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CO_2 Emissions in Layered Cranberry Soils under Simulated Warming

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Abstract: Sanding to bury the overgrowth of uprights and promote new growth results in alternate sand and organic sublayers in the 0–30 cm layer of cranberry soils contributing to global carbon storage. The aim of this study was to measure CO_2 emission rates in cranberry soil sublayers under simulated warming. Soil samples (0–10, 10–20 and 20–30 cm) were incubated in jars for up to 105 days at 10, 20 and 30 °C. The CO_2 emission rate was measured biweekly by gas chromatography. The CO_2 emission rate increased with temperature and decreased in deeper soil sublayers. Linear regression relating CO_2 efflux to soil sublayer and temperature returned $R^2 = 0.87$. Sensitivity of organic matter decomposition to temperature was estimated as activation energy and as Q_{10} coefficient, the increase in reaction rate per 10 °C. Activation energy was 50 kJ mol^{-1}, 59 kJ mol^{-1} and 71 kJ mol^{-1} in the in the 0–10, 10–20 and 20–30 cm sublayers, respectively, indicating higher molecular-weight compounds resisting to decomposition in deeper sublayers. The Q_{10} values were significantly higher ($p < 0.01$) in the 10–30 cm (2.79 ± 0.10) than the 0–10 cm (2.18 ± 0.07) sublayers. The 20–30 cm sublayer where less total carbon was stored was the most sensitive to higher temperature. Cranberry soils could be used as sensitive markers of global warming.

Keywords: carbon accumulation; cranberry soils; activation energy; temperature-dependent CO_2 emissions rate

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1. Introduction

Terrestrial carbon (C) is three times greater than atmospheric C [1]. Soil C sequestration is the conversion of atmospheric CO_2 into long-lived C pools [2]. While soil C sink capacity of managed ecosystems is the estimated historic cumulative C loss of 55–78 Gt, the attainable capacity is only 50–66% of that potential [3]. Cranberry agroecosystems are exceptions to this general perspective [4]. The fate of organic matter in soils depends primarily on its intrinsic decomposability and on protection mechanisms such as soil aggregation [5] in silty or clayey agricultural soils [6].

In North America, conventionally and organically managed cranberry agroecosystems are mostly established on acid sandy soils arranged as flat beds in low-lying positions to facilitate water transfer [7]. Beds are diked, then capped with 0.3–1.0 m of sand. Native soil C is accumulated in dikes, beds, and the subsoil. The seasonal C flux of leaf and stem litterfall was estimated at 2.15–2.57 Mg C ha^{-1} (153-d)$^{-1}$ in Wisconsin [8]. The belowground vegetative biomass may contribute up to 2/3 of total vegetative C stocks. The overgrowth of uprights is buried every 2–5 years by spreading two to five cm of sand onto frozen soil to promote new growth [9]. This results in alternate layers of sand and organic matter in the root zone [10] and high potential for C storage due to physical protection through anthropic surface sanding [4].

The composition and biomass of the microbial community generally differ between upper and lower soil layers [11–13]. The decreasing rates of CO_2 emissions in deeper soil layers [14,15] have been attributed to the vertical distribution of soil organic carbon in

terms of amount and quality [13–16]. Indeed, the C:N ratio is narrower, and soil organic matter (SOM) is more decomposed, in deeper layers of cranberry soils [10]. Temperature at depth should also be considered. The threshold temperature for mineralization activity of cranberry soil was set at 13 °C [8].

The effect of temperature on organic matter decomposition is crucial to understand the global C cycle and potential feedbacks to the climate system [17]. The largest C stocks have been found at high latitude [18,19]. While the seasonal CO_2 emission of Quebec cranberry soils has been estimated at 2.7–3.4 t CO_2 eq ha^{-1} [20], the effect of global warming on CO_2 emission in the soil profile as a function of temperature has not been established. The activation energy of decomposition and the Q_{10} coefficient as increase in reaction rate per 10 °C [17,21,22] can reflect the differential contribution of soil layers to CO_2 emissions in cranberry agroecosystems in areas of rapid climate change such as Eastern Canada.

We hypothesized that activation energy of soil organic matter (SOM) decomposition and Q_{10} differ in alternate sand and organic matter layers due to the differential C/N ratio and decomposition degree of organic matter in two differently managed cranberry soils. The aim of this study was to measure the decomposition rate of SOM in layered cranberry soils as a function of management (conventional vs. organic), soil layer, incubation time and temperature under controlled environments to assess the differential effects of global warming on soil C storage in cranberry soils.

2. Materials and Methods

2.1. Soil Sampling and Analysis

Sites were selected to cover the two main management practices in south-central Quebec. Site #45 (46°16′34.7″ N, 71°51′30.0″ W, elevation 112 m) was conventionally managed, and site #A9 (46°14′16.5″ N, 72°02′13.4″ W, elevation 92 m) was organically farmed. Sites #45 and #A9 have been planted to cultivar "Stevens" in 1999 and 2004, respectively. The climate of the region is sub-humid temperate and continental with cold winters and hot summers. Soil series were the Saint-Jude series at site #45 and Sainte-Sophie series at site #9, both classified as Humo-Ferric Podzols in the Canadian System Haplorthods in the U.S. Soil Taxonomy, and Orthic Podzols in the World Reference Base for Soil Resources. The soil contained 937 g sand kg^{-1}, 37 g silt kg^{-1}, and 26 g clay kg^{-1} at site #45, and 915 g sand kg^{-1}, 49 g silt kg^{-1}, and 36 g clay kg^{-1} at site #9 [4].

Fields received 40 kg N ha^{-1} yr^{-1} as ammonium sulfate (site #45) or granules of poultry manure (site #9). The source of phosphorus was mono-ammonium phosphate at site #45 as recommended locally from soil and tissue tests, and granules of poultry manure at site #9 from a N-based recommendation. Potassium was applied at a rate of 100 kg K ha^{-1} as KCl, sul-po-mag and/or granules of poultry manure. Micro-nutrients were applied at need depending on the results of tissue testing. Fields were sprinkler-irrigated at need.

Soil samples were collected for physical analyses in spring 2018. Three soil layers were sampled (0–10; 10–20; 20–30 cm) at four places per site using cylinders (diameter = 5.5 cm, height = 7.6 cm). Samples were sealed in plastic bags and stored at 4 °C until use within a week. Soil samples were air dried, and 2 mm sieved before analysis. Soil pH was measured in 0.01 M $CaCl_2$ (soil to solution ratio of 1:2 *v*:*v*). Soil carbon and nitrogen were quantified by combustion [23] using the Leco CNS model 630-300-200 (Leco Corporation, Saint-Joseph, MI, USA). Soil bulk density was determined as the mass of air-dry soil divided by the volume of the cylinder. Soil carbon content and porosity were computed in each 10 cm thick layers as follows [24]:

$$C_s = P_b \times C_c \tag{1}$$

$$C_{layer} = C_s \times [layer\ thickness] \times area \tag{2}$$

$$TP = \left(1 - P_b/P_p\right) \times 100 \tag{3}$$

$$P_d = \frac{100}{\frac{\%Organic\ matter}{1.55} + \frac{100-\%Organic\ matter}{2.65}} \tag{4}$$

where Cs = carbon stock (kg m^{-3}), Cc = carbon content (%), TP is total soil porosity (volumetric fraction); P_b = soil bulk density (g cm^{-3}); P_d = soil particle density assuming 1.55 g cm^{-3} as the particle density of organic matter and 2.65 g cm^{-3} as the particle density of mineral matter [25].

2.2. CO_2 Emission

Soils were sampled at three depths (0–10 cm, 10–20 cm, 20–30 cm) and four locations in each field (785 mL per sample using cylinders 10 cm in height and 10 cm Ø) and introduced in plastic bags. The 72 fresh soil samples were 6 mm sieved, filled to 1/3 of the volume of 250-mL Mason jars with 100 g dry-based material, and placed in temperature-controlled chambers following a completely randomized design with four replications per site. There were three (3) soil layers (0–10; 10–20; 20–30 cm), three (3) temperatures (10, 20 and 30 °C), four (4) replicates and two (2) sites. Soil water content was adjusted twice a week with distilled water to water-filled pore space (WFPS) close to 0.50–0.70 as volumetric fraction [24,26]. Water content was assessed by weighing the jars, assuming a density of one g cm^{-3}.

Soil CO_2 flux was measured using a close chamber protocol [26]. At sampling time taken biweekly during 105 d, jars were capped with a lid containing two male slips. One slip was fitted to a septum for headspace sampling using a 20 mL polypropylene syringe. The other slip was used to equilibrate the jar internal pressure during sampling. Air samples were taken at 0 and 24 h, then transferred into pre-evacuated 12 mL glass vials (Exetainer, Labco, High Wycombe, UK). Gas samples were analyzed for CO_2 using a gas chromatograph fitted to a Ni-NO_3 (10%) catalyst column and a flame ionization detector (Model 3800, Varian Inc., Walnut Creek, CA, USA), equipped with a headspace auto-injector (Combi Pal, CTC Analytics, Zurich, Switzerland). The CO_2 flux (Fc, µg g^{-1} h^{-1}) was measured as [26].

$$F_c = \frac{dc}{dt} \times \frac{v}{M_v} \times \frac{M_m}{W}, \tag{5}$$

where dc/dt (µL L^{-1} h^{-1}) is change rate of headspace CO_2 concentration in dry air samples estimated at time = 0 and time = 24 h, assuming that CO_2 emissions vary linearly through time; v (L) is pot headspace volume; Mv (L mol^{-1}) is molecular volume at the pre-deployment air temperature (22–24 °C); Mm (µg mol^{-1}) is molecular mass of CO_2 (44,000,000); and W (g) is dry soil mass.

2.3. Statistical Analysis

2.3.1. First Order Kinetics

The decomposition rate constant (k) was computed as follows [27]:

$$k = \frac{ln([C_{initial} - CO_2\_C_t]/C_{initial})}{t} \tag{6}$$

where $C_{initial}$ (mg kg^{-1}) is initial soil carbon content, and $CO_2\_C_t$ (mg kg^{-1}) is cumulative CO_2 released during incubation period t.

2.3.2. Q_{10} and Activation Energy

The increase in reaction rate per 10 °C was reported as follows [21,22]:

$$Q_{10} = \frac{k \times (t + 10)}{k(t)} \tag{7}$$

where $k_{(t)}$ is k at temperature t (°K) and $k_{(t+10)}$ is k at temperature t + 10 (°K).

Activation energy was derived from the Arrhenius equation [19,22] as follows [21]:

$$k = A \times exp(-E_a/RT) \tag{8}$$

where A is pre-exponential factor and Ea is activation energy assumed to be independent of temperature, R is the universal gas constant, and T is absolute temperature (°K).

2.3.3. Statistical Analysis

Statistical analyses were performed in the R environment version 4.1.0 [28]. The difference between conventional and organic farming systems were tested using a mixed model. The CO_2 emission rates were fitted to elapsed time, temperature and soil layers across farming systems using the *lm* linear regression model as follows [29]:

$$y = \beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k + \varepsilon \quad (9)$$

where y (CO_2 emission rate) is the predicted value, x_1 through x_k are k independent variables or predictors (time, temperature in °K, soil layers), β_0 is the value of y where independent variables take zero values, and β_1 through β_k are estimated regression coefficients. The R codes and dataset are available online at https://bit.ly/3gbi6Ov (accessed on 8 January 2023).

3. Results

3.1. Soil Properties

Soil properties are presented in Figure 1. Soil carbon content varied from 1.67 to 30.9 Mg C ha^{-1}, being larger in the 0–10 cm (16.55 ± 1.15), than in the 10–20 cm (13.63 ± 2.95) and the 20–30 cm (6.09 ± 1.44) layers (Figure 1A). The C:N ratios were 20.08 ± 1.05, 16.01 ± 1.91 and 9.02 ± 1.96 in 0–10, 10–20 and 20–30 cm layers, respectively (Figure 1B). Soil bulk density increased in lower layers as a result of sand accumulation and organic matter decomposition while biomass production reduced bulk density in the upmost layer. Lower pH values in upper layers under conventional farming are attributable to soil acidification by elemental sulfur amendment and ammonium sulfate fertilization. In organic farming, high-ammonium poultry manure granules likely acidified the upper soil layer in the first place. Soil porosity, water content and bulk density followed the same trends as inter-related properties.

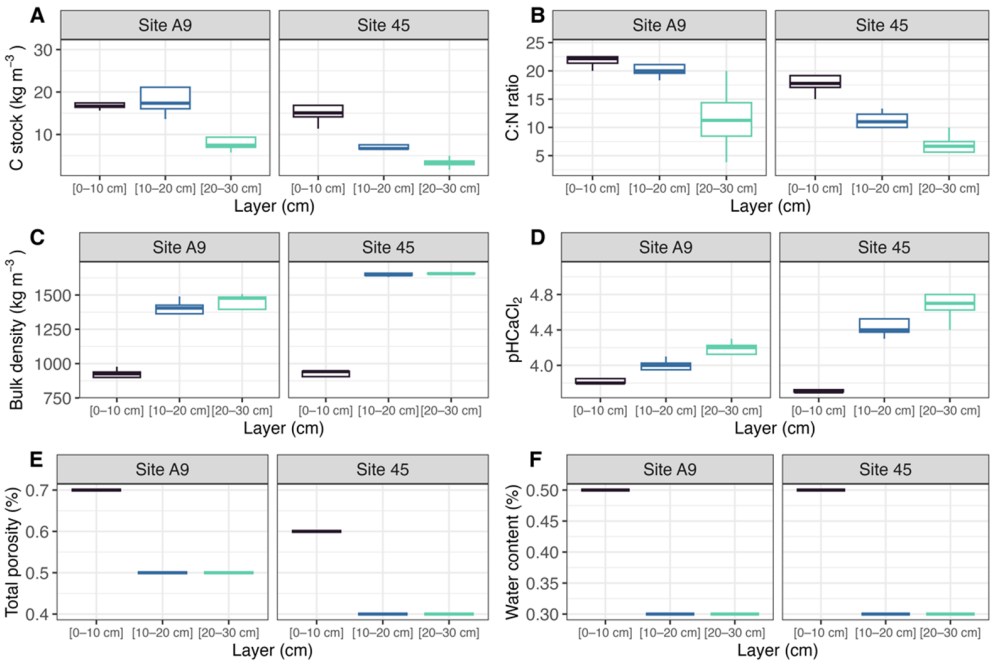

Figure 1. Soil properties in layers of cranberry soils: (**A**) C stock, (**B**) C:N ratio, (**C**) bulk density, (**D**) pH_{CaCl_2}, (**E**) total porosity (volumetric fraction), (**F**) water content (volumetric fraction).

3.2. CO_2 Emission Rate

The CO_2 emission rates did not differ significantly between sites (p-value > 0.05), decreased (p-value $\leq$ 0.05) through time and soil depth, and increased (p-value $\leq$ 0.05) with temperature (Figure 2). The soil layer showed the largest effect followed by temperature and incubation time. The CO_2 emissions are presented in Figure 3 for significant treatments.

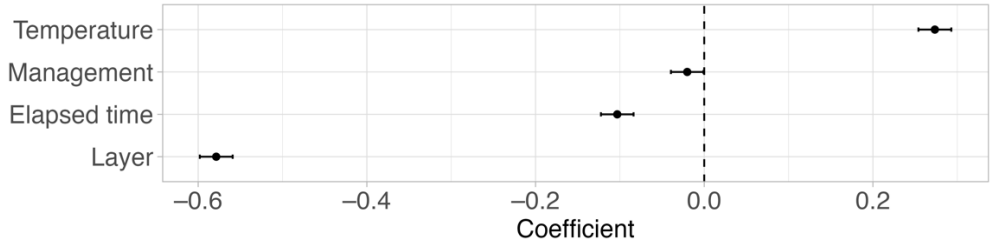

Figure 2. Effect of temperature, management, elapsed time and soil layer on CO_2 emissions. Probability for significance is 0.05.

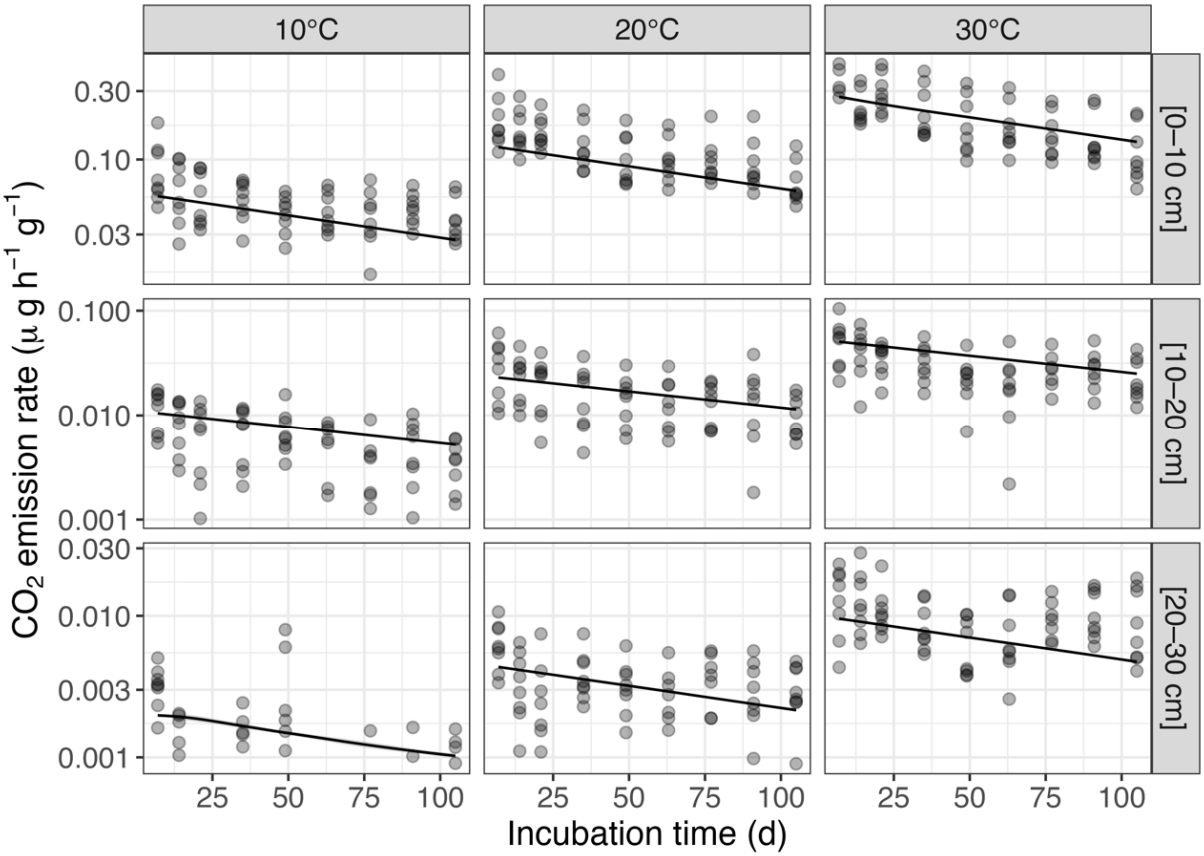

Figure 3. Influence of soil layer, temperature and time on CO_2 emission rate.

The CO_2 emission rate was highest in the 0–10 cm layer at 30 °C and lowest in the 20–30 cm layer at 10 °C. At 10 °C, 87.2% of the total across-layer CO_2 emissions during the incubation period occurred in the 0–10 cm layer compared to 12.1% in the 10–20 cm layer and 0.7% in the 20–30 cm layer. At 20 °C, 83.1% of total across-layer CO_2 emission occurred in the 0–10 cm layer compared to 14.3% in the 10–20 cm layer and 2.5% in the 20–30 cm layer. At 30 °C, 82.8% of total across-layer CO_2 emission occurred in the 0–10 cm layer compared to 13.5% in the 10–20 cm layer and 3.8% in the 20–30 cm layer. The R^2 value of the equation relating CO_2 emission to temperature, soil depth and elapsed time was 0.87 and root-mean-square-error was 0.24 (Figure 3).

The effect of temperature on SOM decomposition rates indicated large differences between layers in biochemical composition of the organic materials and SOM resistance to decomposition. The slope of the Arrhenius equation ($-Ea/R$) was highest in the (0–10 cm) layer, intermediate in the 10–20 cm layer and lowest in the 20–30 cm layer (p-value < 0.001) (Figure 4). The activation energy required to decompose SOM was 50 kJ mol^{-1} in the 0–10 cm layer, 59 kJ mol^{-1} in 10–20 cm layer and 71 kJ mol^{-1} in 20–30 cm layer (Figure 5). The Q_{10} (mean ± SE) was 2.79 ± 0.10 in the 20–30 cm layer and 2.18 ± 0.07 in the 0–10 and 10–20 cm layers (p-value < 0.001) (Figure 6).

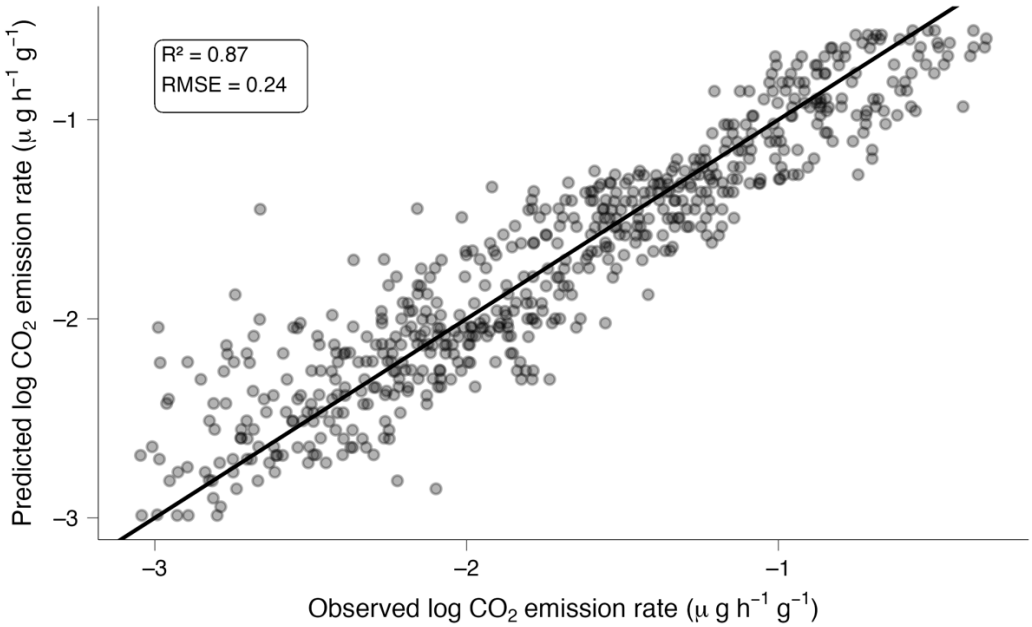

Figure 4. Relationship between observed and predicted CO_2 emission rates.

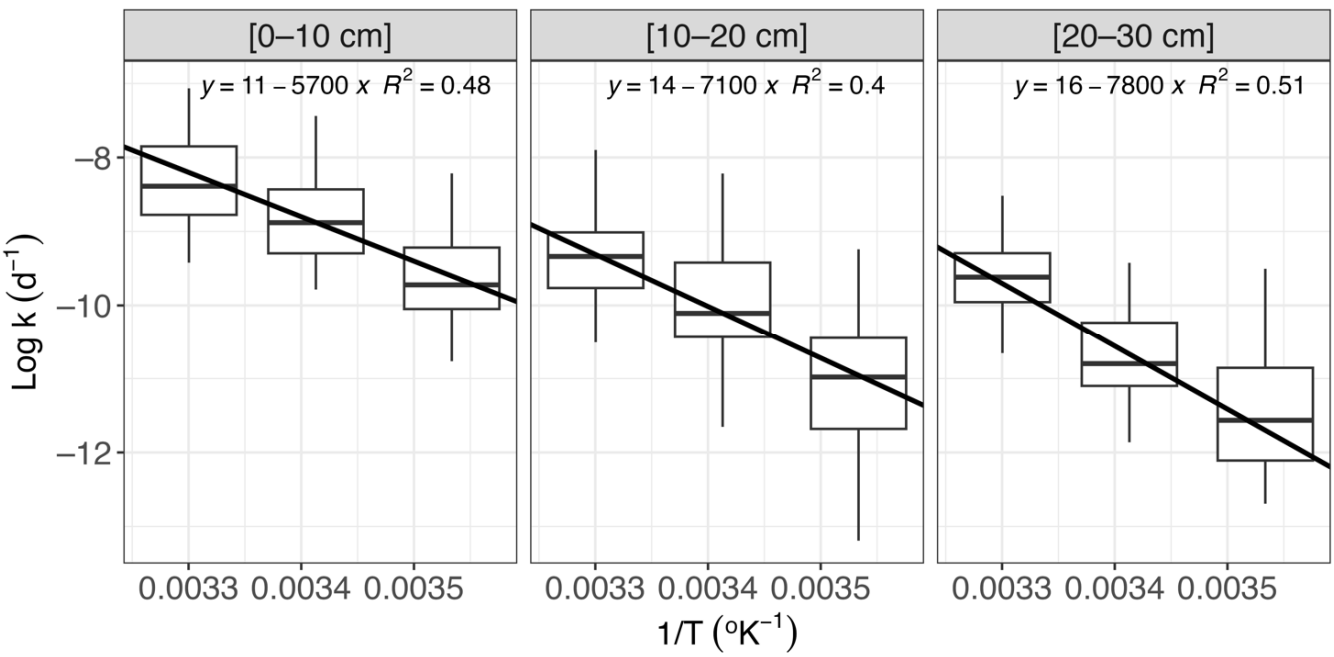

Figure 5. Experimental data fitted to the Arrhenius equation (p-value < 0.001).

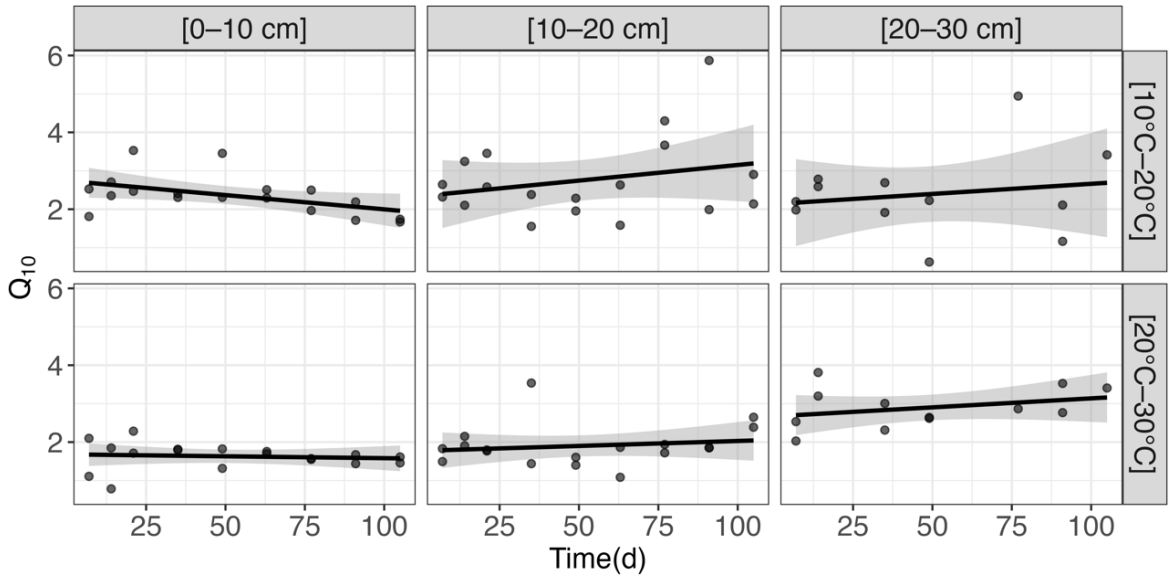

Figure 6. Time variation of Q_{10} across soil layers (p-value < 0.001).

4. Discussion

Several factors such as climate, the amount and quality of plant residues, soil management, mineralogy, texture [30–33], bulk density [34], as well as layer location in the soil profile [10,15,16,35,36] control organic matter turnover in soils. Organic matter decomposition rate also depends on the spatial distribution of organic matter, and the site-specific microbial community impacted by land use, temperature, rainfall, soil type and bulk density [12,37]. In cranberry soils documented in Figure 1, differences in soil parameters should be further addressed in relation with carbon accumulation and microbe abundance and diversity.

Cranberry agroecosystems were shown to contribute to CO_2 emissions much less (2.7–3.4 t CO_2 eq ha^{-1}) compared to other horticultural cropping systems [20]. Indeed, slowly decomposing carbon can accumulate in large amounts in layered cranberry soils after burial of organic matter through regular sanding. This paper quantified layer × temperature interactions regulating CO_2 emissions in cranberry soils.

4.1. Dependency of CO_2 Emission on Soil Depth

The decreasing CO_2 emission rate in deeper soil layers results in part from the vertical distribution of soil organic carbon (SOC) in terms of amount and quality [16]. The biochemical composition varies considerably among cranberry soil layers [4]. The biochemical quality of plant species and that of the soil are the main factors driving litter decomposition under otherwise similar conditions of temperature and rainfall [38–40]. For example, litter quality differs considerably among tundra, grassland, and boreal, conifer, deciduous, and tropical forest biomes [38]. Litter decomposability is associated with species' ecological strategy within different ecosystems globally [39]. The effect of climate on litter mass loss can be offset by differences in soil parameters as mediated by soil microbial populations [40].

Fresh sources of SOC such as shoot litter, senescent roots, and root exudates [41,42] are directly available to soil microbes in upper layers [43]. Fresh organic matter decreases deeper in the soil profile [36,44,45]. There is abundant young fast-cycling C in upper layers compared to ancient slow-cycling C in the subsoil [36]. As a result, soil respiration is greater near soil surface (0–5 and 5–10 cm layers) compared to lower layers [46]. The cranberry litter deposited on the floor of cranberry beds contains approximately 80% of lignocellulose while 89% of the particles are larger than 2 mm in size and the C:N ratio is 55 in average [4]. Lignocellulose is a compact material made of strongly bound cellulose, lignin, and hemicellulose in structural networks in stems and roots [47]. Lignocellulose is

broken down by a suite of extracellular enzymes [48]. Due to structural and biochemical constraints, litter is slowly decomposed in cranberry soils [4].

4.2. Temperature Sensitivity on CO_2 Emission Rates

The activation energy required to decompose SOM in cranberry agroecosystems was lower in upper layers (50–59 kJ mol^{-1}) than in the 20–30 cm layer (71 kJ mol^{-1}) where high-molecular-weight phenolic compounds abound [4]. In comparison, the *Ea* values for enzyme activities were 75 kJ mol^{-1} for phenol oxidase and, 40–45 kJ mol^{-1} for β-glucosidase, cellobiohydrolase and peroxidase in the A horizons of three temperate biomes [48], compared to that of pyrophosphatase that averaged 22–33 kJ mol^{-1} in Histosols and 33–43 kJ mol^{-1} in mineral soils [49].

Low-quality organic C limits the energy available to the microbial community [43,50]. Humic substances, complex organic molecules and recalcitrant SOM as shown by higher activation energy requirements in lower soil layers resist microbial attack and may combine with minerals to reduce microbial degradability even more [51]. As a result, higher temperatures showed disproportionate impacts on the depolymerization of high-molecular weight constituents of SOM [40]. More decomposed soil organic matter in the deepest layer is shown by the lower C:N ratios compared upper layers (Figure 1). In upper layers, cranberry plant residues show high C:N ratio of 66.7 ± 5.7 [4], indicating a decreasing gradient of C:N ratios from litter in upper soil layers and to more decomposed materials in the lower layer of cranberry soils [7].

The Q_{10} values were higher (2.79 ± 0.10) in the 20–30 cm than upper (2.18 ± 0.07) layers in the range of 283–303 K in the present study. In comparison, the Q_{10} values varied between 1.2 and 2.8 within temperature range of 278–308 K in the 0–29 cm layer of cropland, grassland, deciduous forest, and coniferous forest ecosystems [52]. The Q_{10} values of Massachusetts forest soils in the 278–303 K range were 2.43–5.00 for hemlock, 2.62–3.77 for young birch, and 2.59–5.23 for mature birch [53]. Indeed, compared to commonly used values of 1.5–2.0, the Q_{10} values may vary widely from 1 to 12 depending on land use, C:N ratio and degradability of SOM, soil class, moisture content, texture, and acidity [54]. Mycorrhizae may impact Q_{10} values of carbon sources. Ericoid mycorrhizal (ErM) foliar litters, fine roots, fungal biomass and the necromass generally decomposes slower than those of arbuscular and ecto-mycorrhizal fungi, which could contribute to organic matter accumulation in sites where ErM plants occur [55]. This aspect could be further examined in cranberry agroecosystems.

5. Conclusions

The the decomposition rate of SOM in cranberry soils did not vary significantly with management (conventional vs. organic), but varied with soil layer, incubation time and temperature. The rate of CO_2 emissions decreased with elapsed time. Activation energy was 50–59 kJ mol^{-1} in upper layers (0–20 cm) compared to 71 kJ mol^{-1} in the 20–30 cm layer required to decompose high-molecular-weight materials. The Q_{10} values were 2.9–3.1 in the deepest layer compared to 1.9–2.3 for the Q_{10} values in upper layers. Temperature sensitivity of C decomposition rate in layered cranberry soils thus impacted differentially the C storage capacity of cranberry agroecosystems. Activation energy and Q_{10} increased deeper in the soil, indicating higher temperature sensitivity of the most recalcitrant sources of SOM. Despite their smaller contribution to total C storage compared to upper layers of cranberry soils, the 20–30 cm soil layer would contribute increasingly to CO_2 emissions in the context of global warming.

Future research could quantify net C accumulation in cranberry soils through litter burial by sanding since the establishment of cranberry beds and the management practices required to promote C storage as ecosystem service. This will require developing a methodology for site sampling and monitoring covering several aspects of the cranberry production system to meet sustainable development goals, addressing the destruction of native ecosystems as well as the carbon already accumulated in dikes and the subsoil. Or-

ganic layers alternating with sand layers in cranberry beds and showing disproportionate contributions to CO_2 emissions could be used as sensitive markers of the impact of global warming on soil C storage capacity over decades.

Author Contributions: Conceived and designed the experiment: W.D.-Y. and N.Z.; performed the experiment: W.D.-Y.; analyzed the data: W.D.-Y. and S.-É.P.; wrote the first draft of the manuscript: W.D.-Y., S.-É.P. and L.E.P.; all authors provided critical feedback on the manuscript. All authors have read and agreed to the published version of the manuscript.

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