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RESEARCH

Effects of Mineral and Organic Fertilization on Forage Maize Yield, Soil Carbon Balance, and NPK Budgets, Under Rainfed Conditions in the Azores Islands (Portugal)

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Abstract
Green organic fertilizers can be a valuable option to reduce the use of chemical fertilizers, improve the physical and chemical properties of soil, and promote circular agriculture. The effects of two fertilization schemes, (i) a combination of mineral fertilizers with dairy farm slurry (TA) and (ii) an organic substrate (SO) from green waste (TB), on soil fertility and forage maize (*Zea mays* L.) yield were studied in an on-farm trial in the Azores Island of S. Miguel (Portugal). For this purpose, soil chemical parameters were evaluated on three sampling dates, forage maize yield and yield components were compared, and the balances of soil carbon (SC), nitrogen (N), phosphorus (P), and potassium (K) were evaluated. The results showed that the maize yield obtained in TB was significantly higher than in TA. The differences in precipitation that occurred over the two years influenced the yield in both treatments. The SC, available P, and pH were significantly higher in TB at every sampling date, mainly in the subsurface layer, and overall enrichment in nitrogen was observed. Despite the need to extend this evaluation over a longer period, the results indicate that the application of SO could be an alternative to conventional mineral fertilization in forage maize in the Azores and in similar cropping systems in regions of temperate insular nature.

Keywords Green organic fertilizer · Nutrients balance · Slurry · Soil carbon dynamics · *Zea mays* L.

Introduction

The production of forage maize in the Azores Archipelago Islands (Autonomous Region of Azores (ARA), Portugal) was 610,884 tons in 2020, distributed over an area of 13,740 ha, respectively, 19.5% and 19.3% of the Portuguese national production and area (GPP, 2021; SREA, 2022). Its production in the cropping system forage maize – ryegrass (*Lollium multiflorum* L.) for hay/silage in São Miguel, the largest of the nine islands of the ARA, occupied an area of 8575 ha, in 2020 (SREA, 2022). In this cropping system, conventional soil tillage consists of plowing followed by secondary tillage with a rotary tiller, in the case of maize, in May–June, and in harrowing in the case of ryegrass, in October–November. Thereby, the soil is periodically disturbed to plant maize and later to replant the ryegrass, leading to a strong tendency for water erosion, particularly in steep to moderate slopes, as described by Fontes et al. (2004) in the similar environment of the Terceira Island. The fertilization scheme commonly adopted uses a combination of chemical fertilizers and slurry (liquid manure) from dairy farms, making use of some circular agriculture through nutrient recycling within the traditional dairy farming systems. In recent years, dairy farming has intensified through the increase in stabling, mechanical milking, and chemical fertilizers inputs (de Almeida et al., 2020).

Agricultural practices that rely heavily on chemical fertilizers, mostly nitrogen, and phosphorus, can lead to low nutrient absorption efficiency, significant nutrient losses due to leaching, nutrient imbalances in the soil, and overall reduced soil health (Krasilnikov et al., 2022;

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Pahalvi et al., 2021). Alternative fertilization strategies, like fertilization splitting/timing, application of enhanced efficiency fertilizers, or organic fertilizers obtained from animal manures or other types of organic materials, represent environmentally friendly practices that can contribute to sustainable farming systems (Allam et al., 2022; Dinesh et al., 2010; Iqbal et al., 2014; Patanita et al., 2019; Tomaz et al., 2021). Among the latter, organic fertilizers that are obtained from plant residues and subjected to processes like composting may be valid options for the sustainability of traditional agriculture and the enhancement of the ecosystem services, such as nutrient recycling, improvement of soil health, and increment of soil organic carbon (SOC) stocks (Adhikari & Hartemink, 2016; Clapp et al., 2007; Erich et al., 2012; Freibauer et al., 2004).

The benefits of composting, reusing, and recycling nutrients are well known and include pollution reduction, reuse of organic waste, reduction of the inputs and cost of fertilizers, and circularity of nutrients needed for food production (Havlin & Heiniger, 2020; Rosemarin et al., 2020; Sharpley et al., 2001; Winpenny et al., 2010).

In addition to its ability to release nutrients, SOC is responsible for enhancing soil water storage capacity and other improved physical properties of the soil (Weil & Brady, 2016). Moreover, the sequestration of SOC in agroecosystems is one of the key measures to the mitigation of climate change and is of great concern in regions where SOC is low, as is the case of some Southern Europe Countries (Chiti et al., 2012; Rodríguez Martín et al., 2016).

Studies on the use of organic fertilizers from green residues in forage production have reported several benefits, such as: (i) higher soil organic matter and nutrients content (Carr et al., 2020; Diacono et al., 2012; Herencia et al., 2007; Montemurro et al., 2006); (ii) improved soil quality, increased yield, and higher photosynthetic rates (Asaye et al., 2022; Efthimiadou et al., 2010); (iii) increased P availability (Vanden Nest et al., 2016); (iv) higher nutritional value of forage (Moreno-Reséndez et al., 2017). In the face of the growing agricultural intensification within the farming sector of the ARA, with the use of increasing amounts of fertilizers and their current cost, it is relevant to evaluate the use of different organic wastes as alternatives to chemical fertilizers to enhance crop productivity and maintain the agroecosystems' sustainability.

Taking the above into consideration, we studied the effects of two fertilization schemes based, respectively, on combinations of mineral fertilizers with dairy farm slurry and on an organic substrate produced by composting from green waste, during a two-year on-farm trial of forage maize. For this purpose, we evaluated: (i) the effects of fertilization and depth on soil chemical parameters; (ii) the soil morphology modifications due to tillage operations; (iii) the effects of fertilization on forage maize yield and yield components; (iv) the SC balance, and the NPK budgets.

Materials and Methods

Study Design

This study took place in 2020 and 2021 on a commercial farm located on S. Miguel Island, ARA (Portugal) (37°53′03.93″ N; 25°43′40.08″ W). It consisted of two cycles of forage maize, cultivar 'LimaGrain'. Ryegrass was sowed in the Autumn–Winter of 2020–2021, for grazing and hay/silage. Two treatments of fertilization management were evaluated, namely, treatment A (TA) and treatment B (TB) (Table 1). The TA consisted of fertilization commonly applied by producers in the region and adopted by the farmer, with the application of nitrogen (nitrate (NO_3) and ammonium (NH_4)), phosphorus (phosphorus pentoxide (P_2O_5)) and potassium (potassium oxide (K_2O)) in ternary (NPK), binary (NP), simple formulations (P), and top-dressing N mineral fertilizers, complemented with 30 kg ha^{-1} of slurry from dairy farms (NPK = 2.1:0.23:1.8 (kg per 100 kg)). TB consisted of the application of 40 kg m^{-2} (45% moisture content; 22 kg m^{-2} when dry) of an organic

Table 1 Fertilization management treatments over the study

Treatments and NPK applied	TA NPK (kg ha^{-1})	TB NPK (kg ha^{-1})
1st year maize (sowing: 12 June 2020; harvest: 30 September 2020)		
Fertilization		
Mineral		
At sowing	70:26:0	–
Top dressing	105:0:0	
Organic		
At sowing	63:7:54[a]	93:16:98[b,c]
Total	238:33:54	93:16:98
2nd year maize (sowing: 22 May 2021; harvest: 29 September 2021)		
Fertilization		
Mineral		
At sowing	140:24:58	–
Top dressing	35:27:35	–
Total	175:51:93	–

TA Conventional fertilization, *TB* Organic substrate (SO) fertilization

[a]Dairy farm slurry

[b]Organic substrate SO-MUSAMI

[c]Considering a decomposition rate of the SO of 3.59% in 4 months (Oliveira, 2021)

substrate (SO), applied in the first maize cycle, without the addition of mineral fertilizations.

The SO is named SO-MUSAMI and is sanitized (free from pathogenic organisms) and matured by composting from biodegradable green organic waste, specifically from gardening residues, and approved for organic farming, according to EU regulation No. 834/07 (European Commission, 2007) (Table 2).

Soil tillage consisted of the following operations: 1st year maize – (i) spreading of SO in TB and of slurry plus mineral fertilizers in TA, (ii) plowing at a depth of 35 cm with a two-moldboard plow, (iii) break up and smoothing the soil with rotary tiller, and (iv) sowing with a precision seeder (70 cm × 17 cm spacing); 2nd year maize – same tillage operation but with plowing being replaced by subsoiling at a depth of 25 cm.

To address the convex morphology of the terrain, which presented a longitudinal slope of 10–15%, in the South-North direction, and radial slope of 5–10%, the TA and TB treatments were assigned in a randomized complete block design, with two blocks and two replicates of each treatment in each block.

Table 2 Main physical and chemical characteristics of the organic substrate SO-MUSAMI (MUSAMI, 2020)

Bulk density (kg dm^{-3})	0.4
Electrical conductivity (25ºC) (mS cm^{-1})	0.65
Organic matter (%)	30.2
Ratio C/N	13.60
pH (H_2O)	7.5–8.5
Cation Exchange Capacity ($cmol_{(+)}$ kg^{-1})	40
Total Nitrogen (N; %)	1.20%
Extractable Phosphorus ($P_2O_{5;}$ %)	0.49
Extractable Potassium (K_2O; %)	1.17
Extractable Magnesium (MgO; %)	1.30
Extractable Sulfur (SO_3; %)	0.34
Cadmium (Cd; mg kg^{-1})	0
Chromium (Cr, mg kg^{-1})	25.5
Copper (Cu; mg kg^{-1})	33.0
Mercury (Hg; mg kg^{-1})	0.5
Nickel (Ni; mg kg^{-1})	29.4
Lead (Pb; mg kg^{-1})	18.2
Zinc (Zn; mg kg^{-1})	99.0

Site Description

The ARA is the most Western European region, composed of nine islands of volcanic origin in the North Atlantic Ocean. The climate in the region is mostly classified as Warm Summer Mediterranean climate (Csb in Köppen classification), with the western islands presenting a Temperate Oceanic climate (Cfb). In S. Miguel, the annual average temperature is 17.8 °C and annual precipitation is 1053 mm (long-term mean for the period 1981–2010; (IPMA, 2022a)).

Main meteorological data (average temperature -T—and precipitation—P) for 2020 and 2021 were obtained from the climate bulletins of the Portuguese Institute of the Sea and Atmosphere (IPMA, 2022b) (Fig. 1). The warmest months (June–September) had average temperatures of 21 °C, with a total precipitation of 167 mm in 2020 and 224 mm in 2021. Global radiation (Rg) and relative humidity (HR) average values for the period 2013–2016 were acquired from the climatological station of INOVA (Institute of Technological Innovation of the Azores (INOVA, 2022)), located near the experimental site (Fig. 2). Mean relative humidity is 91% and global radiation of 283 W m^{-2}.

Soils in the experimental site are classified as Andic Cambisols (IUSS Working Group WRB, 2015), being derived from weathering of pyroclastic materials, like ash and pumice, with vitric properties of volcanic-glass and containing a limited amount of short-range-order mineral (allophanes) with evidence of pedogenetic alteration (cambic horizon)

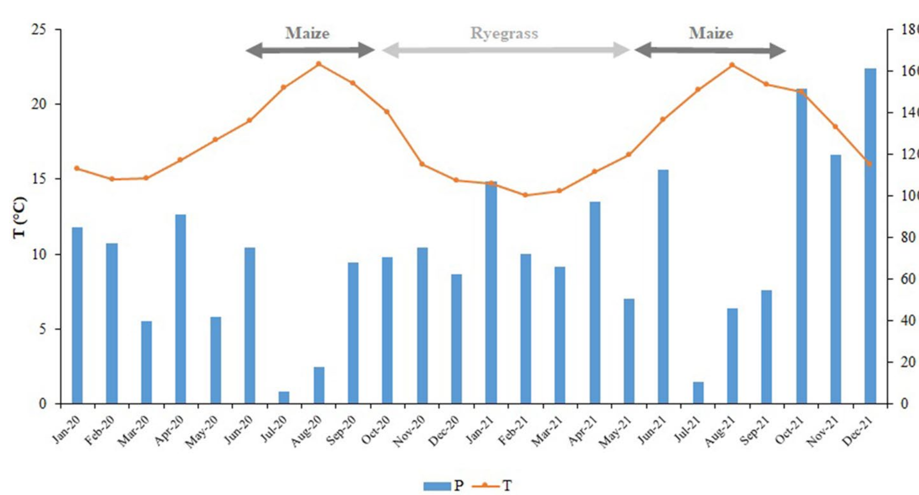

Fig. 1 Average monthly temperature (T) and monthly precipitation (P) over 2020 and 2021

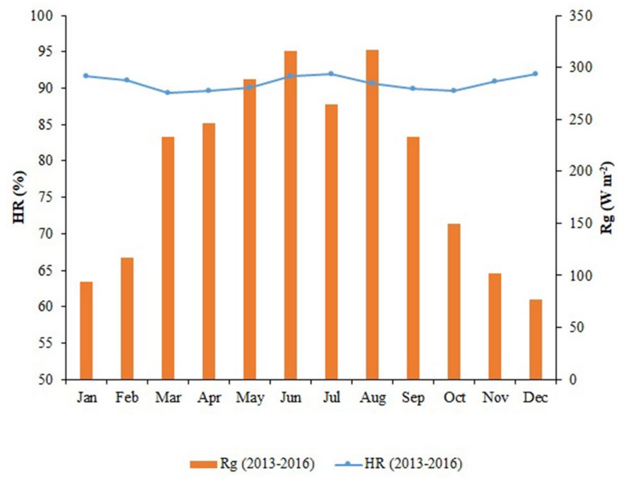

Fig. 2 Mean values for the period 2013–2016 of average monthly relative humidity (HR) and monthly global radiation (Rg)

in the deep soil profile. They present a surface horizon (Ap < 40 cm) with a sandy-loam textural class with 15–20% (w/w) of coarse material of pumice.

Typically, these types of soils present: low bulk density (0.6–1.0); high porosity (58–70%); high water storage capacity (15–30% of gravimetric water content at 33 kPa); variable charge with pH due to the presence of allophane in the soil mineralogical fraction; important phosphorus and potassium fixation (IUSS Working Group WRB, 2015; Ricardo et al., 1977).

Soil Sampling and Analyses

During the study, eight soil samples were collected on three dates, namely, 30 June 2020 (maize in the seedling stage), 07 October 2020 (after the 1st maize crop), and 01 October 2021 (after 2nd maize crop). Soil sampling was performed in an open profile of dimensions 1.4 m wide × 0.5 m deep, with collection in the central 10 cm band of the surface and subsurface horizons, respectively, Ap1 (0 to 15–17 cm depth) and Ap2 (15–17 to 30–35 cm depth). The volumes of soil detached from the sampling area were placed in a plastic bucket, from which approximately 1.5 kg of soil was collected after homogenization. After, the samples were air-dried and sieved with a 2 mm mesh for analysis of the following chemical parameters in the < 2 mm fraction: total soil carbon (SC; g kg^{-1}) by the dry combustion method (Walkley & Black, 1934); total nitrogen (N) (g kg^{-1}) by the Kjeldahl method (Kjeldahl, 1883); extractable phosphorus (P) (mg P_2O_5 kg^{-1}) and extractable potassium (K) (mg K_2O kg^{-1}) by the Egner-Riehm method (Egner et al., 1960); pH (H_2O 1:2.5 suspension (p/v)) and pH (KCl 1:2.5 suspension (p/v)) by the potentiometric method.

Soil Morphology

To study the modifications caused by soil tillage in the TA and TB treatments, in the 1st (plow + rotary tiller) and 2nd (subsoiler + rotary tiller) maize cycles, the soil morphology was characterized through the observation of open profiles of 2.8 m wide × 0.5 m deep in three stages of the maize crops (seedling and harvest, in the 1st maize, and pre-flowering, in the 2nd maize). Morphological units (MU) were defined considering the spatial distribution of organic residues from SO or stubble in the profile. For this purpose, three MU were identified and named TE, TERO, and TESO, respectively: TE—soil material without traces of coarse organic debris; TERO—soil material with a high concentration of stubble (RO); TESO—soil material with a high concentration from organic substrate (SO).

Forage Maize Phenology, Yield, and Yield Components

Eight points per treatment were selected at random and the plants within an area 2 m long comprising two contiguous sowing rows, that is, 2 m × 1.4 m = 2.8 m^2, were evaluated. The phenological stages of maize were registered during the two maize cycles. The studied yield and yield components at harvest were the following: plant density (PD; number of plants per m^2); stems height (SH); leaves weight (LW; g $plant^{-1}$); stem weight (SW; g $plant^{-1}$); cobs weight (CW; g $plant^{-1}$); plant weight (PW; g $plant^{-1}$); fresh matter (FM) and dry matter (DM) yield (kg ha^{-1}).

Balance of Soil Carbon and Nutrients NPK

The dynamics of SC in both treatments was analyzed considering the temporal variation (yearly and through the whole trial) in the two soil horizons, Ap1 and Ap2. For the balance of nutrients NPK, a simplified budget equation was performed for the soil profile, using average values of the Ap1 and Ap2 horizons (Eq. 1) (Diário da República, 2018; Pieri et al., 2011):

$$\Delta n = n_F - n_C \quad (1)$$

where: Δn – nutrient (N, P, or K) variation in the soil; n_F – nutrient applied by mineral and/or organic fertilization during the crop cycle; n_C – nutrient removed by the crop during the crop cycle.

The NPK extractable nutrients removal by maize was estimated according to the recommendations of the Portuguese code of good agricultural practices (Diário da República, 2018), namely: 98–220 kg N ton^{-1}, 40–91 kg

P_2O_5 ton^{-1}, and 133–300 kg K_2O ton^{-1} (considering a potential fresh weight yield of 40–90 ton ha^{-1}).

Since Δn corresponds to the difference between the nutrient content at the end of the crop cycle (n_{fin}) and the nutrient content at the beginning (n_{ini}), the balance equation can be written (Eq. 2):

$$\Delta n = n_{fin} - n_{ini} \quad (2)$$

Thereby, n_{fin}, the nutrient remaining in the soil pool at the end of each cycle, can be obtained using Eq. 3:

$$n_{fin} = n_{ini} + n_R + \Delta n \quad (3)$$

where n_R – nutrient from crop residues at the end of the cycle. To estimate nutrients' NPK in the crop residues left at the end of the experiment, the biomass of 20 maize stems and attached crown roots remaining on the soil after harvest was determined in the 2021 crop cycle, and nutrients extraction by these plant fractions was determined, assuming the premise that their composition did not differ from that of the aerial part.

Since other nutrients' gains, like soil carbon mineralization, or losses, like ammonia volatilization, denitrification, leaching, or soil erosion, were not considered in the simplified Eq. 1, by confronting the final nutrients' content measured by soil analyses and the n_{fin} obtained in Eq. (3), the NPK surplus or deficiency of the cropping system under study can be derived, and its sustainability assessed, from a nutritional and environmental perspective.

Statistical Analyses

Soil data and plant yield parameters were analyzed using Statistica 7 (StatSoft, Inc., 2004). Two-way analyses of variance (ANOVA) were performed to evaluate the effects of year and fertilization management on plant yield parameters and to evaluate the effects of fertilization management and soil depth on soil chemical parameters and SOC balance, conducted separately for each sampling date. Differences between means were compared using Tukey's test ($p < 0.05$).

Results and Discussion

Soil Chemical Parameters

The summary of results of the two-way ANOVA performed for the effects of fertilization and soil depth on soil chemistry in each sampling date is presented in Table 3 (descriptives in Supplementary Table S1). On the first date, both fertilization management and soil depth had significant effects on SC, P, K, and pH, with evident higher values in TB, in the Ap2 layer. Accordingly, there was a statistically significant interaction between the effects of fertilization treatment and soil depth on SC, P, K, and pH(H_2O) (Table 3a).

On the second date, the results followed the same trend, with high or very high significant differences between fertilization treatments and soil depths in all the parameters, except for N (Table 3b). At the end of the trial, no significant differences were obtained between soil layers, indicating an attenuation of the differences within soil depths and a homogeneous distribution of nutrients in the profile (Table 3c).

A possible explanation was the influence of the replacement of soil plowing by subsoiling in the second maize crop since the outcome of subsoiling is to rip the soil in a limited thickness, without turning over the soil, so that the organic residues accumulate on the surface, not affecting the layers beneath.

The temporal trend of soil pH and nutrient availability in the TB treatment, translated in Tables 3a, b, and c, was a general increase in pH and available P, an increase in available K from the first to the second date, followed by a decrease at the end, a global increase in N, from the first to the last sampling date.

Notwithstanding the duration of the study and the need for a longer evaluation of the SO effects in the soil, this set of results indicates a clear positive influence of SO fertilization on soil fertility and soil reaction, when seasonal mineralization of the high organic content in the SO substrate led to increased nutrient availability, despite the lower input of nitrogen (− 77% N), phosphorus (− 81% P), and potassium (− 33% K) (Table 1).

Soil Morphology

In the soil morphology study, the TERO units were observed in TA, the TESO units in the profiles observed in TB, and a TE unit was observed in both profiles of both treatments throughout the 1st cycle of maize (Figs. 3, 4, and 5).

The morphological analysis of the soil profile revealed that the SO distribution in the Ap1 and Ap2 horizons of the TB treatment was characterized by (Figs. 3b, 4b, and 5b): (a) Ap1- low proportion of SO, estimated visually at about 20%, but with regular and uniform distribution; (ii) Ap2- pattern of SO distribution characterized by a high concentration in morphological units systematically distributed in inclined bands and larger pockets in depth, associated with the interfaces created by the soil blocks formed by the two moldboards of the plow; (iii) no traces of SO inside the TE units; (iv) TESO estimated proportion of about 50% of the total volume.

The distribution of these MU indicates that soil mobilization with a moldboard plow incorporates the SO located on the soil surface, as well as other organic debris, in a systematic and non-random manner, which can make the process of soil sampling quite difficult. If, after spreading

Table 3 Effects of fertilization management and soil depth on total carbon (SC), total nitrogen (N), available phosphorus (P), available potassium (K), pH(H2O), and pH(KCl), in each sampling date

Source of variation	SC (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH (H_2O)	pH (KCl)
a) 30-06-2020						
Fertilization management	***	ns	***	***	***	**
TA	29.57 b	2.37	190.1 b	319.7 b	5.46 b	4.62 b
TB	40.25 a	2.41	387.3 a	1004.7 a	6.00 a	5.06 a
Layer	***	ns	***	***	***	*
Ap1	29.36 b	2.38	177.3 b	360.0 b	5.50 b	4.64 b
Ap2	40.46 a	2.40	400.1 a	964.4 a	5.97 a	5.03 a
Fertilization management × Layer	***	ns	***	***	**	ns
b) 07-10-2020						
Fertilization management	***	**	***	***	***	***
TA	27.99 b	1.94 b	175.9 b	301.5 b	5.38 b	4.47 b
TB	44.13 a	2.30 a	544.9 a	1284.4 a	6.09 a	5.25 a
Layer	***	ns	***	***	*	***
Ap1	27.97 b	2.11	185.0 b	566.3 b	5.39 b	4.49 b
Ap2	44.14 a	2.13	535.8 a	1019.7 a	6.08 a	5.23 a
Fertilization management × Layer	***	ns	**	***	**	***
c) 01-10-2021						
Fertilization management	***	***	***	***	***	***
TA	28.06 b	2.29 b	333.9 b	273.9 b	5.50 a	4.53 b
TB	48.28 a	3.52 a	862.4 a	980.7 a	6.67 b	5.74 a
Layer	ns	ns	ns	ns	ns	*
Ap1	36.56	2.85	545.6	622.1	5.95	4.96 b
Ap2	39.78	2.96	650.7	632.5	6.22	5.31 a
Fertilization management × Layer	*	ns	*	*	ns	ns

Different letters indicate statistically significant differences

ns not significant, *TA* Conventional fertilization, *TB* Organic substrate (SO) fertilization

*Significant difference (P < 0.05)

**High significant difference (P < 0.01)

*** Very high significant difference (P < 0.001)

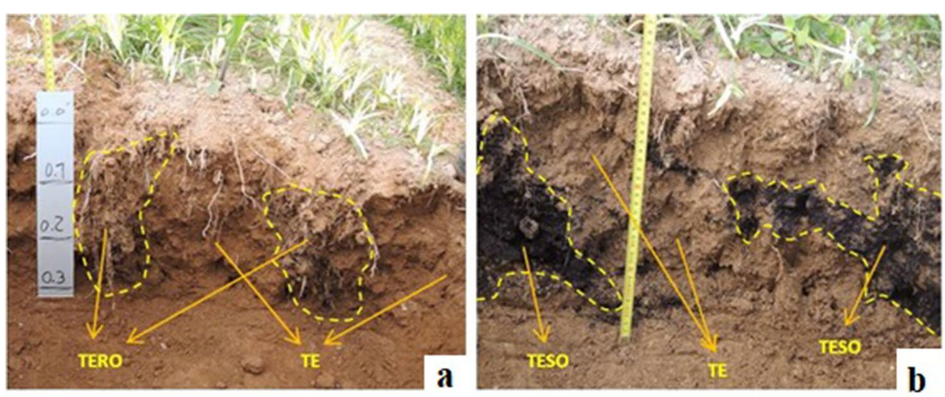

Fig. 3 Morphological Units TE, TERO, and TESO when forage maize was at the seedling stage. **a** TA – Conventional fertilization; **b** TB – Organic substrate (SO) fertilization. *TE* soil material without traces of coarse organic debris, *TERO* soil material with a high concentration of stubble, *TESO* soil material with a high concentration of organic substrate

the SO on the soil surface, there had been a pre-incorporation in the soil with a rotary tiller, and only then the plowing, the concentration of SO in Ap1 would be much higher and the pockets formed in Ap2 would present the SO better mixed with the soil mineral fraction.

Regarding the spatial distribution of RO in the TA treatment, the same pattern was observed (Figs. 3a, 4a, and 5a). However, the MU TESO in TB presented a higher volume than the TERO MU.

The analysis of the soil profile explored by the roots also showed a great affinity between the maize root system and the soil volumes with a higher concentration of RO and SO (Figs. 4 and 5). In Ap1, the distribution of the maize root system was regular and uniform, while in Ap2 the roots were concentrated, almost exclusively, in

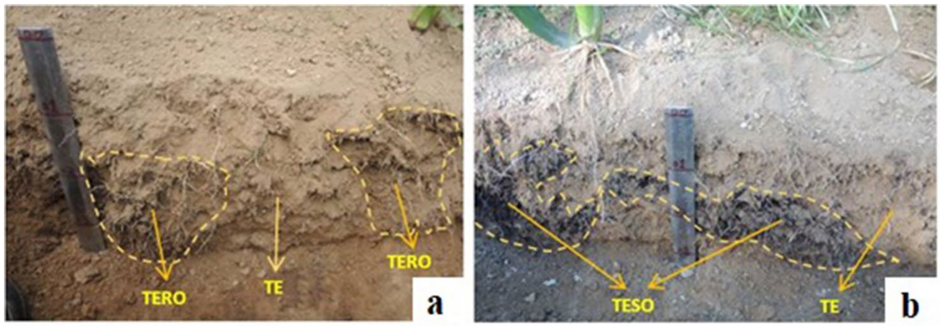

Fig. 4 Morphological Units TE, TERO, and TESO, and roots distribution when forage maize was at the pre-flowering stage. **a** TA – Conventional fertilization; **b** TB – Organic substrate (SO) fertilization. *TE* soil material without traces of coarse organic debris, *TERO* soil material with a high concentration of stubble, *TESO* soil material with a high concentration of organic substrate

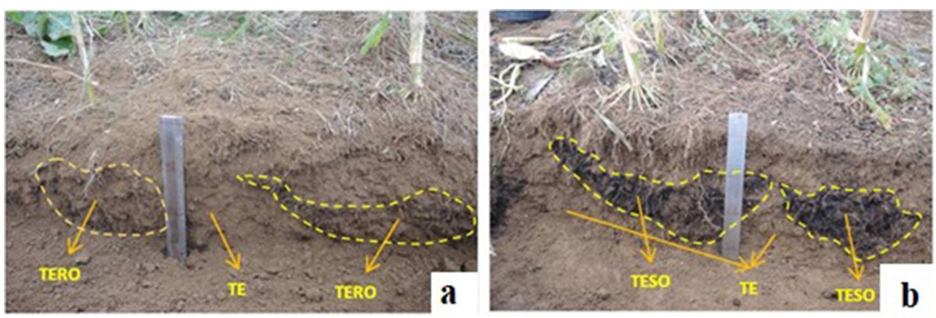

Fig. 5 Morphological Units TE, TERO, and TESO, and roots distribution at maize harvest. **a** TA – Conventional fertilization; **b** TB – Organic substrate (SO) fertilization. *TE* soil material without traces of coarse organic debris, *TERO* soil material with a high concentration of stubble, *TESO* soil material with a high concentration of organic substrate

Table 4 Total soil carbon (SC), total nitrogen (N), available phosphorus (P) and potassium (K), pH (H_2O), and pH (KCl), in the identified soil morphological units (MU) in two profiles of each treatment

Fertilization management/profile	Depth (cm)	MU	SC (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH (H_2O)	pH (KCl)
TA- profile 1	7–15	TE	31.50	2.50	63.21	263.11	5.27	4.31
	7–35	TE	28.29	2.50	67.08	265.6	4.87	4.18
		TERO	38.91	2.10	114.38	346.94	5.82	4.77
TB – profile 1	7–35	TE	26.30	2.30	84.71	404.21	5.00	4.14
		TESO	76.85	2.80	774.43	2473.4	6.94	6.40
TA – profile 2	7–22	TE	24.41	2.00	74.82	182.6	5.80	5.13
	22–35	TE	25.77	2.20	79.98	252.32	6.02	4.79
TB – profile 2	7–35	TE	26.43	2.30	36.55	247.34	5.13	4.48
		TESO	80.72	3.10	673.81	3084.28	7.10	6.71

TE soil material without traces of coarse organic debris, *TERO* soil material with a high concentration of stubble, *TESO* soil material with a high concentration of organic substrate, *TA* Conventional fertilization, *TB* Organic substrate (SO) fertilization the most porous and OM-rich soil volumes, which were greater in TB.

The contrast between the morphological units TE, TESO, and TERO regarding the soil chemical variables is presented in Table 4. At a depth of 7–35 cm the plowing in TA originated the TE and TERO morphological units, the latter presenting an average higher SC of 10 g kg^{-1}, which resulted from the stubble initially located on the soil surface.

In TB, the difference in SC between the TE and TESO units, located at a depth of 7–35 cm in both observed profiles, was approximately 50–54 g kg^{-1}. In the TA treatment, the TERO units present higher SC, P, and K contents than the TE units; in TB, the MU TESO in profiles 1 and 2 presented, respectively, about three times more SC, nine and eighteen times more P, and six and twelve times more K than the TE MU in the same profiles. This increase in SC content was reflected in the increase in soil pH, which was closer to the neutrality range in the TESO units. The N contents were distinctly higher in TESO MU in TB compared to any MU in TA.

The replacement of plowing by subsoiling in the second year resulted in a slight increase in the thickness of the Ap1 horizon after the passage of the rotary tiller, with no effects on the soil at depths greater than 20 cm. In physical terms, the effects of subsoiling in this type of soil are small, corresponding only to the rupture of the soil in a narrow band, 10–15 cm wide, centered on each shank, without affecting the remaining soil volume. Subsoiling, with a much lower cost than plowing, does not cause any significant change in the morphology of the soil profile, hence, minimum tillage or no tillage can bring many advantages for rainfed maize cropping systems (Ghuman & Sur, 2001), allowing for a better soil environment and higher crop yields with minimal impact on the environment (Busari et al., 2015). However, conservation tillage has little expression in the Azores archipelago, on one hand, for a lack of suitable technology, and, on the other hand, because of the soil compaction caused by the trending and grazing of cattle in the humid season. As a result, farmers resort to conventional tillage to overcome unfavorable topsoil physical conditions and to ensure a better seedbed for the maize crop.

Forage Maize Phenology, Yield, and Yield Components

Normally, forage maize in the Azores benefits from very favorable temperatures and global radiation from May to September, with the irregular distribution of rainfall as the main limiting factor. In 2021, the four coldest and most rainy months (November to February) were characterized by having average temperatures of approximately 15 °C, and total precipitation varying from 300 mm to 460 mm (Fig. 1). In this period of the year, the mean relative humidity is approximately 91% and the average global radiation 97.3 W m^{-2} (Fig. 2). When compared to 2021, the year 2020 had lower rainfall throughout the maize crop cycle (– 142.4 mm), which, combined with a very reduced distribution between the stages of emergence and flowering, may have had an impact on maize yield resulting in a water deficit and, thereby, a significantly lower yield in the first maize crop (Table 5). During the emergence to flowering period in 2020, the total precipitation was 30.1 mm, and the soil water storage was probably very low. At sowing, the soil water content was most likely below critical depletion and the rainfall of 35.8 mm only ensured a good emergence of maize. It is important to mention that the maize emergence was accompanied by a strong density of weeds, mainly *Cyperus esculentus* L., whose control is usually carried out with herbicide application when maize has 4–6 leaves.

In 2021, although with higher overall precipitation during the crop cycle, precipitation was low between the 8-Leaf and silking stages, thereby, the crop development in this period of the growing cycle was supported by the soil water storage. By shortening the maize crop cycle, and extending that of ryegrass, producers in the region take a considerable risk, because the probability of rain distribution being favorable is very low since the period from July to September is characterized by benefiting from very modest precipitation amounts. Significant effects of fertilization management

Table 5 Dates and duration of the forage maize phenological stages and distribution of precipitation per stage (P), in 2020 and 2021

Year	Sowing – Emergence	Emergence – 8-Leaf stage	8-Leaf stage – Silking	Silking—Harvest	Total
2020					
Start date (dd/mm)	12/06	26/06	17/07	30/08	–
Duration	12	24	44	31	111 days
P (2020)	35.8	2.0	28.1	51.2	117.1 mm
2021					
Start date (dd/mm)	22/05	03/06	02/07	15/08	–
Duration	13	29	44	46	132 days
P (2021)	23.8	107.3	14.4	114.0	259.5 mm

Table 6 Effects of year and fertilization management on maize plant density (PD), stem height (SH), leaves weight (LW), stem weight (SW), cob weight (CW), plant weight (PW), and fresh matter (FM)

Source of variation	PD (number plants ha^{-1})	SH (m)	LW (g plant^{-1})	SW (g plant^{-1})	CW (g plant^{-1})	PW (g plant^{-1})	FM (kg ha^{-1})[(a)]
Fertilization management	*	ns	**	***	ns	**	***
TA	68,527 b	2.63	128.8 b	252.4 b	299.3	678.5 b	47,054 b
TB	73,661 a	2.71	150.3 a	326.9 a	319.8	797.1 a	59,119 a
Year	***	***	***	ns	***	***	***
2020	61,384 b	2.42 b	108.2 b	275.0	282.6 a	665.8 a	40,804 a
2021	80,804 a	2.93 a	168.9 a	304.4	336.5 b	809.8	65,319 b
Fertilization management × Year	ns	ns	*	ns	ns	ns	ns

Different letters indicate statistically significant differences

ns not significant, *TA* Conventional fertilization, *TB* Organic substrate (SO) fertilization

*Significant difference (P < 0.05)

**High significant difference (P < 0.01)

***Very high significant difference (P < 0.001)

[(a)]Plant water content at harvest in 2020 and 2021, respectively: 57.3%; 56.5%

were observed in maize yield components, namely, PD, LW, SW, and PW, with higher values in the TB fertilization treatment (Table 6). Therefore, maize yield was very significantly higher in TB (59,119 kg ha^{-1}) than in TA (47,054 kg ha^{-1}), indicating that a positive effect of fertilization with SO is to be expected in forage maize productivity. Except for SW, all yield components were significantly higher in 2021, a result that can be attributed to the observed temporal increase in soil fertility parameters like SC, N, or P, and the precipitation distribution during this year. Aside from LW, there was not a statistically significant interaction between the effects of fertilization treatment and year on maize yield. The results show that the treatment with fertilization based on the application of SO (TB) had comparative advantages in relation to the treatment with combined mineral fertilization and slurry (TA).

Table 7 Effects of fertilization management and soil depth on the yearly and global soil carbon balance (ΔSC) (ton ha^{-1})[(a)]

Source of variation	SC_{2020}	ΔSC_{2021}	ΔSC_{Global}
Fertilization management	*	ns	ns
TA	−2.29 b	6.25	3.96
TB	5.50 a	−0.33	5.17
Layer	ns	**	*
Ap1	−1.94	12.02 a	10.07 a
Ap2	5.16	−6.10 b	−0.94 b
Fertilization management × Layer	ns	ns	ns

Different letters indicate statistically significant differences

ns not significant, *TA* Conventional fertilization, *TB* Organic substrate (SO) fertilization

*Significant difference (P < 0.05)

**High significant difference (P < 0.01)

***Very high significant difference (P < 0.001)

[(a)]An average bulk density of 0.8 g cm^{-3} and an average layer depth of 17.5 cm were considered for the calculations of SC in ton ha^{-1}

Soil Carbon Dynamics

A two-way ANOVA revealed that there was not a statistically significant interaction between the effects of fertilization treatment and soil depth on the seasonal and total variation of soil carbon (ΔSC) (Table 7). The simple main effects analysis showed that the fertilization scheme had a statistically significant effect on ΔSC in 2020, but no effect in 2021 or globally. On the other hand, there was a significant effect of the layer in the ΔSC in 2021 and in the 2020–2021 period.

When examining the direction of the variation, the following remarks can be made: from the first to the second sampling date, that is, during the first maize cycle, there was a slight SC reduction in TA, in both layers, and a very substantial increase in Ap2 in the TB treatment (11.57 ton ha^{-1}) (Supplementary Table S2); on average, from 2020 to 2021, SC increased on the surface horizon, Ap1, and decreased in Ap2, probably due to the accumulation of organic residues on this horizon since subsoiling did not revolve the soil; globally, from the first to the last sampling date, a high positive SC variation occurred in TB, higher in the surface horizon, in accordance with other studies (Erich et al., 2012); in the TB treatment, there was a higher global increase in SC than in the TA treatment, mainly in the surface layer (12.32 ton ha^{-1}) (Table S2).

However, this positive temporal variation of SC in TB may have been affected by some uncertainty related to the difficulty in collecting representative samples, even using the profile opening method, arguably the most reliable among all alternative methods, where the soil sample volumes are deterministically selected. Although the surfaces to be sampled had been meticulously prepared, and the collection consisted of detaching small volumes of soil regularly distributed over the entire sampling surface, the mineral matter has a much higher mass density than the organic matter, which to a certain extent could jeopardize the reliability of the process. In addition, another explanation for the strong increase in SC is the achieved gains in the dry aerial biomass of maize (and ryegrass), and the linked increase in underground biomass. Furthermore, the application of compost may have a significant impact on the soil organic matter composition, enriching it with labile carbon, while the carbon retained in deeper soil layers may be more stable than that in surface soil due to differences in source, composition, and environmental factors (Adani et al., 2007; Erich et al., 2012; Yu et al., 2019).

Balance of Nutrients NPK

Table 8 shows a simplified annual budget of NPK nutrients in forage maize in the TA and TB treatments. The differences between the final soil nutrients' contents measured and obtained from the budget equation (Eq. 3) point to an N deficiency at the end of the first year but to a surplus in 2021, much higher in TB (+3.54 ton ha^{-1}) than in TA (+0.92 ton ha^{-1}), which resulted from the decomposition of SOM, which was greatly enriched by the strong incorporation of the SO substrate. Therefore, the N supplied through organic fertilization was not immediately fully available to the crop and the enrichment of N from the mineralization of the SO substrate occurred in the second year of the trial and was not counteracted by the crop N removal.

It should be noted that nutrient losses by leaching, surface runoff, soil erosion, and, in the case of nitrogen, ammonia (NH_3) volatilization or bacterial denitrification of nitrate (NO_3–N), which contribute to emissions of nitrous oxide (N_2O), a greenhouse gas with a high global warming potential (Sapkota et al., 2020), were not computed in the NPK budget. After harvesting, the residual organic nitrogen in the soil will continue to mineralize, giving rise to nitrates that will be susceptible to being lost with rainwater during Autumn and Winter, if the land is not quickly covered with natural vegetation or is not occupied with a new crop capable of absorbing these nitrates.

Ammonia volatilization can cause average losses of 15% and 25% of applied N for inorganic and organic fertilizers, respectively (Pieri et al., 2011; Sainju, 2017). According to the Portuguese code of good agricultural practices (Diário da República, 2018), N losses by denitrification can be 10–15% of N–NO_3 from the mineralization of soil organic matter and of N–NO_3 that is incorporated in the form of chemical fertilizers. Furthermore, in forage maize, the exposure time of bare to very little surface-covered soil is long and very prone to high soil and nutrient losses by erosion.

Table 8 Yearly NPK budget (ton ha^{-1})[a]

Year	2020		2021	
Fertilization management	TA	TB	TA	TB
1- Initial nutrient content in the soil (measured)				
N	6.75	6.66	5.43	6.44
P	0.23	0.47	0.21	0.66
K	0.74	2.34	0.70	2.99
2- Inputs (I): organic fertilization + mineral fertilization				
N	0.24	0.09	0.18	0.00
P	0.03	0.02	0.05	0.00
K	0.05	0.10	0.09	0.00
3- Outputs (O): removal by the crop				
N	0.09	0.11	0.14	0.18
P	0.02	0.02	0.03	0.03
K	0.10	0.13	0.16	0.20
4- Δn = I—O				
N	0.15	−0.02	0.04	−0.14
P	0.01	0.00	0.02	0.00
K	−0.05	−0.03	−0.07	−0.16
5- NPK in crop residues[b]				
N	–	–	0.02	0.02
P	–	–	0.01	0.01
K	–	–	0.02	0.02
6- Final nutrient content in the soil from Eq. 3 (1 + 4 + 5)				
N	6.90	6.64	5.49	6.32
P	0.24	0.47	0.24	0.67
K	0.69	2.31	0.65	2.85
7- Final nutrient content in the soil (measured)				
N	5.43	6.44	6.41	9.86
P	0.21	0.66	0.40	1.04
K	0.70	2.99	0.64	2.28
8- Potential Surplus (S) /Deficiency (D) (7–6)				
N	D (−1.47)	D (−0.20)	S (+0.92)	S (+3.54)
P	D (−0.03)	S (+0.19)	S (+0.16)	S (+0.37)
K	S (+0.01)	S (+0.68)	D (−0.01)	D (−0.57)

TA Conventional fertilization, *TB* Organic substrate (SO) fertilization

[a]An average bulk density of 0.8 g cm^{-3} and a profile depth of 35 cm were considered for the calculations

[b]Not measured in 2020

Except for TA in 2020 (−0.03 ton ha^{-1}), an average surplus of P occurred in both years, indicating that, in general, the real gain in phosphorus was higher than the estimated from the mineral and organic fertilizers inputs. In cases where there was a surplus of P, losses by leaching could be expected, especially in soils whose P retention capacity is already saturated (high soil phosphorus levels). The same can occur in soils subjected to high applications of P in organic forms. Likewise, losses of P from the soil in surface runoff may be particularly high when water erosion occurs, particularly on sloping terrain and after highly erosive rainfall (Reid et al., 2018; Sharpley et al., 2001).

A contrasting balance of K occurred throughout 2020 and 2021. In 2021, exports were higher than inputs, demonstrating the need to increase the amount of K applied through fertilization. Apart from K, the forage maize in 2021 benefited from nutritional comfort in both TA and TB. The significantly higher biomass production in TB compared to TA in 2021 (Table 7), which was indicative of a suitable nutritional status, can also be attributed to increased soil water availability, which is indirectly provided by an increase in soil carbon content, particularly in the MU where maize root activity was more intense.

The nutrients in the soil pool after the forage maize harvest, as well as the maize stubble that remained in the soil, were not considered by the farmer. In 2021, this stubble accounted for about 11% of the dry aerial biomass (ratio between the average dry biomass of the stubble, 3.1 ton ha^{-1}, and the total dry aerial biomass, 28.1 ton ha^{-1}), contributing with 17.8 kg N ha^{-1}, 7.6 kg P ha^{-1}, and 19.3 kg K ha^{-1} to the nutrients' balance at the end of the experiment. The excessive use of N fertilizers is a common practice in the farming systems of S. Miguel, Azores, which constitutes an agricultural practice that is strongly inadvisable, both from an environmental and economic point of view, as it represents an unnecessary burden on the costs of farms.

Conclusions

The use of compost may contribute to a reduction in the inputs of chemical fertilizers, improve soil physicochemical properties, and enhance agriculture circularity. The fertilization with SO organic substrate compared to conventional fertilization in forage maize in S. Miguel, Azores, led to an increase in soil organic content and an overall enrichment in nitrogen, phosphorus, and potassium. Moreover, the yield of forage maize was higher with SO fertilization. Despite the lower mineral content in nitrogen, phosphorus, and potassium, when compared to conventional fertilization, the high organic content of the SO substrate promoted nutrient mineralization and availability. The results indicate that the application of the organic substrate SO in high doses could be an alternative to mineral fertilizers.

The progressive decomposition of organic matter in interaction with environmental factors and management practices is a constraint of research on the impact of organic fertilizers on soil fertility. Although short-term studies can provide insight on their immediate effects on soil properties and crop responses, they may not capture the long-term benefits of the use of fertilizers with high organic content. Additionally, soil fertility is influenced by different biological, chemical, and physical factors, making it important to consider the effects of green organic substrates in the context of other environments, crops, and agronomic options.

Alternative organic sources of nutrients could play an important role in the recovery and/or increase of the productive potential of soils under rainfed conditions in the Azores, contributing not only to increase soil fertility but also to improve soil structure and increase microbial activity, ensuring the sustainability of maize-based cropping systems in the region or in similar temperate island regions.

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Declarations

Conflict of Interest The authors report there are no competing interests to declare.

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