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Effect of Three Types of Exogenous Organic Carbon on Soil Organic Matter and Physical Properties of a Sandy Technosol

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Abstract: Technosols made by covering agricultural soils with coastal sediments need additional organic matter (OM) to be suitable for agricultural use. Climate change will likely increase the frequency and intensity of droughts in several areas. The choice of the nature and quantity of OM to add depends on dose-response curves for soil quality. This study quantifies the influence of three contrasting organic materials (vermicompost (VF), green waste compost (GWC) and dairy manure (DM)) on four soil properties: soil organic carbon, evaporation rate, bulk density and structural stability. Soil was sampled in April and May 2014 in an artificial crop field of the vegetable production basin of Mont Saint-Michel (France) made with sediments from the bay of Mont Saint-Michel in 2013. Increasing the dose of OM increased soil organic carbon from 10 to 45 g C kg^{-1} dry soil and increased the porosity and the structural stability, thus decreasing compaction. Increasing the dose of OM also decreased the evaporation rate. VF and DM had similar effects, while those of GWC were weaker. Compared to DM, VF had greater biological stability. Therefore, high OM inputs along with soil decompaction can increase drought resistance by increasing rooting depth and water retention.

Keywords: soil quality; compaction; water retention; soil porosity; vermicompost; municipal compost; dairy manure

1. Introduction

Optimal use of aquatic sediments in agricultural systems is a challenge for the sustainable use of natural resources [1,2]. Indeed, reclamation of marine sediments reclamation is defined here as the creation of land area from marine or river sediments for agricultural fields may become more frequent in the future. Moreover, some regions need to dredge surplus sediments from rivers or coastlines to prevent silting [1,3]. Supplying soil to make or restore agricultural fields is thus a common practice in coastal areas [4]. In France, reclaimed coastal soils in Brittany and Normandy are frequent. The sediments used, called "tangue", are river and estuary sediments dredged principally in Mont-Saint-Michel Bay [5–7] and composed mainly of silt, sand and limestone. Their fine texture and high calcium and trace element contents make them interesting, particularly for vegetable cropping systems; however, they are low in organic carbon (C).

Soil organic matter is one of the most crucial components of sustainable soil use [8,9]. Organic matter (OM) inputs influence short- and mid-term soil physical properties, such as water retention and structural stability [10–13]. They also influence biological activity either directly [14] or indirectly through their effects on structural stability and water retention [15]. Since both physical properties and biological impacts on plant health are critical to sustainable vegetable production, research strategies seeking optimal management of soil organic matter should combine short-term experiments in controlled conditions with long-term system monitoring in field conditions. Tolerance to drought is a key issue in vegetable cropping systems because climate change will likely increase the frequency and intensity of droughts in several areas [16].

The objective of this study was to quantify effects of three exogenous products rich in organic C (vermicompost from vermifiltration (VF), green waste compost (GWC) and dairy manure (DM)) on soil organic matter, water evaporation, bulk density and structural stability of a technosol. We chose to work with VF because of the physical and biological benefits expected from vermicompost in horticultural cropping systems [17–21]. These properties are associated with the feedstuff given to the earthworms and the microbial community associated with the earthworms [22–24]. Vermicompost is produced by vermicomposting or vermifiltration [25]. We preferred VF because its fine texture is well-adapted to vegetable cropping systems. We compared this new product to GWC and DM [26,27], which are already used in the vegetable production basin studied. They were considered as two reference organic products with contrasting rates of mineralization [28]. The experiment was designed to assess whether the three products had similar short-term dose-response effects on soil organic matter, water evaporation, bulk density and structural stability.

2. Materials and Methods

2.1. Soil and Organic Matter Used

The control soil (SS) of the experiment was a technosol made by covering an agricultural field with 1 m of marine sediments dredged from the bed of the Couesnon River estuary during coastal planning operations. The field was located in the basin of Mont Saint Michel, at Saint Georges-de-Gréhaigne, France (48.5° N; −1.5° W). The marine sediments were applied to the field one year before sampling. The climate is oceanic, with mean annual rainfall of 788 mm and mean annual temperature of 11 °C [29].

To collect soil for the experiment, the control soil was sampled twice, first in April 2014 (SS1) and again in May 2014 (SS2), but in the same place in the field in order to obtain identical samples. We sampled the soil shortly before we mixed it with the organic products to reproduce the biological behavior induced by mixing a fresh soil with a fresh organic product. This biological behavior is reputed to have a major influence on the effect of an organic product on the structural stability of aggregates [30]. Since VF contained much more water than GWC or DM, the VF mixture had to dry for several days in order to start the experiment with all three products at the same initial moisture. The main objective during preparation of the experimental design was to assess the existence of dose-response curves between the mass of OM input and soil structural stability. Microbial activity is known to play an important role in the link between organic input and structural stability [30]. The overall microbial activity of mixtures of soil and organic products depends on the respective initial microbial activities of the latter and on dynamics of water content (WC) and temperature. We were concerned that sampling the soil, mixing it, and then storing it at given water-content and temperature conditions could strongly affect the dose-response curve by altering microbial activity. Therefore, we decided to sample the soil in the same place on two successive dates, just before preparing the soil-organic product mixtures. Since sampling the same field in the same place ensured repeatability, we considered that SS2 was a replicate of SS1. We were fully conscious, however, that repeatability with living products cannot be as accurate as repeatability with reference materials used for chemical or physical metrology studies. Characteristics of the field soil are shown in Table 1.

Table 1. Main properties of the soil samples (*n* = 1) in April 2014 (SS1) and May 2014 (SS2) and their range observed in the same field (*n* = 26).

Soil Property	SS1	SS2	Range
Clay (%) [a]	5.3	4.6	2.8–8.5
Silt (%) [a]	32.3	27.3	27.3–38.4
Sand (%) [a]	62.5	67.8	54.7–67.8
$CaCO_3$ (%) [b]	40.5	42.4	37.9–44.0
Texture	Sandy loam	Sandy loam	Sandy loam
Organic matter (%) [b]	0.9	<0.7	<0.7–1.5
$CaCO_3$-C (g kg^{-1})	48.6	50.9	45.5–52.8
Organic C (g kg^{-1})	5.5	4.3	4.3–8.9
pH KCl	8.4	8.5	7.7–8.5
Conductivity (mS cm^{-1})	0.2	0.2	-

[a] % of total clay + silt + sand only; [b] % of total dry soil.

The experiment concerned four doses (3, 30, 60 and 120 g dry matter kg^{-1} dry soil) of three exogenous products rich in organic C differing in origin and biochemical stability: VF of liquid pig manure [31,32], GWC and fresh DM (Table 2).

Table 2. Main physical and chemical properties of vermicompost (VF), municipal green waste compost (GWC) and dairy manure (DM). (3 analyses of VF and 1 each of GWC and DM).

Property	VF	GWC	DM
Dry matter content (%)	5.6	45.0	19.1
pH	7.2	7.9	9.1
Conductivity (mS cm^{-1}), 1:1.5 extraction	4.6	N/A	11.6
C:N ratio	9.4	18.5	20.1
Total organic C (g C kg^{-1} dry matter)	369	315	370
Total N (g N kg^{-1} dry matter)	39.2	17.0	18.4
BSI [a] (% organic matter)	0.61	0.71	(0.27 [b])

N/A: analysis not available; [a] BSI: Biological Stability Index [33]; [b] not measured, assumed from [34].

2.2. Preparation of Soil and Organic Product Mixtures

SS1 was mixed with VF (0.05–2 L kg^1 wet soil) to obtain the four doses and air dried for 4 weeks to obtain the same WC as those of the other two mixtures. SS2 was mixed with GWC and DM at the same four doses. SS1 and SS2 were also used as control treatments without the addition of organic products. After 475±0.2 g of each control soil and soil mixture was placed in a plastic container (L × W × H = 13 × 11 × 6 cm), tap water was added (only at the beginning of the study) to reach a WC of 32 ± 1.2%. Finally, a 30 kg metal plate with the same area as the soil surface was placed on each sample to pack them identically. Despite applying the same pressure, the bulk density of samples differed due to differences in the relative quantities of soil and organic product. We thus measured soil volume at the end of the experiment.

The experimental design consisted of 14 treatments (four doses of each organic product, plus two control soils) with three replicates each, totaling 42 plastic containers (Figure 1).

All containers were air dried for 45 days under ambient temperature and relative humidity (23 ± 1.6 °C and 63 ± 4%, respectively) to assess benefits adding OM under “extreme” dry conditions as well. In the field, rain falling on these soils when dry can form slaking crusts, but increased structural stability (e.g., from increased OM content) can increase resistance to crusting [35]. We allowed WC to decrease until samples reached a constant mass. All containers were weighed at increasing intervals every 0.5 to 8 days, except on weekends. Soil WC was measured at the beginning and the end of the incubation period. Soil structural stability, organic C content and volume were measured at the end of the experiment.

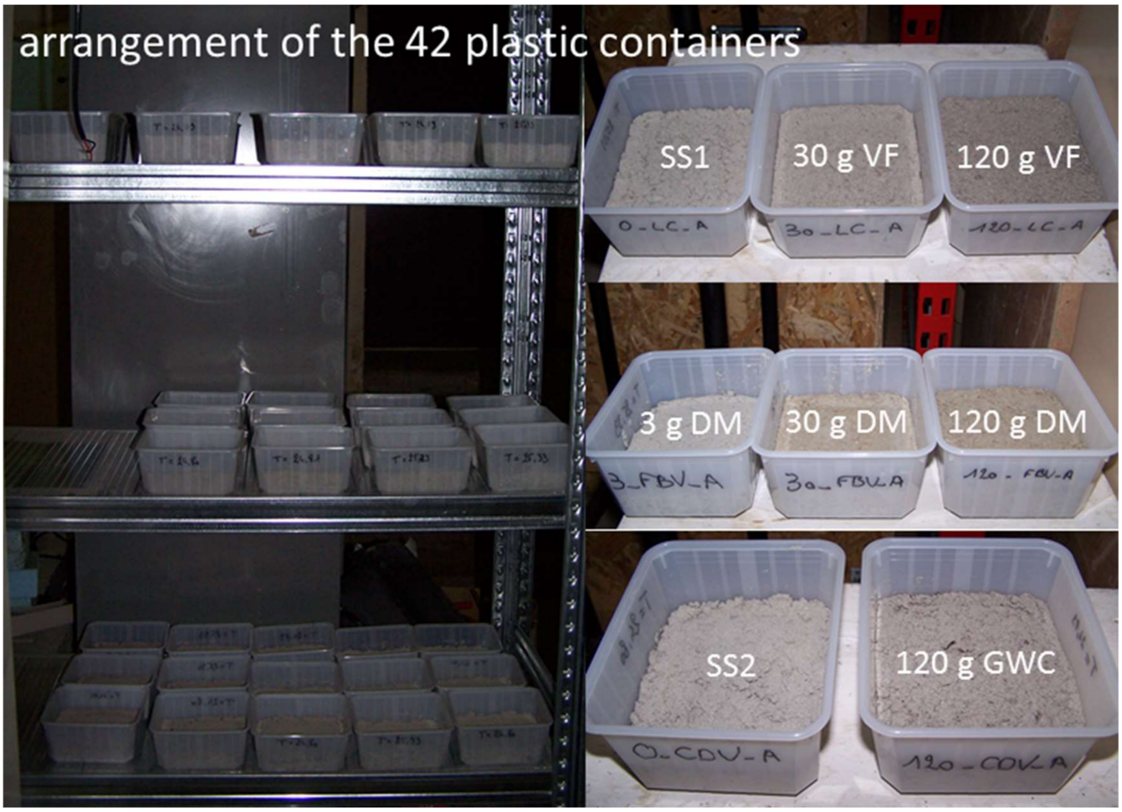

Figure 1. The 42 plastic containers of the experiment containing control soils from the first (SS1) and second (SS2) sampling dates and mixtures of soil with different doses of vermicompost from vermifiltration (VF), dairy manure (DM) and green waste compost (GWC).

2.3. Chemical and Physical Measurements

Soil composition (texture: NF EN 15428 [36]; pH: NF ISO 10390 [37]; cation exchange capacity, CEC: NF X 31.130 [38]; organic matter and organic C: NF ISO 14235 [39]) was analyzed at SAS Laboratory (Olivet, France). The following properties of VF and GWC were analyzed at SAS Laboratory: OM and mineral matter (NF EN 13039 [40]), pH (BS EN 12176 [41]), C:nitrogen (N) ratio, deduced from total N (NF EN 13342 [42]) and organic C (BS EN 12879 [43]). We considered dynamics of both endogenous OM (initial soil content) and exogenous OM (added VF, GWC or DM) as a single pool. Total C at the end of experiment was analyzed in all containers at INRA (NF ISO 10694, [44]). The mineralization of organic C was estimated as the initial organic C calculated minus the final organic C measured, provided that it was larger than the standard deviation of final organic C.

WC (kg water kg^{-1} dry soil) of all treatments was measured after drying a sample of each at 80 °C for 48 h at the beginning and end of the experiment. Structural stability was assessed by mechanically disaggregating each sample and measuring its mean weight diameter [35]. Bulk density (kg dry soil L^{-1} soil) was calculated by dividing the dry matter of each container's soil by its volume. Porosity was estimated from bulk density by assuming a density of 2.7 for stone and 1.7 for OM:

$$Porosity = 1 - bulk\ density \times \frac{\frac{mass\ dry\ soil}{stone\ density} + \frac{mass\ dry\ organic\ matter}{density\ of\ organic\ matter}}{mass\ dry\ soil + mass\ dry\ organic\ matter}$$

Evaporation rate (g water evaporated kg^{-1} dry soil day^{-1}) was calculated by dividing the loss of mass between two dates (assumed to be only water) by the mass of dry soil (more precisely: initial dry soil + added dry matter of organic products) and by the duration between the two dates. Mean values used for dose-response curves were calculated from values observed when soil moisture was 10–25%. We ignored the loss of mass due to OM decomposition (mineralization) during the study, since 75% of the samples showed no significant difference between initial and final mass of organic C, and the maximum loss of OM observed was ca. 3% of initial dry mass.

Statistical analysis was performed with Excel® (Microsoft, Issy-les-Moulineaux, France). A Welch *t*-test was used to test the significance of differences between treatments because the variance of samples could not be assumed equal.

3. Results

3.1. Effect of an Organic Product on Evaporation Rate Depends on WC

All organic products increased the C content of the soil (Figure 2). The increase was slightly less for GWC because of its lower content in C (Table A1). The difference between doses was significant for all products except certain products between two consecutive doses (Table A1). At the same dose, the difference between products was significant only between VF and DM at 3 g OM kg^{-1} soil (Table A1). Mineralization of organic C was observed at the highest dose (120 g dry matter kg^{-1} dry soil). The decrease in C content was respectively 18 ± 8%, 33 ± 1% and 15 ± 12% for VF, GWC and DM. The final C content of GWC at the highest dose was significantly lower than those of VF and DM ($p < 0.05$; Table A1).

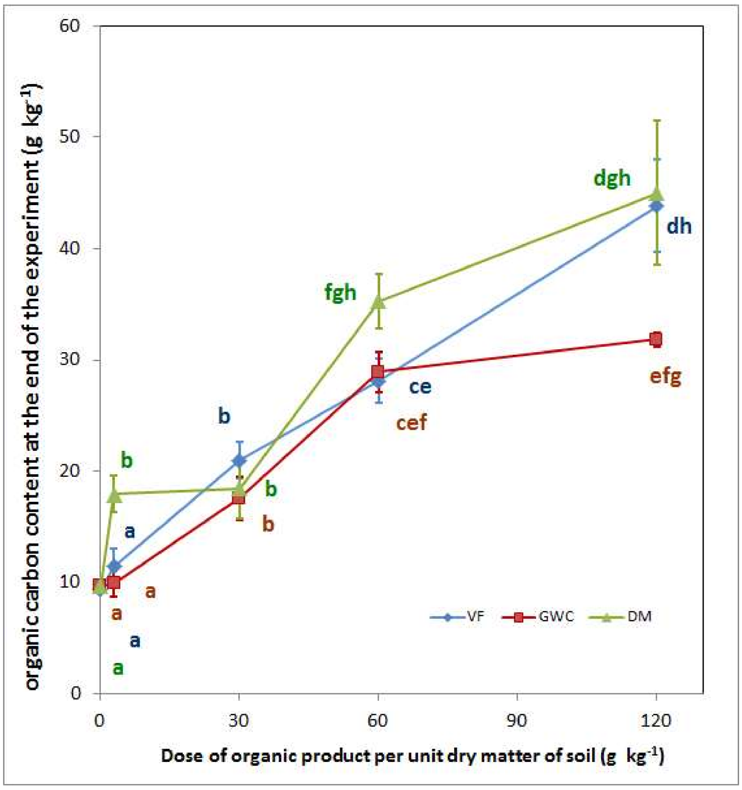

Figure 2. Effect of different doses of vermicompost (VF), green waste compost (GWC) and dairy manure (DM) on soil organic carbon content. Error bars represent 1 standard deviation of three replicates. Points with the same letter are not significantly different ($p < 0.05$). (Details are in Table A1).

Large differences in evaporation rate were observed between control soils: from 10 to 33% WC, SS2 (mixed with VF) dried faster than SS1 (mixed with GWC and DM) (Figure 3). This difference can be explained by SS2 having slightly less clay and silt but more sand. At medium WC (10–25%), increasing the dose of OM decreased the evaporation rate, regardless of the product (Figure 3). In dry soils (WC < 10%), the lowest dose of all three products (3 g OM kg^{-1} soil) increased the evaporation rate for all 3 OM. The thresholds of inversion depended on the soil (5% and 10% for SS1 and SS2, respectively). In wet soils (WC > 25%), large inputs of VF or DM (120 g OM kg^{-1} soil) increased the evaporation rate. It was not the case of GWC. The thresholds of this inversion depended on the soil (25% and 28% WC for SS1 and SS2, respectively). A high dose of VF slightly increased the WC at which evaporation became negligible: 2% WC for 120 g VF kg^{-1} soil, and ca. 1 ± 0.4% for all other doses and products.

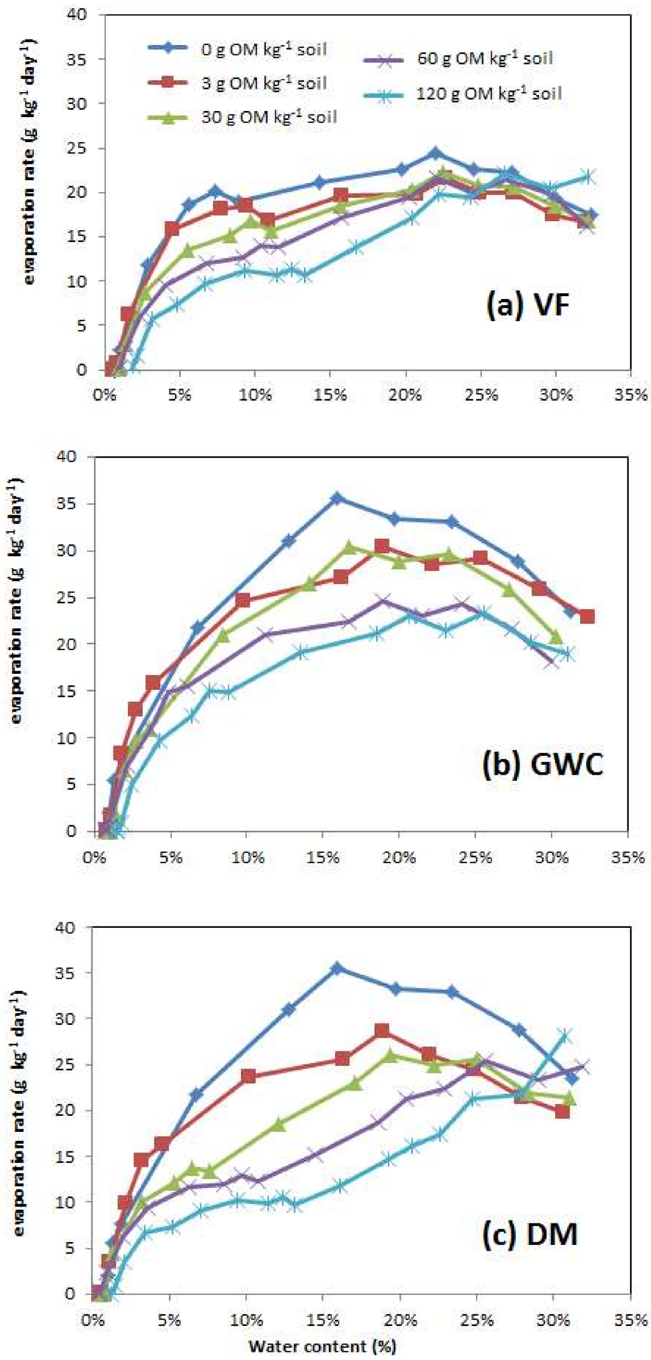

Figure 3. Effect of addition of (**a**) vermicompost (VF) to control soil SS1 and (**b**) green waste compost (GWC) and (**c**) dairy manure (DM) to control soil SS2 on the soils' evaporation rates.

3.2. Dose-Response Curves for Evaporation Rate, Bulk Density, Structural Stability and Porosity

Mean evaporation rate decreased with increasing dose of product, regardless of the product (Figure 4a). The effect of adding GWC on evaporation rate decreased with the dose but remained proportional when adding DM. Differences between products were more significant at doses 3 and 30 g OM kg^{-1} soil (Table A2).

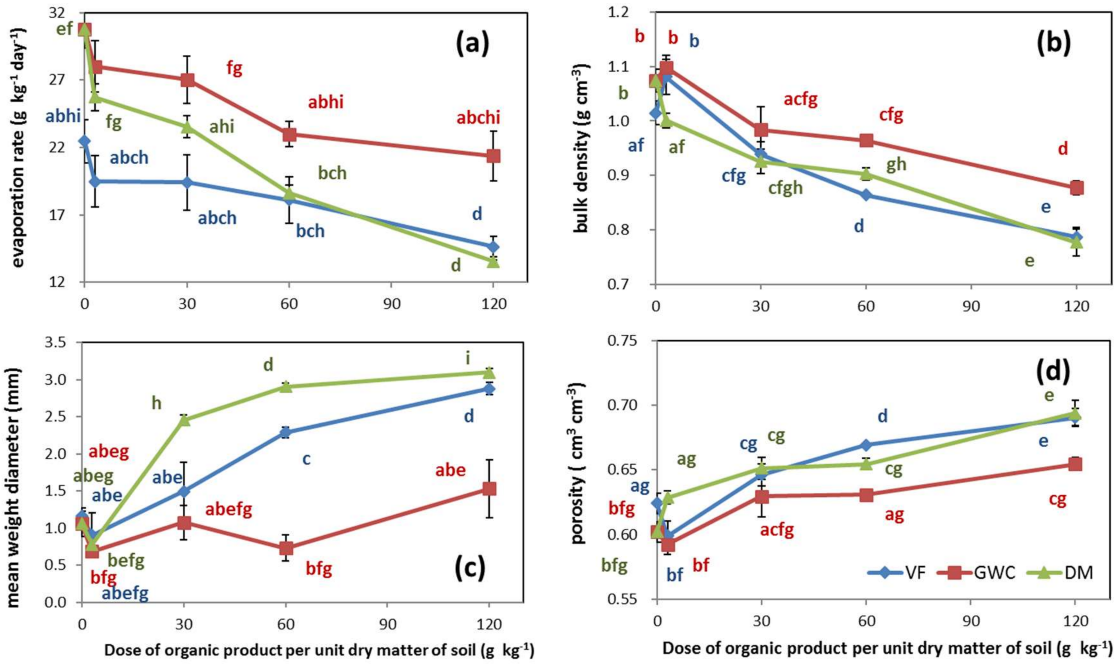

Figure 4. Mean dose-response curves to addition of vermicompost (VF), green waste compost (GWC) and dairy manure (DM) at water contents of 10–25% for (**a**) evaporation rate; (**b**) bulk density; (**c**) mean weight diameter and (**d**) porosity. Error bars represent 1 standard deviation of three replicates. Points with the same letter are not significantly different ($p < 0.05$). (Details are in Tables A2–A5).

Bulk density decreased with increasing dose of product, regardless of the product (Figure 4b). The effect of dose was significant for all three products (Table A3). SS1 and SS2 had similar bulk densities. The volume of mixtures increased by 22%, 26%, and 38% between control soil and 120 g OM kg^{-1} soil for GWC, VF, and DM respectively. In contrast, the lowest dose of VF and GWC (3 g OM kg^{-1} soil) increased bulk density. At the same dose, GWC had significantly less effect on bulk density than VF or DM (Table A3; higher bulk density with GWC, Figure 4b).

Structural stability increased with increasing dose of VF or DM (Figure 4c) but not always significantly with GWC (Table A4). SS1 and SS2 had similar structural stabilities. The lowest dose of product (3 g OM kg^{-1} soil), especially DM and then VF, decreased structural stability. The largest slope was observed with DM between 3 and 30 g OM kg^{-1} soil. The effect of VF and GWC on structural stability was nearly linear.

Porosity increased with increasing dose of OM, regardless of the product (Figure 4d). VF and DM had a significantly larger effect than GWC (Table A5).

4. Discussion

4.1. Relative Effects of Soil Characteristics and Organic Inputs on Evaporation Rate

Results showed that the effect of organic inputs on physical properties depended on the organic product and dose but also on the initial soil. Spatial variability in soil properties within the same field is commonly observed and has various origins [45,46]. We sampled field soil on two successive dates to reproduce the microbial behavior that occurs when mixing fresh organic products with soils. Control soils SS1 and SS2 differed, even though both were sampled at the same place in the field. Other technosols may experience this variability because the technical operations of producing, loading and unloading material can induce spatial variability over short distances due to small differences in the material supplied. Therefore, we recommend (1) checking the reproducibility of laboratory results obtained for soils sampled from technosols and (2) developing field indicators that allow for spatial validation of results extrapolated at the field scale.

An increasing dose of OM decreased evaporation rate at WC below 25%, regardless of the soil and organic product. The effect of organic inputs on evaporation rate was similar to that of the initial variability in soil (ca. 8 g water kg^{-1} dry soil day^{-1}) for VF and GWC, while the effect of DM was larger (ca. 17 g water kg^{-1} dry soil day^{-1}). Differences in fine-particle and salt content can explain these differences. SS1 contained more silt and clay than SS2 (+56 g kg^{-1} dry soil). VF was composed exclusively of fine organic particles (<0.1 mm), while GWC and DM were composed of a range of particle sizes (up to ca. 1 cm). Therefore, the larger effect of DM cannot be due only to adding a large amount of fine particles. DM had a much higher conductivity than VF (Table 2). The effect of salt content on evaporation rate increases during drying because of increasing osmotic pressure of water. The higher salt content of DM can also explain why differences in points on the dose-effect curve of DM on evaporation rate were more significant than those of VF and GWC (Table A2; comparing doses of the same product). Since salinity may decrease after rainfall, we assume that the observed effect of DM would be smaller following field application.

4.2. Effects of Organic Product and Dose on Organic Carbon Content, Porosity and Structural Stability

The observed effects of organic product and dose on organic C content, porosity and structural stability can be explained by both biochemical characteristics and particle-size distribution. An increasing dose of OM increased organic C content. The differences between organic products and doses observed were much larger than those between initial soil samples. The increases in organic C observed should be smaller after field application because of further mineralization of added OM. In our experiment, the drying of samples limited mineralization compared to that under field conditions. The Biological Stability Index (BSI) should help assess the fraction of stable C added to soils. Composted animal products mineralize more slowly than fresh animal manure [28,34,47]. We therefore expected that DM would lose more C than VF and GWC, which would have similar C losses. In the experiment, however, C loss was not detected at doses of organic input below 60 g OM kg^{-1} soil. This can be explained by the drying of samples, which decreased microbial activity and thus mineralization. The high OM input that we used was much higher than that usually spread in the field (i.e., limited to 150 kg N ha^{-1} for animal manure). The high loss of C observed in all replicates of GWC show that the theoretical loss indicated by the BSI may vary under field conditions due to variability in soil texture and microbial activity. The literature shows that C mineralization increases when the content of fine particles decreases [48,49]. The soil considered here was a sandy loam and thus susceptible to induce high mineralization. Extrapolating C mineralization to the field scale from the observations in this study requires further validation. Since VF had both fine particles and a high BSI, we assume that it would have lower C mineralization than GWC (larger particles) and DM (larger particles and lower BSI).

An increasing dose of OM increased porosity. The differences between organic products and doses observed were much larger than those between initial soil samples (Figure 4b). Studies have observed organic inputs increasing porosity [17,50,51], thus decreasing compaction. At high WC, the increase in porosity induced more free air space and thus increased gas diffusion, leading to higher evaporation rates. At WC below 20%, evaporation rate was decreased. Increased porosity and decreased evaporation rate can increase the tolerance of vegetable crops to drought. Water transport and retention are determined by texture and OM content [52,53]. Since SS1 contained more fine particles than SS2, we assume that the effect of OM was larger than that of the particle-size distribution of the soils. Consequently, we assume that observations can be extrapolated to other technosols made with similar sediments.

An increasing dose of OM increased structural stability. Among the processes explaining the relationship between organic input and structural stability [30], either a direct abiotic effect of organic products or microbial activity stimulated by initial biochemical characteristics of the organic products could contribute to the short-term effect observed. At the highest dose, GWC lost the most C but had less effect on structural stability than VF or DM. Therefore, we believe that an abiotic effect of VF and DM had a larger influence. At a low dose of OM, an opposite effect was observed: bulk density increased and structural stability decreased. This opposite effect can be explained by the high calcium content and physical interactions between stable OM, calcium and soil [10,54,55] that decreased the stability of initial soil aggregates when they were mixed with OM and water.

4.3. Choice of Organic Product

VF had effects similar to those of DM except on evaporation rate. At similar doses, effects of VF and DM on structural stability, bulk density and porosity were greater than those of GWC. In addition, GWC lost more C than VF or DM. Therefore, from the present results, the maximum effect can be expected from either VF or DM.

Increased stability of OM should increase the duration of effects on soil properties due to a higher OM content of the soil. The BSI of VF was higher than that of DM. Other measurements in controlled conditions show that fresh products from animal farms mineralize more rapidly than stabilized products [28,47]. This experiment showed a larger effect of DM on evaporation rate than VF, but as mentioned, it may be due to the higher salt content of DM, which should decrease rapidly after rainfall. VF and DM had a similar influence on bulk density. Since VF should be more stable, we assume that it should have a longer effect on bulk density than DM. Since bulk density can be decreased by decompacting the soil, we recommend adding high doses of VF when soils are decompacted to increase the duration of physical effects.

5. Conclusions

Increasing the dose of organic matter input to a soil made with marine sediments increased total soil organic carbon content (i.e., initial soil organic matter plus added organic matter), porosity and structural stability. Increasing the dose of organic matter also decreased the evaporation rate of soil. Despite differences in biological stability of the organic products used, differences in final carbon content were small after 45 days. We assumed that the dry conditions of our experiment explained the low mineralization and small differences between products.

We suggest that high doses of organic matter will increase the tolerance of vegetable crops to drought. In areas where one can choose among different types of organic matter, vermicompost is preferable because of its biological stability and larger effects on physical properties, such as decreasing bulk density and evaporation rate.

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Author Contributions: Paul Robin, Nouraya Akkal-Corfini and Camille Morel conceived and designed the experiments; Camille Morel performed the experiments; Camille Morel and Paul Robin analyzed the data; Franck Vial, Brigitte Landrain, Aurore Toudic and Yinsheng Li contributed to analysis; Nouraya Akkal-Corfini contributed analysis tools; Paul Robin, Camille Morel and Nouraya Akkal-Corfini wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Significance of differences between carbon content of treatments (product—dose; 3 products were VF: vermicompost; GWC: green waste compost; DM: dairy manure; 5 doses of OM input were: 0, 3, 30, 60 and 120 g dry organic matter kg^{-1} dry soil). (ns): non-significant; (*): $p < 0.05$; (**): $p < 0.01$; (***): $p < 0.001$.

Carbon Content	VF-0	VF-3	VF-30	VF-60	VF-120	GWC-0	GWC-3	GWC-30	GWC-60	GWC-120	DM-0	DM-3	DM-30	DM-60	DM-120
VF-0	-	ns	**	**	**	ns	ns	**	**	***	ns	**	*	**	**
VF-3	ns	-	**	***	**	ns	ns	*	***	**	ns	**	*	***	**
VF-30	**	**	-	**	**	**	**	ns	**	**	**	ns	ns	**	*
VF-60	**	***	**	-	*	**	***	**	ns	*	**	**	**	*	*
VF-120	**	**	**	*	-	**	**	**	*	*	**	**	**	*	ns
GWC-0	ns	ns	**	**	**	-	ns	**	**	***	ns	**	*	**	**
GWC-3	ns	ns	**	***	**	ns	-	**	***	***	ns	**	*	**	**
GWC-30	**	*	ns	**	**	**	**	-	**	**	**	ns	ns	**	**
GWC-60	**	***	**	ns	*	**	***	**	-	ns	**	**	**	*	*
GWC-120	***	**	**	*	*	***	***	**	ns	-	***	**	**	ns	*
DM-0	ns	ns	**	**	**	ns	ns	**	**	***	-	**	*	**	**
DM-3	**	**	ns	**	**	**	**	ns	**	**	**	-	ns	***	**
DM-30	*	*	ns	**	**	*	*	ns	**	**	*	ns	-	**	*
DM-60	**	***	**	*	*	**	**	**	*	ns	**	***	**	-	ns
DM-120	**	**	*	*	ns	**	**	**	*	*	**	**	*	ns	-

Gray cells correspond to intra-product differences. Underlined bold text corresponds to differences between products (same dose).

Table A2. Significance of differences between evaporation rate of treatments (product—dose; 3 products were VF: vermicompost; GWC: green waste compost; DM: dairy manure; 5 doses of OM input were: 0, 3, 30, 60 and 120 g dry organic matter kg^{-1} dry soil). (ns): non-significant; (*): $p < 0.05$; (**): $p < 0.01$; (***): $p < 0.001$.

Evaporation Rate	VF-0	VF-3	VF-30	VF-60	VF-120	GWC-0	GWC-3	GWC-30	GWC-60	GWC-120	DM-0	DM-3	DM-30	DM-60	DM-120
VF-0	-	ns	ns	*	**	**	*	*	ns	ns	**	*	ns	*	**
VF-3	ns	-	ns	ns	*	**	**	**	ns	ns	**	**	*	ns	*
VF-30	ns	ns	-	ns	*	**	**	**	ns	ns	**	*	*	ns	*
VF-60	*	ns	ns	-	*	**	**	**	*	ns	**	**	*	ns	*
VF-120	**	*	*	*	-	***	**	**	***	*	***	***	***	**	ns
GWC-0	**	**	**	**	***	-	ns	*	**	**	ns	**	**	**	**
GWC-3	*	**	**	**	**	ns	-	ns	*	*	ns	ns	*	**	**
GWC-30	*	**	**	**	**	*	ns	-	*	*	*	ns	*	**	**
GWC-60	ns	ns	ns	*	***	**	*	*	-	ns	**	*	ns	**	**
GWC-120	ns	ns	ns	ns	*	**	*	*	ns	-	**	*	ns	ns	**
DM-0	**	**	**	**	***	ns	ns	*	**	**	-	**	**	**	**
DM-3	*	**	*	**	***	**	ns	ns	*	*	**	-	*	***	**
DM-30	ns	*	*	*	***	**	*	*	ns	ns	**	*	-	**	**
DM-60	*	ns	ns	ns	**	**	**	**	**	ns	**	***	**	-	**
DM-120	**	*	*	*	ns	**	**	**	**	**	**	**	**	**	-

Gray cells correspond to intra-product differences. Underlined bold text corresponds to differences between products (same dose).

Table A3. Significance of differences between bulk density of treatments (product—dose; 3 products were VF: vermicompost; GWC: green waste compost; DM: dairy manure; 5 doses of OM input were: 0, 3, 30, 60 and 120 g dry organic matter kg^{-1} dry soil). (ns): non-significant; (*): $p < 0.05$; (**): $p < 0.01$; (***): $p < 0.001$.

Bulk Density	VF-0	VF-3	VF-30	VF-60	VF-120	GWC-0	GWC-3	GWC-30	GWC-60	GWC-120	DM-0	DM-3	DM-30	DM-60	DM-120
VF-0	-	*	*	**	***	*	**	ns	*	**	*	ns	**	**	***
VF-3	*	-	**	**	***	ns	ns	*	*	**	ns	*	**	**	***
VF-30	*	**	-	*	**	**	**	ns	ns	*	**	*	ns	*	**
VF-60	**	**	*	-	**	**	**	*	***	ns	**	**	*	*	*
VF-120	***	***	**	**	-	***	***	**	**	**	***	***	**	**	ns
GWC-0	*	ns	**	**	***	-	ns	*	**	***	ns	**	**	***	***
GWC-3	**	ns	**	**	***	ns	-	*	**	***	ns	**	**	***	***
GWC-30	ns	*	ns	*	**	*	*	-	ns	*	*	ns	ns	*	**
GWC-60	*	*	ns	***	**	**	**	ns	-	**	**	*	ns	**	**
GWC-120	**	**	*	ns	**	***	***	*	**	-	***	***	*	*	**
DM-0	*	ns	**	**	***	ns	ns	*	**	***	-	**	**	***	***
DM-3	ns	*	*	**	***	**	**	ns	*	***	**	-	**	**	***
DM-30	**	**	ns	*	**	**	**	ns	ns	*	**	**	-	ns	**
DM-60	**	**	*	*	**	***	***	*	**	*	***	**	ns	-	**
DM-120	***	***	**	*	ns	***	***	**	**	**	***	***	**	**	-

Gray cells correspond to intra-product differences. Underlined bold text corresponds to differences between products (same dose).

Table A4. Significance of differences between structural stability of treatments (product—dose; 3 products were VF: vermicompost; GWC: green waste compost; DM: dairy manure; 5 doses of OM input were: 0, 3, 30, 60 and 120 g dry organic matter kg^{-1} dry soil). (ns): non-significant; (*): $p < 0.05$; (**): $p < 0.01$; (***): $p < 0.001$.

Structural Stability	VF-0	VF-3	VF-30	VF-60	VF-120	GWC-0	GWC-3	GWC-30	GWC-60	GWC-120	DM-0	DM-3	DM-30	DM-60	DM-120
VF-0	-	ns	ns	***	***	ns	**	ns	*	ns	ns	*	***	***	***
VF-3	ns	-	ns	**	**	ns	ns	ns	ns	ns	ns	ns	**	**	**
VF-30	ns	ns	-	*	*	ns	*	ns	*	ns	ns	*	*	*	**
VF-60	***	**	*	-	**	**	***	**	**	*	**	***	*	***	***
VF-120	***	**	*	**	-	**	***	**	**	*	**	***	**	ns	*
GWC-0	ns	ns	ns	**	**	-	*	ns	*	ns	ns	ns	**	**	**
GWC-3	**	ns	*	***	***	*	-	ns	ns	*	*	ns	***	***	***
GWC-30	ns	ns	ns	**	**	ns	ns	-	ns	ns	ns	ns	**	**	**
GWC-60	*	ns	*	**	**	*	ns	ns	-	*	*	ns	**	**	***
GWC-120	ns	ns	ns	*	*	ns	*	ns	*	-	ns	*	*	*	*
DM-0	ns	ns	ns	**	**	ns	*	ns	*	ns	-	ns	**	**	**
DM-3	*	ns	*	***	***	ns	ns	ns	ns	*	ns	-	***	***	***
DM-30	***	**	*	*	**	**	***	**	**	*	**	***	-	**	***
DM-60	***	**	*	***	ns	**	***	**	**	*	**	***	**	-	*
DM-120	***	**	**	***	*	**	***	**	***	*	**	***	***	*	-

Gray cells correspond to intra-product differences. Underlined bold text corresponds to differences between products (same dose).

Table A5. Significance of differences between porosity of treatments (product—dose; 3 products were VF: vermicompost; GWC: green waste compost; DM: dairy manure; 5 doses of OM input were: 0, 3, 30, 60 and 120 g dry organic matter kg^{-1} dry soil). (ns): non-significant; (*): $p < 0.05$; (**): $p < 0.01$; (***): $p < 0.001$.

Porosity	**VF-0**	**VF-3**	**VF-30**	**VF-60**	**VF-120**	**GWC-0**	**GWC-3**	**GWC-30**	**GWC-60**	**GWC-120**	**DM-0**	**DM-3**	**DM-30**	**DM-60**	**DM-120**
VF-0	-	*	*	**	***	*	**	ns	ns	**	*	ns	*	**	**
VF-3	*	-	**	**	***	ns	ns	*	*	**	ns	*	**	**	***
VF-30	*	**	-	*	**	**	**	ns	*	ns	**	*	ns	ns	**
VF-60	**	**	*	-	*	**	**	*	***	*	**	**	*	*	*
VF-120	***	***	**	*	-	***	***	*	**	**	***	***	**	**	ns
GWC-0	*	ns	**	**	***	-	ns	ns	*	**	ns	**	**	**	***
GWC-3	**	ns	**	**	***	ns	-	*	**	***	ns	**	**	***	***
GWC-30	ns	*	ns	*	*	ns	*	-	ns	ns	ns	ns	ns	ns	**
GWC-60	ns	*	*	***	**	*	**	ns	-	**	*	ns	*	**	**
GWC-120	**	**	ns	*	**	**	***	ns	**	-	**	**	ns	ns	**
DM-0	*	ns	**	**	***	ns	ns	ns	*	**	-	**	**	**	***
DM-3	ns	*	*	**	***	**	**	ns	ns	**	**	-	*	**	**
DM-30	*	**	ns	*	**	**	**	ns	*	ns	**	*	-	ns	**
DM-60	**	**	ns	*	**	**	***	ns	**	ns	**	**	ns	-	*
DM-120	**	***	**	*	ns	***	***	**	**	**	***	**	**	*	-

Gray cells correspond to intra-product differences. Underlined bold text corresponds to differences between products (same dose).

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