 1.5–2.0 m. Soil core samples from each of the eight sampling points within a paired-site land use were bulked per soil depth increment. The total soil collected was weighed and mixed, and a subsample was removed and bagged for analysis.

2.3. *Soil analyses and calculations*

A 40-g portion of each subsample was oven-dried at 105 °C to calculate the gravimetric soil moisture content. The remaining soil was air-dried and sieved through a 2-mm sieve. Soil samples were analysed for total C and N concentrations with a LECO TruMac CN analyser (LECO Corporation, St. Joseph, Michigan, USA). The total C concentrations measured were taken to be equivalent to the SOC concentrations in the samples as the contribution from carbonates is negligible in these soils (Blakemore et al., 1987). Cold and hot water extractable C were measured according to Ghani et al. (2003). In brief, 3 g of soil was extracted with 30 mL of cold water, shaken for 30 min, centrifuged, decanted and filtered for the cold water extract. A second 30-mL aliquot of water was then added and samples incubated at 80 °C for 16 h before also being centrifuged, decanted and filtered for the hot water extract. Total organic C concentration in the extracts was measured on a Shimadzu TOC-V_{CSH} analyser (Shimadzu Corporation, Kyoto, Japan).

The mass of soil collected for each depth increment was corrected for the soil moisture content and converted to Mg dry soil ha^{-1} to a given depth using the area sampled by the corer and the number of cores collected. The stocks of SOC and N were calculated from the measured C and N concentrations and soil masses. To compare stocks between land uses and paired sites, SOC and N stocks were calculated on an equivalent soil mass according to Wendt and Hauser (2013) using a cubic spline fitted curve to estimate cumulative SOC masses. The reference soil masses used per depth increment were the mean soil masses of all sites sampled.

Table 1
Region, maximum sampling depth, soil characteristics, orchard age, land use and climate data for each paired site. Soil characteristics are from S-Map (Manaaki Whenua - Landcare Research, 2019). Climate data are annual normals (30-year averages for 1981–2010) from the nearest National Climate Database station (NIWA, 2019).

Region	Sampling depth (m)	Soil order[a]	Soil texture	pH topsoil	Kiwifruit orchard age (years)	Kiwifruit cultivar	Pasture use	MAT (°C)	MAP (mm)
Waikato	1.5	Allophanic	Clay	6.4	25	'Hayward'	Dairy	13.6	1322
Waikato	1.5	Allophanic	Clay	6.3	30	'Hayward'	Dairy	13.6	1322
Waikato	1.5	Allophanic	Clay	7.1	18	'Zesy002'	Dairy/ drystock	13.6	1322
Waikato	1.0	Allophanic	Clay	6.9	20	'Hayward'	Drystock	13.6	1322
Waikato	1.5	Allophanic	Clay	6.6	15	'Hayward'	Drystock	13.6	1322
Waikato	1.5	Allophanic	Clay	6.9	39	'Hayward'	Drystock	13.6	1168
Waikato	2.0	Allophanic	Silt	6.6	38	'Zesy002'	Drystock	13.3	1273
Waikato	1.5	Allophanic	Loam	6.4	18	'Hayward'	Drystock	13.3	1273
Waikato	2.0	Allophanic	Loam	6.5	20	'Hayward'	Dairy	13.3	2078
Bay of Plenty	1.5	Allophanic	Loam	6.8	38	'Hayward'	Dairy	14.9	2078
Bay of Plenty	2.0	Recent	Loam	6.6	35	'Zesy002'	Drystock	14.9	1189
Bay of Plenty	2.0	Pumice	Loam	6.8	30	'Hayward'	Dairy	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.8	40	'Hayward'	Dairy	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.9	18	'Zesy002'	Dairy	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.7	30	'Hayward'	Drystock	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.1	37	'Hayward'	Drystock	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.9	20	'Zesy002'	Dairy	14.0	1642
Bay of Plenty	2.0	Pumice	Loam	6.5	18	'Hayward'	Dairy	14.0	1642
Bay of Plenty	2.0	Allophanic	Loam	6.3	33	various	Drystock	14.0	1642

MAT, mean annual temperature; MAP, mean annual precipitation.
[a] New Zealand soil classification (Hewitt, 1998).

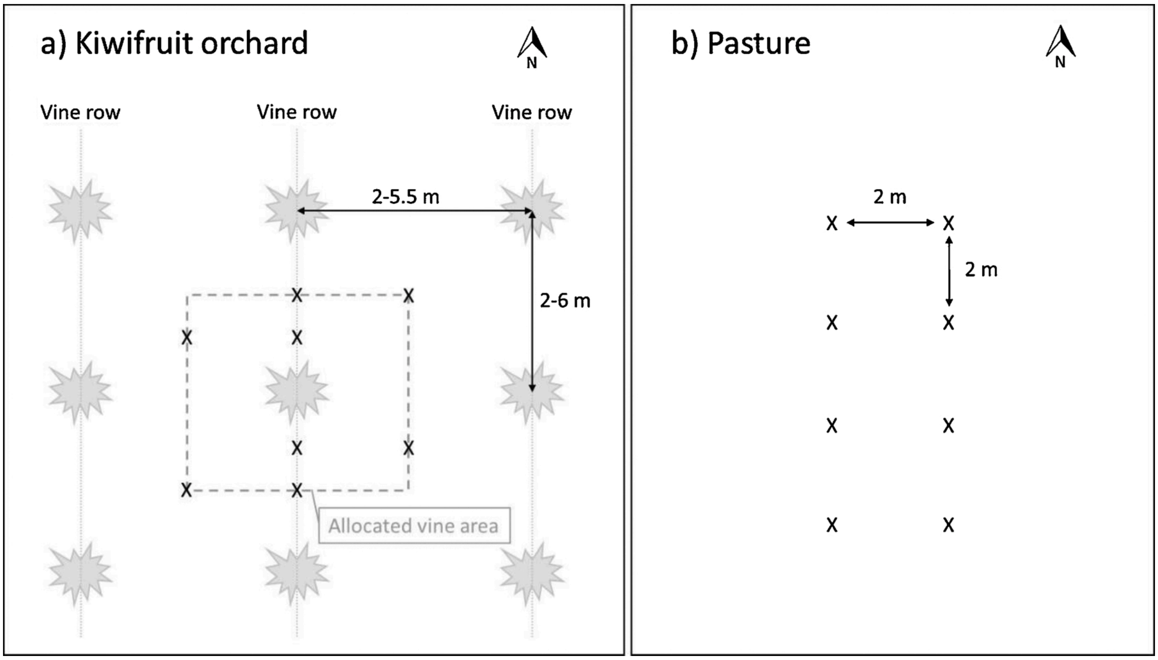

Fig. 2. Schematic of the soil sample positions (X) in a) a kiwifruit orchard, and b) a pasture.

2.4. Statistical analyses

Data for SOC and N stocks were analysed by individual depth increments using analysis of variance (ANOVA) in Genstat version 17.1 (VSN International Ltd., Hemel Hempstead, UK) with land use as the treatment factor and paired site as the blocking factor. Regression analysis was used to test the relationships between the change in stocks (difference of kiwifruit minus pasture) and kiwifruit orchard age and long-term annual average climatic variables. Results are reported as significant at $P < 0.05$.

3. Results

3.1. Total C and N stocks

The mean cumulative SOC stock of the kiwifruit orchards and pasture was 169 and 168 Mg C ha^{-1} down to 2-m depth, respectively. There were no significant differences between the land uses in cumulative SOC stocks throughout the profile sampled. However, SOC stocks in the 1.5–2.0 m depth were significantly greater under kiwifruit than pasture with a mean difference of 1.6 Mg C ha^{-1} (Table 2). There were no significant differences in SOC stocks between kiwifruit and pasture land uses in any of the other depth increments.

Mean cumulative soil N stocks were 15.5 and 15.9 Mg N ha^{-1} to 2.0-m depth for the kiwifruit and pasture land uses, respectively. There were no significant differences between the cumulative soil N stocks beyond the topsoil layer for the land uses. Soil N stocks in the 0–0.1 m topsoil layer were significantly greater under pasture than kiwifruit with a mean difference of 0.52 Mg N ha^{-1} (Table 2). Conversely, soil N stocks in the 1.5–2.0 m depth were significantly greater under kiwifruit than pasture with a mean difference of 0.17 Mg N ha^{-1}.

The C:N ratio of the soil stocks was significantly lower under pasture than kiwifruit for the 0–0.1 m topsoil layer, but was not significantly different between the land uses at any of the other depths in the soil profile.

There were no significant relationships between the differences in SOC and N stocks and kiwifruit orchard age for any of the sampled depth increments including 1.5–2.0 m (Fig. 3). Similarly, there were no significant relationships between differences in SOC and N stocks and mean annual temperature or mean annual precipitation of the paired sites (data not shown).

3.2. Labile C stocks

CWEC represented only 0.4–0.9 % of the SOC stocks. The mean cumulative soil CWEC stocks were 1.00 and 1.04 Mg C ha^{-1} for the kiwifruit and pasture land uses, respectively. CWEC stocks in the 0–0.1 m topsoil layer were significantly greater under pasture than kiwifruit with a mean difference of 0.052 Mg C ha^{-1} (Table 3). Land use did not have a significant effect on CWEC stocks at any other depth. Cumulative

Table 2
Mean soil carbon and nitrogen stocks by depth under paired kiwifruit and pasture land uses to 2-m depth.

			Carbon stocks (Mg ha^{-1})				Nitrogen stocks (Mg ha^{-1})				C:N ratio		
Depth (m)	Reference soil mass (t ha^{-1})	Paired sites	Kiwifruit	Pasture	Change in stock[a]	P	Kiwifruit	Pasture	Change in stock	P	Kiwifruit	Pasture	P
0.0–0.1	0–834	19	52.9	55.7	−2.8	0.216	4.92	5.45	−0.52	**0.015**	10.9	10.3	**0.005**
0.1–0.3	834–2590	19	54.6	57.5	−2.9	0.430	5.16	5.33	−0.17	0.598	11.0	11.0	0.981
0.3–0.5	2590–4271	19	23.7	24.7	−1.0	0.714	2.36	2.44	−0.08	0.763	10.2	10.3	0.748
0.5–0.7	4271–6054	19	16.8	15.3	1.5	0.391	1.72	1.52	0.20	0.261	9.9	10.2	0.218
0.7–1.0	6054–8628	19	13.7	13.1	0.6	0.569	1.37	1.25	0.12	0.196	10.1	10.5	0.331
1.0–1.5	8628–12,556	18	16.8	15.4	1.4	0.300	1.60	1.42	0.18	0.158	10.3	10.9	0.109
1.5–2.0	12,556–17,461	11	16.1	14.5	1.6	**0.020**	1.49	1.32	0.17	**0.045**	10.5	10.7	0.469

[a] Change in stock is the difference of kiwifruit minus pasture.

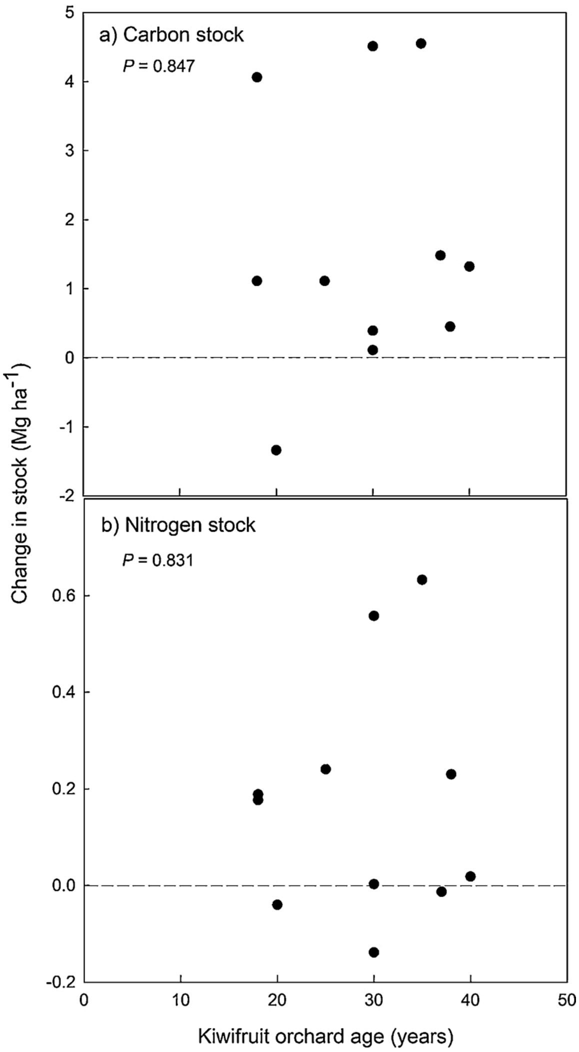

Fig. 3. Change in a) soil carbon stock and b) soil nitrogen stock at a depth of 1.5–2.0 m between kiwifruit and pasture land uses of 11 paired sites as a function of kiwifruit orchard age.

CWEC stocks were greater under pasture than kiwifruit for the top 0.5 m and there was no significant difference between land uses below this depth.

HWEC comprised a larger labile pool of C and accounted for 0.4–3.0 % of the SOC stocks in the different depth increments. Cumulative soil HWEC stocks to 2-m depth were 2.62 and 3.42 Mg C ha^{-1} for the kiwifruit and pasture land uses, respectively. HWEC stocks were significantly lower under kiwifruit than pasture for the depths between 0–0.3 m and 0.7–1.5 m (Table 3).

There were no significant relationships between the differences in CWEC and HWEC stocks between land uses and kiwifruit orchard age for any of the sampled depth increments including 0–0.1 m (Fig. 4). Similarly, there were no significant relationships between differences in labile SOC stocks and climatic variables of the paired sites (data not shown).

4. Discussion

Kiwifruit orchards had significantly greater SOC and N stocks at depth (1.5–2.0 m) than adjacent pasture soils. This supports our hypothesis that kiwifruit production would increase subsoil SOC stocks, though the difference in stocks measured was modest (1.6 Mg C ha^{-1} and 0.52 Mg N ha^{-1}) equating to increases of 11 % and 13 % of observed pasture SOC and N stocks. Using the mean age of the kiwifruit orchards sampled, 27 years, this difference would be an increase of 0.06 Mg C ha^{-1} y^{-1} and 0.02 Mg N ha^{-1} y^{-1}.

Qualitatively, our findings support the results of Deurer et al. (2010) and Holmes et al. (2015) who found kiwifruit production increased subsoil SOC stocks. These previous studies reported larger changes in SOC stock than found in the present study. Deurer et al. (2010) observed an increase of 0.4 Mg C ha^{-1} y^{-1} in subsoil SOC between 0.5 and 1.0 m, and Holmes et al. (2015) measured an increase of 1.4 Mg C ha^{-1} y^{-1} for the 0.5–1.0 m depth and a total of 6.3 Mg C ha^{-1} y^{-1} down to 9-m depth under kiwifruit. This discrepancy in the quantity of SOC change reported is likely because these previous studies each sampled a single pair of sites and do not account for any of the variability in SOC stocks in the region. We re-sampled the paired site of Holmes et al. (2015) in the present soil survey and observed 38 Mg C ha^{-1} greater cumulative SOC stocks to a depth of 1.5 m under kiwifruit than pasture for an increase of 1.0 Mg C ha^{-1} y^{-1} at this specific site, which is comparable with their previous findings. However, our more robust study design with multiple paired sites estimates the variability of land use effects on SOC stocks in the region and increases the accuracy of the estimate of the change in SOC stocks. Additionally, the previous studies used different methodology for SOC determination. Our study used an automatic elemental analyser to measure soil C concentrations (LECO TruMac CN analyser, LECO Corporation, St. Joseph, Michigan, USA); whereas Deurer et al. (2010) and Holmes et al. (2015) used the loss on ignition (LOI) method calibrated to reference soil samples from 0 to 1-m depth analysed by an elemental analyser. The LOI method is dependent on the quality of calibration with another standard method, which will likely vary with changes in organic matter and clay contents with depth in the soil profile (Johns et al., 2015). Indeed, Rahman et al. (2011) showed how the calibration varied across three depth increments down to 1 m, and this surface soil calibration was further used to estimate SOC stocks down to 9-m depth by Holmes et al. (2015).

We would expect that if SOC and N stocks at depth were increasing under kiwifruit because of increased input from deep root growth and deposition that any measured difference in SOC stocks would increase with increasing orchard age. However, there was no relationship between kiwifruit orchard age and the measured increase in SOC and N

Table 3
Mean soil cold water extractable carbon (CWEC) and hot water extractable carbon (HWEC) stocks by depth under paired kiwifruit and pasture land uses to 2-m depth.

Depth (m)	Reference soil mass (t ha^{-1})	Paired sites	CWEC stocks (Mg ha^{-1}) Kiwifruit	Pasture	Change in stock[a]	*P*	HWEC stocks (Mg ha^{-1}) Kiwifruit	Pasture	Change in stock	*P*
0.0–0.1	0–834	19	0.274	0.325	−0.052	**0.004**	1.095	1.616	−0.521	**<.001**
0.1–0.3	834–2590	19	0.220	0.265	−0.045	0.114	0.709	0.896	−0.187	**0.016**
0.3–0.5	2590–4271	19	0.103	0.111	−0.008	0.622	0.217	0.261	−0.044	0.345
0.5–0.7	4271–6054	19	0.063	0.064	−0.001	0.908	0.087	0.120	−0.033	0.115
0.7–1.0	6054–8628	19	0.061	0.064	−0.003	0.636	0.058	0.095	−0.038	**0.028**
1.0–1.5	8628–12,556	18	0.105	0.092	0.013	0.082	0.058	0.101	−0.043	**0.049**
1.5–2.0	12,556–17,461	11	0.131	0.117	0.014	0.187	0.069	0.095	−0.026	0.375

[a] Change in stock is the difference of kiwifruit minus pasture.

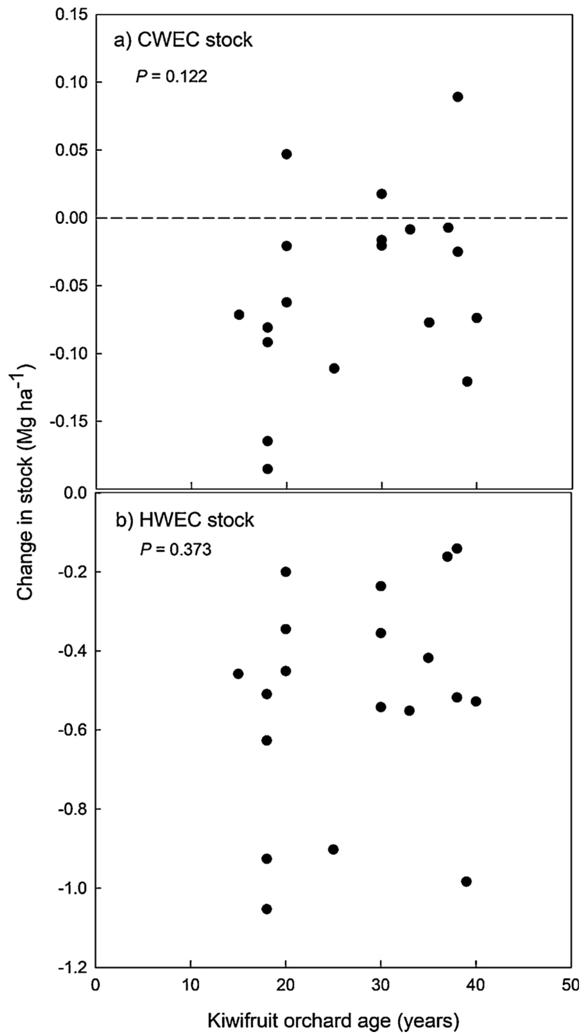

Fig. 4. Change in a) cold water extractable carbon (CWEC) stock and b) hot water extractable carbon (HWEC) stock at a depth of 0–0.1 m between kiwifruit and pasture land uses of 19 paired sites as a function of kiwifruit orchard age.

stocks between kiwifruit and pasture at depth (1.5–2.0 m). A possible explanation may be that kiwifruit vines contribute the greatest C input to subsoil during their initial root exploration, growth and establishment as a young orchard and the maintenance of a more mature orchard root system simply maintains these C stocks. Hughes and Gandar (1989) found the weight of higher turnover fine roots increased in orchards for the first 10 years, while the weight of structural roots continued to increase with increasing orchard age. Root growth is a small sink for C in mature plants, where root growth balances the biomass lost in root turnover (Buwalda, 1993). The youngest orchard sampled in the present study was 15 years old and would have already developed an extensive root system. Repeated sampling over time would be needed to determine if the rate of SOC change under kiwifruit is linear or not.

The measured increase in total SOC and N stocks at depth (1.5–2.0 m) was not great enough to have a significant effect on the cumulative SOC and N stocks measured under kiwifruit and pasture land uses to 2 m. The greater variability of SOC and N stocks in the whole soil profile obscured the difference we detected analysing the soil layers (Kravchenko and Robertson, 2011; Syswerda et al., 2011). We developed the present study to have a robust sampling scheme of 19 paired sites across the Waikato and Bay of Plenty regions based on the changes in SOC stocks reported in the previous single-site studies of Deurer et al. (2010) and Holmes et al. (2015). However, the smaller difference in subsoil SOC stocks measured in the present study may mean that a larger number of paired sites may have been necessary to detect significant differences at additional soil depths or in the whole soil profile, if indeed there was a real difference (Kravchenko and Robertson, 2011).

While we found only a small increase in subsoil SOC and N stocks under kiwifruit, our study is evidence that SOC and N stocks are at least being maintained and are not declining under kiwifruit production in New Zealand. These findings contrast with the Intergovernmental Panel on Climate Change (IPCC) methodology for greenhouse gas inventory accounting (IPCC et al., 2016). In the Tier 2 IPCC accounting, upon the conversion of grassland to perennial cropland there is presumed to be an annual loss of SOC of 0.85 Mg C ha^{-1} y^{-1} over the first 20 years following conversion. However, under kiwifruit production in New Zealand where permanent vegetative cover is maintained in the orchard alleyways there does not appear to be any net loss of SOC upon conversion from pasture. Similarly, Périé (2015) found no change in SOC stocks to 1-m depth over 12 years under apple orchards in the Hawke's Bay region of New Zealand.

Kiwifruit orchards had significantly lower total N stocks and higher C:N ratios in the topsoil (0–0.1 m) than adjacent pasture soils. This lower soil N under horticultural production may come from lower fertiliser inputs and N-fixation, or larger plant uptake and losses of N from the soil. We don't have detailed data on the nutrient management histories or plant composition and yields of the sites sampled. Additional factors than land use, such as grazing management (Schipper et al., 2010) and irrigation (Mudge et al., 2017), can also affect soil N stocks. The observed differences in topsoil C:N ratios may reflect the high C:N ratios of leaf litter and pruning residues under kiwifruit production (Tagliavini and Scandellari, 2007).

In contrast to the measured differences in total SOC stocks, kiwifruit orchards had significantly lower labile SOC stocks (both CWEC and HWEC) in the surface soil (0–0.1 m) than pasture soils. Additionally, lower HWEC stocks were measured further down in the soil profile under kiwifruit than pasture leading to lower cumulative HWEC stocks. HWEC has been found to be a more sensitive indicator of land use change on SOC than CWEC (Ćirić et al., 2016; Ghani et al., 2003; Hamkalo and Bedernichek, 2014), and is correlated with microbial activity and soil nutrient availability (Curtin et al., 2006; Ghani et al., 2003). It was the fraction found to be most strongly correlated with decadal changes in topsoil SOC and N stocks in New Zealand pasture soils (Lambie et al., 2019). The observed lower stocks of labile SOC under kiwifruit correspond to measures of lower total N stocks for the topsoil layer (0–0.1 m) as discussed previously. The extension of lower HWEC stocks in the next soil depth (0.1–0.3 m) may indicate that soil fertility is beginning to change with land management at this depth as well. HWEC concentrations can show large seasonal variation due to microbial population dynamics, root turnover and climatic conditions (Leinweber et al., 1995). Our sampling occurred during the winter period with low soil temperatures when the kiwifruit vines are largely dormant with low root growth rates (Buwalda and Hutton, 1988), and there could be seasonal effects contributing to the land use differences observed in HWEC stocks.

Unlike the difference measured in the topsoil, the lower kiwifruit HWEC stocks further down the soil profile (0.7–1.0 and 1.0–1.5 m) do not correspond to measured changes in total SOC or N stocks. Furthermore, they show the opposite trend to the increase in total SOC stocks measured at the 1.5–2.0 m depth under kiwifruit. We cannot fully explain this discrepancy. While statistically significant, the subsoil decreases in HWEC under kiwifruit measured in our study below 0.7 m were very low (0.038–0.43 Mg C ha^{-1}) and are smaller than the measurement error of these low C concentrations in the subsoil. The use of HWEC as an indicator of SOC change has largely focused on topsoil concentrations and dynamics (Ghani et al., 2003; Lambie et al., 2019; Sparling et al., 1998). The dynamics of subsoil HWEC concentrations to the depth we sampled have not been previously studied, and their relationship to SOC stock changes are unknown. HWEC concentrations decrease rapidly down the soil profile (Ćirić et al., 2016; Hamkalo and

Bedernichek, 2014) and Jinbo et al. (2006) found land use effects on HWEC concentrations occurred only in the topsoil (0–0.2 m). It is difficult to analyse changes in SOC fractions with increasing soil depth due to measurement limitations of detecting low concentrations. The lower HWEC stocks throughout the soil profile under kiwifruit production may also indicate that SOC under kiwifruit is more stable and less vulnerable to mineralisation than SOC stocks under pasture (McNally et al., 2018). It is a bit surprising that no differences in HWEC stock were measured at the 1.5–2.0 m depth where total SOC stocks were greater under kiwifruit than pasture, but this again may be a limitation of low concentrations of HWEC. Further work on the size and dynamics of subsoil SOC pools is needed to explain our observed changes in total SOC and HWEC stocks under kiwifruit.

5. Conclusions

Cumulative SOC and N stocks were similar under kiwifruit and pasture production, indicating that SOC stocks did not change under land use conversion to perennial horticulture. Furthermore, there was a significant increase in SOC and N stocks under kiwifruit production at the 1.5–2.0 m depth of 1.6 Mg C ha^{-1} and 0.52 Mg N ha^{-1}, revealing that kiwifruit may contribute to modest increases in subsoil SOC. Topsoil stocks of soil N and HWEC were lower under kiwifruit production implying reduced N storage and labile SOC. Our robust study design with multiple paired sites provides a more accurate comparison of SOC changes under New Zealand kiwifruit production than previous studies examining single pair differences.

Declaration of Competing Interest

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

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