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Carbon Sequestration in Kiwifruit Orchard Soils at Depth to Mitigate Carbon Emissions

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Management practices designed to increase carbon sequestration via perennial tree crops are potential tools to mitigate the consequences of climate change. Changes in orchard management could enable growers to meet eco-verification market demands for products with a low carbon footprint and potentially exploit the emerging business opportunity in carbon storage, while enhancing the delivery of ecosystem services that depend on soil carbon stocks. However, there is no standard methodology to verify any potential claims of carbon storage by perennial vine crops. We developed a robust methodology to quantify carbon storage in kiwifruit orchards. Soil carbon stocks (SCS) were determined in six depth increments to 1 m deep in two adjacent kiwifruit blocks, which had been established 10 ("young") and 25 ("old") years earlier. We used a space-for-time analysis. Our key results were the young and old kiwifruit block stored about 139 and 145 t C/ha to 1 m depth. Between 80–90 percent of the SCS were stored in the top 0.5 m, and 89–95 percent in the top 0.7 m; there was no significant difference between the SCS in row and alley to a depth of 0.5 m; a CV of 5–15 percent indicates that 4–10 cores are needed for 80 percent confidence in the estimated SCS; we recommend separating each core into the depths 0–0.1, 0.1–0.3, 0.3–0.5, and 0.5–1 m to allow the assessment of SCS dynamics; we detected a weak spatial pattern of the SCS only for the old kiwifruit block with a range of about 3 m. A sampling bay along a vine row should have a maximum length of 3 m. We then assessed SCS in more than sixty kiwifruit orchards throughout New Zealand. They stored on average 174.9 ± 3 t C ha^{-1} to 1 m depth. On average, 51 percent of the SCS down to 1 m depth were stored in the top 0.3 m, which is the standard depth according to the Kyoto protocol. About 72 percent of the SCS to 1 m depth were captured when increasing the sampling depth to 0.5 m. These results underscore the necessity to analyze SCS in an orchard to at least 0.5 m deep. Using the same methodology to 1 m deep, we determined SCS in two wine grape vineyards on shallow, stony alluvial soils. We found a difference between vineyard and adjacent pasture SCS of nearly 16 t/ha. As the vines are 25 years old, this equates to carbon sequestration rates of 640 kg ha^{-1} yr^{-1}. Our results of the space-for-time analysis also showed that all sequestration had occurred below 0.5 m. Therefore, we decided to sample C to a greater depth. In a 30-year old kiwifruit orchard and an adjacent pasture, SCS was measured to 9 m deep. In the kiwifruit orchard, we found a sequestration

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rate of 6.3 tons of C per hectare per year greater than in the adjacent pasture that was the antecedent land use.

Keywords Carbon sequestration, ecosystem services, kiwifruit, Soil Carbon Stock

Introduction

Soil organic carbon (SOC) is critical natural capital for primary producers, providing storage of water and nutrients, encouraging microbial activity, and imparting resilience to the soil in periods of climatic extremes such as drought or high rainfall events, which are more likely given predictions of climate changes. Soil organic carbon is a key indicator of soil health because it plays a role in a number of key functions (Allison 1973; Bationo et al. 2007; Six et al. 2004). Functions of SOC can be divided into three types:

- Biological functions of SOC:
  - provides nutrients and habitat for organisms living in the soil
  - provides energy for biological processes
  - contributes to soil resilience, which is the ability of soil to return to its initial state after a disturbance, for example, after tillage
- Chemical functions of SOC:
  - acts as a store and enhances nutrient retention capacity
  - enhances the mineralization of key nutrients from the soil itself
  - provides resilience against pH change
- Physical functions of SOC:
  - binds soil particles into aggregates improving soil structural stability
  - enhances the water holding capacity of soil
  - moderates changes in soil temperature

Implementing management strategies to maintain or enhance natural SOC levels in soils is crucial for growers. For example, mulches and residues provide sources of carbon (C) that can improve soil functioning and health. An improvement in soil health leads to greater plant productivity and healthier root growth, which in turn will maintain or enhance soil C stock. There is therefore a virtuous circle between the inputs of C in residues and mulches, soil health, plant productivity, and carbon sequestration.

The SOC stock is the biggest ecosystem C reservoir in the world. Estimates for this stock in the top 1 m of soil range from 1500 to 2000 Pg C (Batjes 1996; IPCC 2007). Carbon storage potential of subsoil below 1 m deep was approximated to be between 760 and 1520 Pg C based on estimates of the C pool between 1 and 3 m and maximum rooting depths (Lorenz and Lal 2005). The major pools of subsoil organic matter are dissolved organic matter (Kaiser and Guggenberg 2000), root biomass (Rasse, Rumpel, and Dignac 2005), and particulate organic matter (Don et al. 2008). The main transfer routes for SOC to the subsoil are root channels and bio-turbation, which is the consumption of organic material and transportation by earthworms (Rumpel, Chabbi, and Marschner 2012).

It has been suggested that a good estimation of C pools in the soils, and how they can be maintained, or better enhanced, could also help mitigate atmospheric carbon dioxide (CO_2) increases and anticipated changes in climate (Batjes and Sombroek 1997; Lal, Kimble, and Follett 1998). Regional and global estimates of soil C stocks can be determined by extrapolating the means of soil C content for broad categories of soil types or vegetation across the areas occupied by those categories (Batjes 1996; Bernoux et al. 2002).

Kiwifruit is the fruit of a perennial woody vine. Most kiwifruit grown in New Zealand is grown on Andisol soils, mainly derived during the weathering of tephra and other parent materials with a significant amount of volcanic glass (Lowe and Palmer 2005). These have many distinctive properties that are rarely found in soils from other parent materials under similar conditions, including high contents of organic matter, high porosity, low bulk density, high water-holding capacity, high P retention, and the tendency to bind organic C. Also, the turnover of soil organic material is slower than in nonallophanic soils (Parfitt 1990, 2009). The allophanic Andisols are very important for agriculture and for studies investigating carbon sequestration as they occur predominantly in the North Island volcanic ash in New Zealand. With more than 32,100 km^2, they comprise about 12.5 percent of NZ soils (Lowe and Palmer 2005).

Management practices designed for C storage in kiwifruit orchards, and other perennial crops, are potential tools for New Zealand growers to help mitigate consequences of climate change. Changes in management methods could also enable growers to meet eco-verification market demands for products with a low C footprint and potentially exploit the emerging business opportunity in carbon storage. In previous work, we found significantly greater SOC levels in kiwifruit orchards in the 0.5- to 1.0-m depth than in pasture land of similar soils (Rahman and Holmes 2010). This result led us to hypothesize that there was significantly more carbon at even greater depths due to the deep, explorative rooting nature of kiwifruit in free-draining allophanic soils in the Bay of Plenty. These findings also raised the question of how deep the increased levels of soil C would continue to be present in kiwifruit orchards, compared to pasture sites.

The objective of this article was to summarize our results from investigating soil C status and dynamics in kiwifruit orchards in New Zealand with particular emphasis on our findings for C storage in subsoil horizons of allophanic soils in the Bay of Plenty.

Background to "Carbon Sequestration in Kiwifruit Orchard Soils at Depth to Mitigate Carbon Emissions" Work: The Carbon in Orchard Soils Team

The estimation of C storage is very important in the context of greenhouse gas assessment and effect of soil C dynamics on the global C cycle (Tremblay, Perie, and Ouimet 2006; Ouimet et al. 2007). The potential for using SOC as a metric for the ecosystem service of C sequestration reinforces the importance of having appropriate techniques to accurately measure SOC concentrations and to predict adequately C storage in soils. The choice of methodology for C assessment is critical to the accurate quantification of SOC concentration, content, and change over time (Périe and Ouimet 2008).

Globally, concern about food security is high due to growing demand from population growth, rising energy-related costs, vulnerability to extreme events, as well as degradation of soil and water resources. There is also growing concern that many existing land-management practices for food production are releasing additional C into the atmosphere. Energy-intensive food production on agricultural land does result in a net increase in C emissions through this land use.

Carbon storage within perennial crops systems could be recognized as a progressive step in environment management. Currently, there is no standard methodology to verify claims of C storage in kiwifruit orchards that might be needed in future stewardship initiatives, or to participate in C trading schemes.

The Carbon in Orchard Systems project aimed to address three key areas.

Mitigation

We calculated the rate of C sequestration and the C footprint of the orchard phase of kiwifruit. More soil C increases the storage of water and supply of nutrients, and in turn this would reduce the energy-related C footprint of irrigation and fertilizers, increase the water-use efficiency of the production, and reduce the application of nitrogen fertilizer that causes direct and indirect emissions of nitrous oxide. These functions help New Zealand kiwifruit producers to manage input costs while reducing environmental and climate-related risks.

Opportunities

Carbon storage management could help New Zealand growers to adapt to or meet new market requirements or qualify for a price eco-premium. Findings from this project will assist growers in the development of their environmental stewardship as well as demonstrate leadership in the primary industry as it adapts to climate change. This could help avoid additional environmental legislation, including the resulting compliance costs, and enable them to take advantage of any C trading schemes that might become available.

Benefits

Generally, greater soil C contents increase the soil‘s ability to filter excessive amounts of nutrients and contaminants, to mineralize nutrients, to reduce the run-off of nutrients and erosion, to act as a net sink for greenhouse gases, and to reduce the need for water resources. Soils with greater C contents may have more macro-pores that lead to a better aeration of wet or irrigated soils, and are consequently a safeguard against the occurrence of root diseases such as *Armillaria*, and possibly the conditions that make kiwifruit vines more vulnerable to *Pseudomonas syringae* pv. actinidiae (Psa-V). Kiwifruit has a low tolerance to root anoxia associated with water logging and inundation by floodwaters.

Methodology undertaken by the Carbon in Orchards Systems Team (COST) group (Holmes, Müller, and Clothier 2012) involved sampling to 1 m deep, and the COST team was able to assess the SOC stock of sites in different growing regions of NZ, with results shown in Figure 1 below. The subject orchards of the work undertaken by Holmes, Müller,

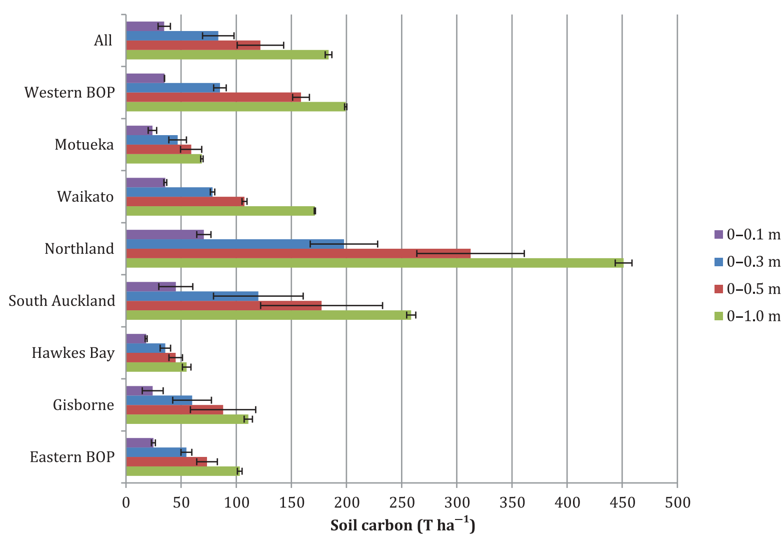

Figure 1. Soil C (total C from surface to four depths) in Hayward kiwifruit orchards. The bars represent the standard error of the measurements (Holmes, Müller, and Clothier 2012).

and Clothier (2012) were practicing integrated management and were located in the eight most important kiwifruit-growing regions in New Zealand. In every region, three representative orchards were sampled with six samples taken per depth (0–0.1, 0.1–0.3, 0.3–0.5, and 0.5–1 m depth). Exceptions were Waikato and Gisborne, where six pastures and two kiwifruit orchards were sampled, and the Bay of Plenty, where ten kiwifruit orchards were sampled. The SOC stocks varied between 42.46 t ha^{-1} and 600.84 t ha^{-1}, with the greatest average regional SOC stock recorded in Northland and the lowest in Hawkes Bay (Holmes, Müller, and Clothier 2012).

In earlier work undertaken as part of this project (Deurer and Rahman 2010), we compared the rate of C sequestration between two blocks of kiwifruit that had been established 10 and 25 years earlier side by side on the same property. In soil samples collected to a depth of 1 m, we found that the "old" block had 6 t ha^{-1} more C than the "young" block. This equates to an apparent annual C sequestration rate of 400 kg C ha^{-1} $year^{-1}$ in the top meter of soil (Deurer and Rahman 2010). However, a more detailed analysis showed that there was actually no difference in the C stocks between the orchards if only the top 50 cm were considered. A large proportion of the sequestration had occurred between 50 cm and 1 m. Moreover, we found significantly greater soil organic C levels in kiwifruit orchards in the 0.5–1.0 m depth than in pasture land of similar soils (Rahman and Holmes 2010). Based on these results, we speculated that kiwifruit orchards accumulate significantly greater deep subsoil C amounts than pastoral land in the free-draining allophanic soils in the Bay of Plenty. There is anecdotal evidence of kiwifruit roots at a depth of 7 m in excavations of old kiwifruit sites, and it is likely that these roots will have added C in the soil at depth, as well as possibly opening up channels for earthworm exploration.

Materials and Methods

To calculate the total amount of C per hectare of land, it is important that the soil bulk density of the soil profiles be measured (Fang, Liu, and Xu 1996). Also, it is necessary to measure SOC and soil bulk density at equivalent depths over time, because both these variables are changing with time and depth (Don et al. 2007). Sampling soil according to genetic horizon is technically difficult and sample preparation and analysis is costly as well as time-consuming. Thus, most of the studies have been conducted on SOC in the upper 15 to 30 cm of soils. Lorenz and Lal (2005) stated that soil below a depth of 30 cm may store large amounts of SOC. To elucidate the impact of kiwifruit vines on C storage, we collected soil samples at depths to 9 m from kiwifruit orchard and adjacent pastureland in June 2011. We selected an orchard with Hayward vines over 30 years old managed conventionally, and an adjacent pasture paddock, which was managed for the production of sheep and beef. Prior to being planted with kiwifruit, both the sites had been used for extensive sheep and beef production. The sites were located in the Bay of Plenty region of the North Island of New Zealand with the latitude of 37° 37' S and longitude of 175° 55' E. The experimental sites are approximately 26 m above sea level, free draining, and have little or no compaction. The average lowest and highest monthly maximum temperatures of the study site are in July (9.8 °C) and February (19.3 °C), respectively. The average lowest and highest precipitation amounts of the study area are January (74 mm) and March (128 mm), respectively. The soil at the experimental site is classified as Allophanic Orthic Pumice soil (Vitrads/Vitricryands Andisol, USDA; Mollic Andosol, FAO) formed predominantly from ryolitic tephra between ~4000 and 40,000 years ago during the region's geographic history of periodic volcanic eruptions (New Zealand Soil Bureau 1954; Molloy 1988; Hewitt 1993). Core samples were obtained from the soil surface to 9.0 m deep using

Figure 2. Soil sampling to 9 m in a kiwifruit orchard.

a geotechnical probe (Figure 2) in June 2011. Three holes (replicates) were drilled and samples were collected at each of the kiwifruit and pasture sites.

These cores were stored frozen in boxes, and samples for soil analysis were collected at selected points representative for the following eleven depth intervals: 0–0.3, 0.3–0.5, 0.5–0–1, 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, 7–8, and 8–9 m of the profile. Soil color was measured using Munsell Soil Color Chart (USA). Bulk density to 9 m deep was measured with undisturbed soil samples using the method of Blake and Hartge (1986). The other soil properties were measured from air-dried, disturbed, and sieved (<2.0 mm) soil samples. Yoder's (1936) wet sieving procedure was used to determine the size distribution of individual particles of soil. Hygroscopic moisture was measured according to Gardner (1986). Soil pH was determined using an IQ Stainless Steel ISFET pH probe in a 1:2.5 soil-to-water suspension (Jackson 1973). Electrical conductivity (EC) was measured by an IQ Conductivity Probe (Kalra and Maynard 1994). The ionic strength was estimated according to Griffin and Jurinak (1973). Soil organic C was determined using the loss-on ignition (LOI) methodology, where heat-proof crucibles were dried at 105 °C for 12 h and then allowed to cool in a desiccator containing calcium chloride ($CaCl_2$) to remove any moisture for 30 min before a tare weight to four decimal places was obtained. Approximately 3 g of air-dried soil was added to the crucible, and then the crucible was again dried at 105 °C for 24 h. The crucible was then placed in the desiccators for 30 min to cool, and the weight recorded. The weight of the sample was determined by subtracting the tare weight of the empty crucible. The samples were then ignited in a Phoenix microwave oven at 400 °C for 3 h. When the oven cooled to less than 200 °C, the crucibles were placed in the desiccators for 30 min prior to being weighed.

$$\mathrm{LOI-C} = \frac{\mathrm{Weight}_{105} - \mathrm{Weight}_{400}}{\mathrm{Weight}_{105}}$$

where LOI-C is organic C concentration (%) and Weight_{105} and Weight_{400} are the weight of the soil sample (g) after heating at 105 °C and ignition at 400 °C, respectively.

Soil organic C concentration was calculated using the regression equation developed by the COST project team (Rahman et al. 2011). Carbon stock in kiwifruit soil was calculated on a per-hectare basis with the two measured parameters, SOC concentration and bulk density.

Results and Discussion

Soil organic C concentrations of 10.66 percent (standard deviation [SD] = 3.39 percent) and 14.37 percent (SD = 4.45 percent) were estimated for surface soils (0–30 cm) of kiwifruit and pasture, respectively (Figure 3). In the surface soil (0–30 cm), the organic C concentration was statistically significantly greater in pasture than kiwifruit. The SOC in the first subsurface soil layer (30–50 cm) was identical between kiwifruit and pasture soil. However, in all other lower subsurface horizons to the layer at 900 cm deep, SOC concentrations tended to be greater in the kiwifruit orchard than under pasture land (Figure 3).

Detailed work with three kiwifruit management vs. pasture land management at three agroecological zones in three growing seasons similarly indicated that there was significantly more soil organic C present under pasture management in the 0- to 15-cm depth than in kiwifruit orchards (Rahman, Holmes, and Saunders 2011). The vertical variation with depth observed in our project may be related to the lower bulk density and kiwifruit roots down to 9 m deep and it is likely that these roots will have added C in the soil at depth, as well as possibly opening up channels for earthworm exploration. The bulk density in all but two of the depth profiles was significantly greater in pasture land than kiwifruit orchard (Table 1). Bulk density in soils varies by depth, but the mean value was 1.09 and 1.20 Mg/m^3 for the soil profile of kiwifruit and pasture land, respectively. The greatest bulk density of kiwifruit profile was recorded at 800–900 cm deep whereas the lowest was in topsoils. We found significantly greater amounts of soil organic C stocks (SCS) in the kiwifruit orchard than the adjacent pasture block in all depths except in the surface soil (0–30 cm) as shown in Figure 3. This result confirms our hypothesis that there is significantly more SOC at depth under kiwifruit orchards than pasture.

This 30-year-old kiwifruit orchard had sequestered 6.3 tons C per hectare per year more than the pasture soil in the top 9 m of soil, assuming that the soil C stock of the two adjacent sites with the same land use were similar before the establishment of the kiwifruit

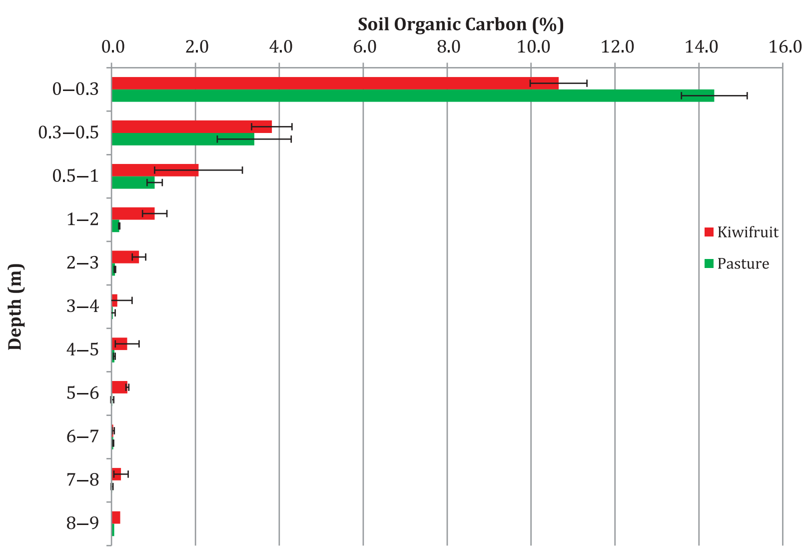

Figure 3. Soil organic C concentrations in an allophanic soil in a Hayward kiwifruit orchard and an adjacent pasture. The bars represent the standard deviation of three measurements.

Table 1
Selected physical properties of allophanic soil profile

Depth (cm)	Color		Sand (%)		Silt and clay (%)		Bulk density (Mg/m^3)		HM[a] (%)	
	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture
0–30	2.5Y 5/3	10YR 4/2	30.1	35.4	69.9	64.6	0.90	1.01	20.2	26.8
30–50	10YR 6/6	10YR 6/6	35.1	34.8	64.9	65.2	1.17	1.02	8.10	7.36
50–100	10YR 7/6	10YR 7/6	55.0	36.1	45.0	63.9	1.13	1.45	5.01	3.16
100–200	2.5Y 7/4	2.5Y 6/4	55.4	44.1	44.6	55.9	1.13	1.33	3.16	1.67
200–300	2.5Y 7/6	2.5Y 7/4	43.8	55.8	56.2	44.2	1.17	1.18	2.50	1.49
300–400	10YR 6/6	2.5Y 7/2	46.1	46.9	53.9	53.1	1.09	1.41	1.74	1.43
400–500	2.5Y 6/3	2.5Y 7/2	44.0	40.8	56.0	59.2	1.01	1.08	2.00	1.46
500–600	2.5Y 7/2	2.5Y 6/2	39.5	44.3	60.5	55.7	0.97	1.14	2.01	1.37
600–700	2.5Y 6/2	2.5Y 6/2	45.8	37.2	54.2	62.8	1.11	1.29	1.41	1.41
700–800	2.5Y 6/3	2.5Y 7/2	36.4	50.6	63.6	49.4	1.01	1.18	1.74	1.36
800–900	2.5Y 6/2	2.5Y 6/4	47.6	45.9	52.4	54.1	1.31	1.15	1.71	1.46
LSD[b]			*5.02*	*4.19*	*5.02*	*4.29*	*0.07*	*0.09*	*3.97*	*5.15*

[a]HM, hygroscopic moisture.
[b]LSD (least significant difference) at $P < 0.05$.

orchard. If we extrapolate our earlier finding of the 0.4 tons ha^{-1} y^{-1} (t/ha/y) for the 50 cm between 0.5–1.0 m, down to 9 m, we arrive at an extrapolated estimate of 6.8 t/ha/y (Deurer and Rahman 2010), which is very close to our measured value. By extrapolating the findings of our study, we estimate that the New Zealand kiwifruit industry sequesters about 0.9 million tons of C annually on orchards to 9 m deep.

However, our result is based on one paired sample site, and the estimation of SOC from LOI results is based on the conversion factor calculated using samples from 0- to 1-m depths in BOP kiwifruit orchards. To definitively calculate SOC at depth further work will be needed to calibrate LOI results with SOC, by measuring SOC in soils at depth using wet chemistry and/or LECO auto C analyzer. Conventional soil sampling to no more than 30 cm deep is easily undertaken with handheld borers and core samplers. Even the COST sampling to 1 m was undertaken using a handheld and inexpensive petrol powered post-hole borer. Obtaining soil samples at depths up to 9 m requires specialist geotechnical equipment, skilled operators, and good access and is expensive, with each hole for this project costing around NZ$1,200 in 2011. Obviously this preliminary study was very limited in the number of holes bored and samples analyzed. Chabbi, Kogel-Knabner, and Rumpel (2009) found that SOC is not evenly distributed in subsoil, with tongues of younger upper strata soil material being found extending into the deep subsoil matrix. Although we have not undertaken the stratigraphy analysis, it is possible that the results obtained are not representative as we may have unintentionally sampled from a tongue of upper strata material extending into the subsoil, therefore skewing the results. This potential situation could only be overcome by increasing the number of samples collected.

Data in Table 2 show the relative C stock (RCS) decreased with increasing soil depth. The greatest value was recorded in the top soil of the pasture profile. However, with increasing soil depth lower RSCs were found in pasture as compared to kiwifruit orchard. Carbon in the subsoil has been found to have longer residence times by up to several thousand years than C in the topsoil, measured by the use of radioactive C dating (Rumpel, Chabbi, and Marschner 2012). All SOC sampled by this author at 1 m deep was found to be at least 1,000 years old. In a recent review, sorption of SOC to minerals, in particular to iron or aluminum oxides, was proposed as main stabilization mechanism for SOC in subsoils (Rumpel, Chabbi, and Marschner 2012). The incorporation of SOC into soil aggregates, resulting in a spatial separation of SOC from microorganisms, and the general lower microbial activity at depth have also been discussed as stabilization factors for C in subsoils (Chabbi, Kogel-Knabner, and Rumpel 2009).

Our results indicate that as a greater percentage of C is present in the upper pasture soil horizons than the kiwifruit orchard horizons, pasture SOC will be lost more easily than kiwifruit SOC. It is likely that SOC is more stable in kiwifruit orchards than under pasture management, because a greater percentage of it is present at depth in the profile. Therefore, the conversion into perennial horticulture and desirable land use and management practices could increase the SOC pool and mitigate climate change. Given that pasture plants are shallow rooting, trees are intermediate depth rooting, and vines have extensive and deep root systems, it is possible that the production of vine crops such as kiwifruit and grapes will provide the greatest increase in SOC at depth. Soil structure and physical properties affect root growth and distribution, and therefore soil properties also play an important role in the distribution of SOC. Western Bay of Plenty allophanic soils are deep with relatively loose structure, encouraging extensive root growth. In other soils and for plants with less extensive root systems, genetic or agri-technical manipulations of the root system to promote root growth or mycorrhization of plant roots might be strategies to enhance deep C sequestration. Our results show that subsoil C sequestration can effectively address the

Table 2
Selected chemical properties of allophanic soil

Depth (cm)	Total N (%)		RCS[a] (%)		pH		EC (μS/cm)		IS[b] (mol/L)	
	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture	Kiwifruit	Pasture
0–30	0.92	1.28	29.0	60.6	6.83	5.96	135	231	7.04	12.01
30–50	0.33	0.30	9.01	9.66	7.05	5.79	132	157	6.86	8.17
50–100	0.21	0.11	26.3	20.9	7.04	5.80	129	155	6.70	8.07
100–200	0.13	0.04	13.9	3.43	5.98	5.87	87.7	89.0	4.56	4.63
200–300	0.09	0.04	7.76	1.36	5.37	5.87	109	87.3	5.67	4.54
300–400	0.04	0.03	1.30	0.63	5.89	5.60	112	119	5.84	6.17
400–500	0.06	0.02	3.65	1.04	5.76	5.50	116	134	6.04	6.96
500–600	0.07	0.03	3.72	0.31	5.67	5.64	91.7	170	4.77	8.85
600–700	0.06	0.04	0.47	0.73	5.52	5.49	95.3	247	4.96	12.84
700–800	0.05	0.03	2.13	0.23	5.45	5.70	97.9	106	5.09	5.49
800–900	0.04	0.03	2.73	1.07	5.44	5.69	100	85.0	5.22	4.42
LSD[c]	*0.07*	*0.24*	*6.60*	*12.81*	*0.53*	*0.12*	*11*	*36.0*	*0.53*	*1.32*

[a]Relative C storage.
[b]IS, ionic strength, multiply by 0.001.
[c]LSD (least significant difference) at $P < 0.05$.

soil-C dilemma that Janzen (2006) posted: Should we hoard C or use it? Or in other words, should we enhance C sequestration or encourage the oxidation of C for microbial activity, nutrient circulation, and growth? Managing the vertical C distribution in the soil profile with sequestration at depth and burning C in the topsoil might solve this predicament.

Conclusions

These results support our hypothesis that soils at depth under kiwifruit store significantly greater levels of SOC than those under pasture management. Growing kiwifruit on allophanic soils appears to be a viable management option to increase SOC storage in subsoil horizons in a relatively short timeframe. Further work is required to collect samples from multiple paired sites of pasture and kiwifruit to confirm if this trend is consistent across different orchards and regions.

The implication of this finding is that the SOC sequestered each year within the top 1 m of soil equates to about 4 percent of the emissions of Hayward kiwifruit grown in New Zealand and consumed in the United Kingdom when a conversion factor of 3.67 is used to convert SOC to CO_2 equivalents. If the results from this one site are extrapolated and top 9 m of soil are included in this calculation then the amount of SOC sequestered equates to about 42 percent of the emissions associated with growing fruit in New Zealand for consumption in the United Kingdom. Practically, it will be difficult to develop a robust and cost-effective methodology based on this depth of sampling (Table 3).

These findings also show that if the SOC contents were measured to a depth of 30 cm, as required under the Kyoto Protocol, only 34.5 percent of the SOC in the top 9 m of kiwifruit soils would be measured, as opposed to 60.6 percent of the SOC in pasture.

As between 46–63 percent of the SOC in soil is held in the subsoil (Batjes 1996), it is essential that the C stock is measured deeper than the 30-cm depth required by the Kyoto Protocol. By extrapolating these findings, we estimate that the total C stock in the top 9 m of kiwifruit orchard soils in New Zealand is 3,779,540 tons. This compares to 2,240,760 tons in the top meter of soils. This result requires more study into C sequestration at depth. It is also highly likely that increased atmospheric CO_2 levels will lead to more root growth at depth. Change of management practices (i.e., deep irrigation, deeper growing rootstocks, and subsoil ripping) may encourage deep root growth. There is also a decrease in the numbers of microbes at depth, and earthworms deep in the profile feed on fresh C material (Rumpel, Chabbi, and Marschner 2012).

Table 3
Soil C stock in NZ kiwifruit industry based on different sampling depths

	T ha^{-1}	Industry (million t)
Soil to 1 m deep	179.2	2.2
Vines	19.7	0.2
Shelterbelts	43.5	0.5
Total (1 m deep)	242.5	3.0
Soil to 9 m deep	295.8	3.7
Vines	19.7	0.2
Shelterbelts	43.5	0.5
Total (9 m deep)	359.1	4.5

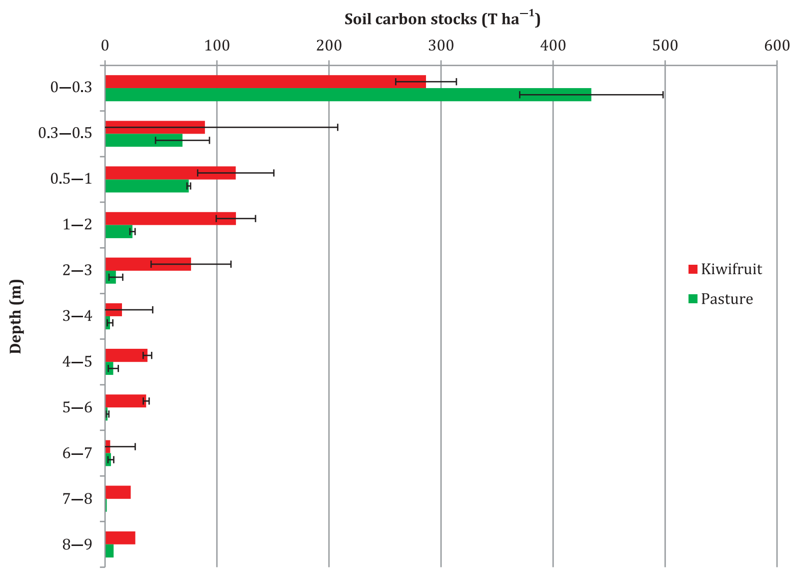

Figure 4. Soil organic C stocks in an allophanic soil measured in eleven depths (0–0.3, 0.3–0.5, 0.5–0-1, 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, 7–8, and 8–9 m depth) under a Hayward kiwifruit orchard under integrated management and an adjacent pasture. Three soil cores were taken per depth. The bars represent the standard deviation of the measurements.

By extrapolating the findings of our study, we estimate that the New Zealand kiwifruit industry sequesters about 90,000 tons of C annually on orchard to 9 m deep (Figure 4).

These results to 9 m deep are from just six holes on one property in the Western Bay of Plenty. Further work would be needed to sample more orchards and more regions to determine if these results are representative. It would also be very interesting to see if the SOC trend at depth is present under other perennial horticultural crops. Understanding the relationship between stable and labile C in the soil profile would also allow us to better understand the dynamics of C in the soil profile. Other soil investigation techniques, such as x-ray computed tomography, could be used to investigate if the increased levels of SOC at depth under kiwifruit are associated with other soil characteristics. For example, does greater SOC at depth result in longer residence times of water in the soil, therefore more soil water storage?

Carbon is generally present at reasonably low concentration in soils, being generally less than 5 percent soil mass, but the total stock down to depth is large. Small changes in the concentration over time can be important but strain the limits of measurement within the relatively short timeframes desirable for C trading. The large variations in the content of soil C across the landscape and down the soil profile challenge the reliability of sampling methods. On a worldwide scale, other large perennial horticultural industries such as South African fruit and wine grape producers are aware of the potential to sequester C in soils and biomass on orchards and vineyards. The South Africa Fruit and Wine Initiative (2012) is using this as part of their efforts to mitigate the effects of climate change and ultimately secure the long-term viability of their businesses.

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