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ORIGINAL RESEARCH

Sewage sludge organic fertilizer as a promoter of initial growth of *Euterpe edulis* Mart., an endangered palm

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Abstract

Purpose The overharvesting of the endemic palm tree *Euterpe edulis* Mart. (Arecaceae) from the Brazilian Atlantic Forest hotspot and the destination given to the sludge produced from urban sewage treatment are both serious environmental issues caused by human activities. In order to find solutions or alternatives for both the issues, we aimed to investigate the effect of increasing rates of a sewage sludge organic fertilizer (SSOF), produced by composting sewage sludge and solid waste, on the initial growth of *E. edulis*.

Methods We mixed sand with 0, 62.5, 125, and 250 kg·m^{-3} of SSOF in 8 L (21 cm height × 24 cm top diameter × 20.5 cm base diameter) pots and then planted a seedling of *E. edulis* in each pot. We assessed the seedlings' height and stem diameter relative growth rate (RGR), biomass, root to shoot ratio, and shoot macronutrient (nitrogen, phosphorous, potassium, calcium, magnesium, and sulphur) concentrations in relation to fertilizer levels. We also evaluated the relation between plant height and diameter over time for each fertilization level.

Results We found that height and stem diameter RGRs, biomass accumulation, and N and P shoot concentrations of *E. edulis* were positively related to SSOF levels between 120 and 250 kg·m^{-3} in the substrate.

Conclusion Our study demonstrates that SSOF can be further used as an alternative to sewage sludge disposal and contribute to *E. edulis* cultivation, and, hence, its conservation.

Keywords *Euterpe edulis*, Organic fertilizer, Palm tree, Sewage sludge, Soil amendment, Organic waste

Introduction

There is a growing concern regarding the conservation of natural resources and plant species that are adversely affected by human activities, mainly those related to food and waste production. The harvesting of the endemic palm tree *Euterpe edulis* Mart. (Arecaceae) from the Brazilian Atlantic Forest hotspot is an example, given that uncontrolled harvesting threatens the conservation of this species in its natural habitat (Galetti and Chivers 1995; Brancalion et al. 2012; Muler et al. 2014). Moreover, the huge amount of sludge produced as a result of sewage treatment in urban centres is another major concern, given that its inappropriate destination can cause negative impacts on the environment (Abreu et al. 2017; Yoshida et al. 2018).

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The Brazilian Atlantic Forest is a hotspot for global biodiversity conservation (Myers et al. 2000); however, the uncontrolled harvesting of *E. edulis* contributes to the loss of its biodiversity (Muler et al. 2014). *E. edulis* is extensively harvested because it provides an edible and highly appreciated palm heart, which comprises its shoot apical meristem and developing undifferentiated leaves. Palm heart harvesting leads to the plant's death, because it is a single-stemmed palm with no resprouting after harvesting (Reis et al. 2000). Besides, fruits from *E. edulis* are also exploited for consumption as food (Schulz et al. 2016). Despite the fact that fruit extraction does not cause plant death, it can be harmful to the fauna that is dependent on the plant and to the regeneration dynamics of this species in native forests (Galetti and Aleixo 2002; Castro et al. 2007; Muler et al. 2014). To reduce the harvesting of *E. edulis* from native forests, its cultivation as an agricultural crop has been suggested; however, to date, knowledge on the efficient cultivation of this species is lacking. This species is reported to be tolerant to acidic and nutrient-poor soils; however, in highly fertility and humid soils, its growth accelerates

(Mattos and Mattos 1976; Bovi et al. 1987; Nogueira Junior et al. 2003; Castro et al. 2008; Neuburger et al. 2010). Thus, the use of fertilizers in the cultivation of *E. edulis* is recommended for faster and increased growth, and fertilizers produced from sewage sludge can be a suitable alternative.

Sewage sludge is the waste that results from sewage treatment, and its production on a large scale is of concern worldwide; the disposal of sludge in landfills or via incineration may lead to water and subsurface contamination or to the increase in greenhouse gases, respectively (Campbell 2000; Abreu et al. 2017; Yoshida et al. 2018). An alternative strategy for the disposal of sewage sludge is its treatment to eliminate sanitation issues and the production of a useful fertilizer for agricultural systems (Alvarenga et al. 2015). Several studies have shown the favourable characteristics of sewage sludge to improve soil physical and chemical properties and promote plant growth, as it contains high levels of organic matter and most nutrients demanded by plants (Bertoncini et al. 2008; Bourioug et al. 2015; Kacprzak et al. 2017; Hamdi et al. 2019). Consequently, sewage sludge has been tested as a fertilizer to promote the growth of a large number of cultivated plants species (Motta and Maggiore 2013; Bedada et al. 2014; Latare et al. 2014; Afáz et al. 2017; Bertolazi et al. 2017; Kchaou et al. 2018). In addition, the use of sewage sludge-based organic fertilizers could promote the economy of chemical fertilizers and the utilization of regional products, leading to more sustainable agricultural systems (Petersen et al. 2003; Ribeiro et al. 2009).

The use of sanitary waste as raw material for fertilizer production is a reality in many countries and is described and regulated by government directives (Kelessidis and Stasinakis 2012; Kacprzak et al. 2017; Kchaou et al. 2018). In Brazil, the Normative Instruction No. 25 of 23/07/2009 of the Ministry of Agriculture (2009) states that the fertilizer produced from sewage sludge from sanitary wastes, resulting in a safe product, can be used in agricultural crops where the edible part of the plant does not touch the ground, such as *E. edulis*. This represents a potential strategy for alleviating the problems caused by destination of sewage sludge from sanitary wastes. However, for this to happen, we need to advance the understanding of the responses of crop plants to the application of sewage sludge-based fertilizers.

Based on the potential of using sewage sludge as a fertilizer in cultivation, we found it relevant to test its use to promote the initial growth of *E. edulis*, in order to find solutions or alternatives to both the issues mentioned above. Thus, we investigate the initial growth of *E. edulis* in response to levels of a sewage sludge organic fertilizer (SSOF) produced by composting sewage sludge and solid waste.

Materials and methods

Experiment assembly

The tested SSOF was characterized as the available nutrients, organic matter and C/N (Table 1). This fertilizer was produced by windrow composting of sewage sludge from an urban sewage treatment plant located in Jundiaí-SP, Southeast Brazil, and solid waste (pruning waste and sugarcane bagasse). This process facilitates the release of mineral substances, formation of stable organic matter, and to a significant reduction of pathogenic organisms, such as thermotolerants (absent) and total coliforms ($<10^{-3}$) (Table 1), making the compound safe for use in agriculture as a fertilizer (Afáz et al. 2017; Bertolazi et al. 2017). As substrate to fill the pots and add the SSOF, we used sand, aiming to represent a nutrient-poor sandy soil as demonstrated by the soil fertility analysis (Table 2).

Table 1 Characteristics of the sewage sludge organic fertilizer produced from the composting of sewage sludge and solid waste tested as a fertilizer to grow *Euterpe edulis* palm tree. Analysis was made in composed samples, according to Ministry of Agriculture (2014)

Attribute	Value
pH	7.3
Humidity (%)	16
Organic matter (g kg^{-1})	490
C:N	7.6
Carbon (g kg^{-1})	137
Nitrogen (g kg^{-1})	18
P_2O_5 (g kg^{-1})	14.8
K_2O (g kg^{-1})	19.5
CaO (g kg^{-1})	35.8
MgO (g kg^{-1})	4.3
SO_4 (g kg^{-1})	18.6
Total coliforms	$< 10^{-3}$
Thermotolerants coliforms	Absent

Table 2 Sand chemical and fertility attributes which was mixed with the sewage sludge organic fertilizer to grow *Euterpe edulis* palm tree. Analysis was made in composite samples according to Raij et al. (2001)

Attribute	Value
pH ($CaCl_2$)	4.4
Organic matter (g dm^{-3})	9
Available-P (mg dm^{-3})	5
K ($mmol_c$ dm^{-3})	0.5
Ca ($mmol_c$ dm^{-3})	2
Mg ($mmol_c$ dm^{-3})	1
S (mg dm^{-3})	19
Sum of bases ($mmol_c$ dm^{-3})	3.3
Base saturation (%)	23
Cation exchange capacity($mmol_c$ dm^{-3})	14.3

We defined the levels of SSOF fertilization based on the recommendation of organic fertilizer for *Bactris gasipaes* Kunth (Arecaceae) cultivation (Raij et al. 1997). We chose the recommendations for *Bactris gasipaes* due to the lack of information on fertilization for *E. edulis*; furthermore, both belong to the Arecaceae family and are closely related phylogenetically. First, we defined a plant density of 5,000 plants ha^{-1} (spacing 2 m × 1 m), for which the recommended organic fertilizer level is 10 t ha^{-1} (Raij et al. 1997). Adjusting the recommendation for the 8 L (21 cm height × 24 cm top diameter × 20.5 cm base diameter) pots used in the experiment, we fixed the dosage as 2 kg of SSOF per pot. Then, we included a control pot with no fertilization and the SSOF dosages of 0.5 and 1 kg per pot to compare the four treatments (Table 3). Thus, converting the values, we had 0, 62.5, 125 and 250 kg·m^{-3} of SSOF as the treatment dosages (Table 3). For the experimental setup, we filled pots with the assigned quantity of SSOF; we then added sand until the pots were full. Subsequently, we mixed SSOF with the sand to obtain a homogeneous substrate and planted the *E. edulis* seedlings.

Table 3 Dosages of sewage sludge organic fertilizer (SSOF) used for growing *Euterpe edulis* and the amount of available nutrients provided by each

Level of SSOF			Macronutrient concentration (g kg^{-1})					
kg·pot^{-1}	**t·ha^{-1}**	**kg·m^{-3}**	**N**	**P_2O_5**	**K_2O**	**CaO**	**MgO**	**SO_4**
0	**0**	**0**	0	0	0	0	0	0
0.5	**2.5**	**62.5**	0.02	0.02	0.02	0.04	0.01	0.02
1	**5**	**125**	0.05	0.04	0.05	0.09	0.01	0.05
2	**10***	**250**	0.09	0.07	0.10	0.18	0.02	0.09

*Recommended dosage (Raij et al. 1997).

E. edulis seedlings were obtained from a local commercial forest nursery. They were grown in 110 cm^3 plastic tubes, and the seedlings' mean height and stem diameter were 33 cm and 0.78 cm, respectively, at the time of transplantation into the pots (December, 2015). For each treatment, we used 12 pots, and we planted one seedling of *E. edulis* per pot. The experiment was conducted in a completely randomized design in a nursery with a 50% shade net and automated micro-sprinkler irrigation, located in the Agricultural Sciences Center of the Federal University of São Carlos (22°18′45″S, 47°23′4″W), Araras, SP, Southeast Brazil.

Data collection

We measured the height of the seedlings using a measuring tape, from the soil level to the tip of the highest leaf, with the seedlings positioned vertically. We obtained the stem diameter converting the stem circumference (measured with a measuring tape) and dividing it by 3.14. We collected these data every 30 days until 210 days after the seedling planting. With the data collected at the beginning and at the end of the experiment, we calculated the relative growth rate (RGR) in height and stem diameter, according to the equation described by Benincasa (2003) (Eq. 1).

Eq. 1 Relative growth rate was calculated using the equation given below:

$$RGR = \frac{(\ln M2 - \ln M1)}{(t2 - t1)};$$

Where, *M1* and *M2* are the values for the variables during initial and final evaluation, respectively, and ($t2 - t1$) is the interval between the evaluations (seven months).

We also assessed the seedlings' biomass and calculated the root and shoot ratio (R:S) at the end of the experiment (210 days). We carefully removed the seedlings from the pots, washed their roots to eliminate soil particles, and oven dried the entire plants at 60°C until a constant mass was reached. After drying, we separated and weighed each plant's shoot and root. Finally, we used the dry shoot of the plants for the analysis of shoot macronutrient (N, P, K, Ca, Mg, and S) concentrations in different fertilization treatments, following the methods described by Silva (2009).

Data analysis

We analysed the relations between levels of SSOF and the height and stem diameter RGRs, total dry matter mass, R:S ratio, and shoot macronutrient concentrations of *E. edulis* by regression analyses, fitting to the significant polynomial or simple linear relationship. We chose the more adjusted equation based on the regression effect significance (p-value ≤ 0.05) and on the R-squared (R^2), which shows the proportion of variation in the outcome that is explained by the predictor variables. The height and stem diameter data every 30 days until the end of the experiment (210 days) were also analysed using regression analysis (p-value ≤ 0.05) for each treatment, fitting to the significant linear relationship. We chose linear regression for all significant results of height and stem diameter data over time because it is more coherent biologically for temporal analyses of plant growth.

Results and discussion

The growth of *E. edulis* was significantly related with SSOF fertilization dosages (Fig. 1). Height and stem diameter RGRs had a quadratic effect in relation to the SSOF fertilization dosages, with maximum growth when between the 125 and 250 kg·m^{-3} dosages of SSOF (Fig. 1). The maximum height RGR was estimated and related to the 179.6 kg·m^{-3} dosage of SSOF, whereas the stem diameter RGR was maximum at the estimated dosage of 184.6 kg·m^{-3} SSOF.

The *E. edulis* biomass had a quadratic relation with the fertilization dosages, showing the higher biomass when grown at a dosage of approximately 125 kg·m^{-3} of SSOF, with maximum estimated at the dosage of 121.6 kg·m^{-3} (Fig. 1). Plants cultivated without SSOF had an R:S ratio of approximately one unit, whereas those with SSOF showed a proportionate reduction in root investment with an increase in shoot, until the estimated rate of 162.5 kg·m^{-3} (Fig. 1).

The plants of *E. edulis* fertilized with SSOF had higher height RGR, stem diameter RGR, and biomass than those without SSOF fertilization. These results reinforce the positive impact of fertilizers derived from sewage sludge and solid wastes on the development of palm trees, as observed with *B. gasipaes* (Vega et al. 2004; Vega et al. 2005; Bovi et al. 2007). Besides, our results add *E. edulis* to the list of cultivated plant species that positively respond to additions of sewage sludge-based organic fertilizers (Motta and Maggiore 2013; Bedada et al. 2014; Latare et al. 2014; Afáz et al. 2017; Bertolazi et al. 2017; Kchaou et al. 2018).

In addition, it is essential to highlight the importance of having a stable and mature compost to use as fertilizer, which is determined by the C/N ratio. A compost may be considered stable and mature when presenting C/N between 15 and 20 (Garcia et al. 1992). However, when the compost is from municipal waste, such as sewagr sludge, it can considered stable and mature with C/N lower than 12 (Jimenez and Garcia 1992; Wei and Liu 2005; Gajalakshmi and Abbasi 2008). The SSOF used for growing *E. edulis* presented a C/N of 7.6 (Table 1), demonstrating that the compost was stable and mature, and capable to provide nutrients to the plants (Garcia et al. 1992).

The highest growth of the plants in the fertilized treatments may be related to the SSOF ability to increase soil pH, organic matter, and nutrient availability (Melo et al. 2002; Bertoncini et al. 2008; Kacprzaka et al. 2017; Bourioug et al. 2015; Černe et al. 2019; Hamdi et al. 2019). The increase in soil organic matter brings advantages to the soil fertility, as it increases the proportion of humic acids in the soil and, consequently, its cation exchange capacity, causing a greater retention of metallic ions, a reduction of leaching loss, and an increase in nutrient cations available for long-term plant growth, especially in sandy soils (Bertoncini et al. 2008). This may contribute to the cultivation of forest species that require high availability of water, such as *E. edulis* (Mattos and Mattos 1976; Bovi et al. 1987; Nogueira Junior et al. 2003). Thus, using SSOF as a fertilizer could, for instance, be an alternative to the expansion of *E. edulis* cultivation in poor-nutrient sandy soils.

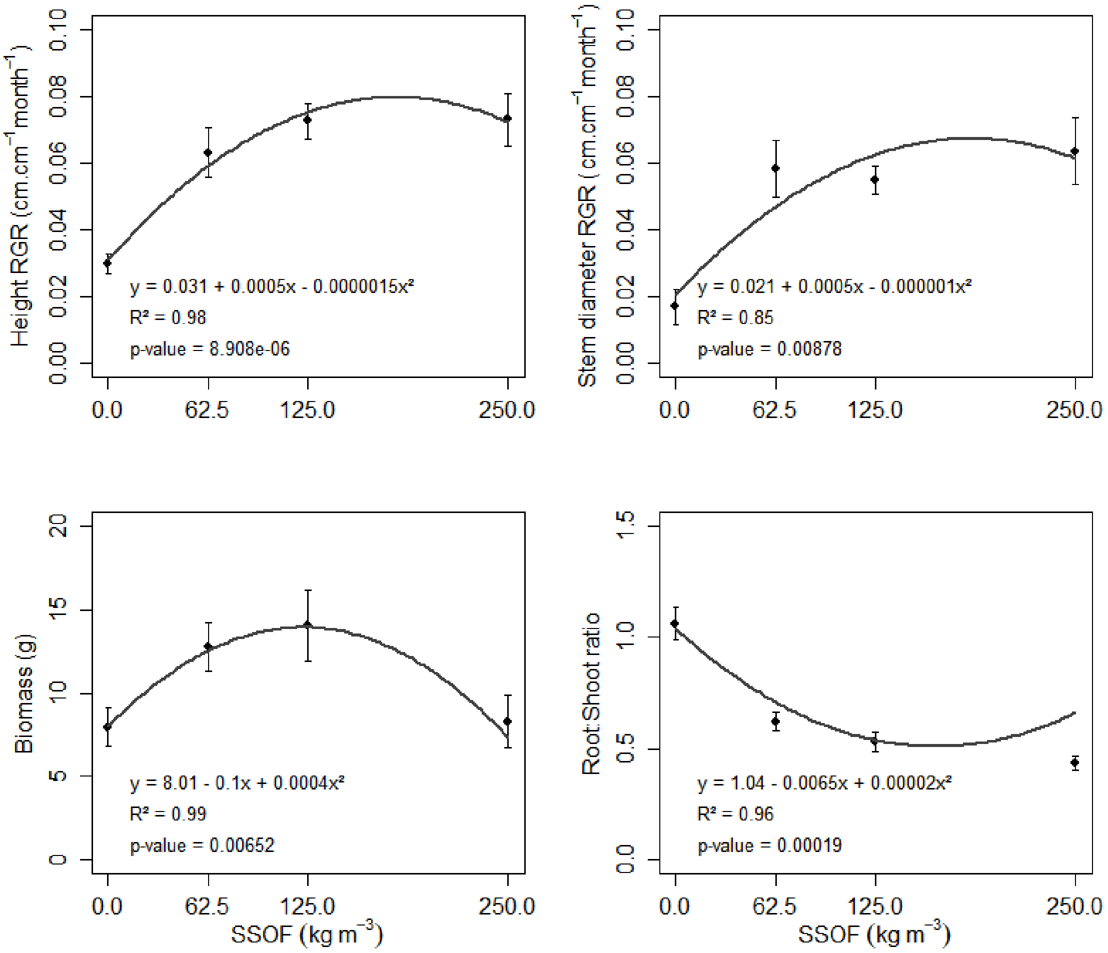

Fig. 1 Height and stem diameter relative growth rate (RGR; cm cm^{-1} month^{-1}), biomass, and root to shoot ratio (R:S) means (± SE) of *Euterpe edulis* seedlings 210 days after planting in pots with 0, 62.5, 125, and 250 kg·m^{-3} of sewage sludge organic fertilizer (SSOF)

For N and P, shoot nutrient concentrations increased over the increasing dosages of SSOF, until the estimated rate of approximately 173 kg·m^{-3}, with reduction after this point (Fig. 2). At the same dosage, we also observed an increase in seedling growth (Fig. 1), highlighting the importance of N and P for *E. edulis* growth (Illenseer and Paulilo 2002; Lima et al. 2008). The growth and the N and P shoot concentrations reached their maximum values at fertilization levels between 125 and 250 kg·m^{-3} of SSOF, suggesting that doses closer to the maximum tested dose could harm *E. edulis* growth despite providing higher availability of nutrients and organic matter. We can consider that the highest SSOF fertilization level we tested (250 kg·m^{-3}) can cause toxic effects on *E. edulis* growth, probably because of excess nutrients in the substrate, which lead to the inhibition of plant growth (Fageria 2001).

There was a higher concentration of Mg in plants cultivated without SSOF, which reduced along with the addition of SSOF, until the estimated dosage of 151.2 kg·m^{-3} (Fig. 2). We can attribute this behaviour to the lower pH in the treatment without fertilization (sand substrate), which contributes to the availability of Mg in the soil, allowing it to be absorbed at a greater degree by the plant (Clark and Baligar 2000; Fageria 2001). The addition of SSOF in the other treatments may have led to an increase in soil pH (Bai et al. 2017), making Mg less available for plant absorption. The concentrations of K, Ca, and S in the shoot exhibited no significant relationship with the increase in SSOF fertilization levels (Fig. 2).

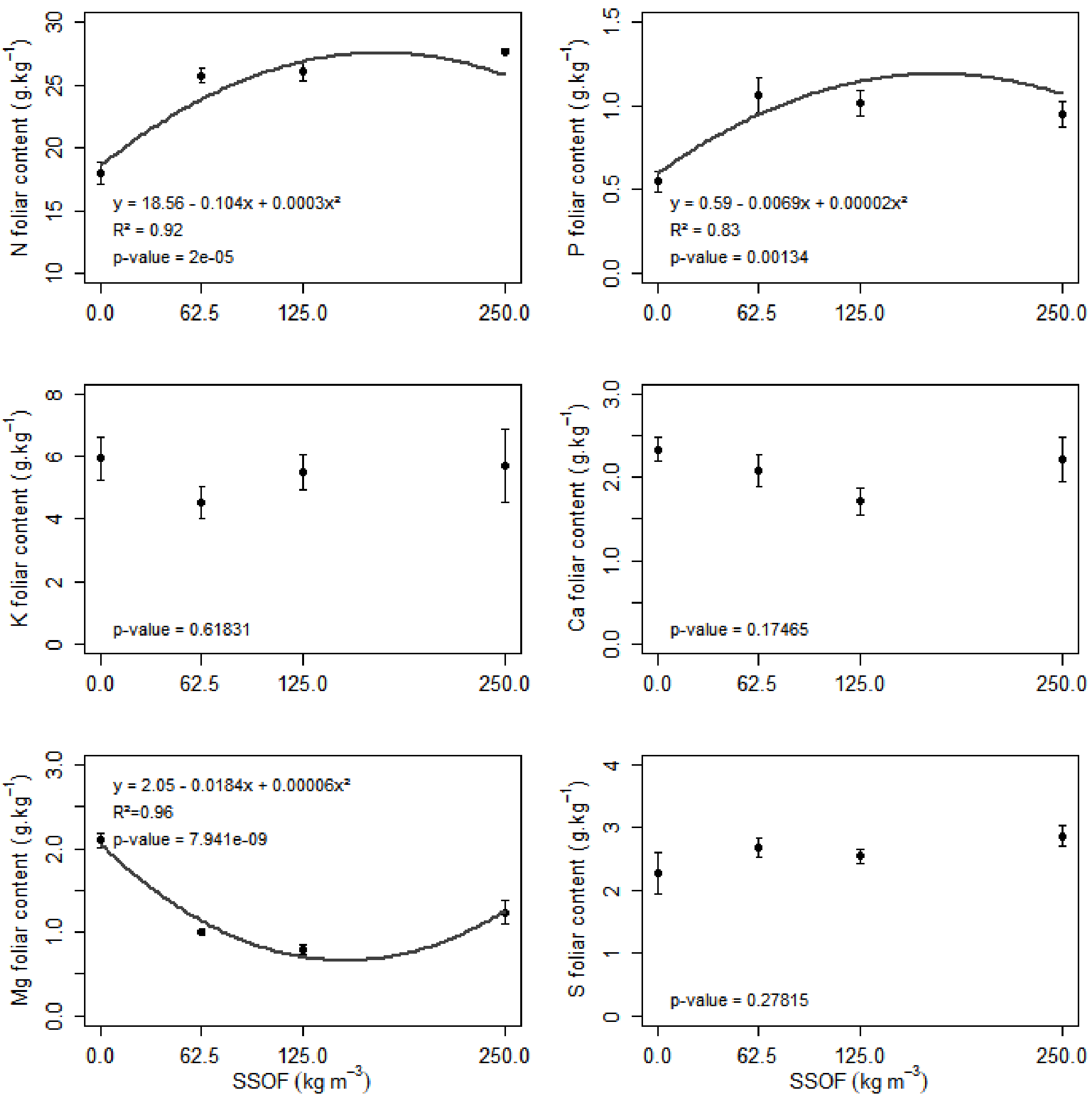

Fig. 2 Macronutrient shoot concentration (g kg^{-1}) means (± SE) of *Euterpe edulis* seedlings 210 days after planting in pots with 0, 62.5, 125, and 250 kg·m^{-3} of sewage sludge organic fertilizer (SSOF). When *p*-value < 0.05, we adjusted to quadratic regression

When cultivated without SSOF, growth of *E. edulis* in terms of height and stem diameter did not vary with the duration of cultivation, presenting a linear growth over time (Fig. 3). When fertilized with SSOF, the highest height increase was observed at 125 kg·m^{-3} of SSOF, with the mean height being 52.3 cm at 210 days. We found a significant linear and quadratic relationship between stem diameter and duration of plant growth with 62.5 and 125 kg·m^{-3} of SSOF.

Studies have shown that *E. edulis* is a plant that can tolerate acidic and nutrient-poor soils; however, its growth is accelerated in soils with high fertility conditions (Castro et al. 2008), such as when cultivated with SSOF, which adds some information to the body of knowledge regarding the cultivation of this species. Once it is known that the species reaches the reproductive stage when it is approximately 7 cm in diameter at breast height (Silva and Reis 2018), the fruit production could be also accelerated using SSOF on its cultivation. Thereafter, contributing to the earlier fruit harvesting to commercialization and to the amount of seed dispersed, enhancing natural regeneration of the species and, thus, its overall conservation in agricultural and native forest landscapes.

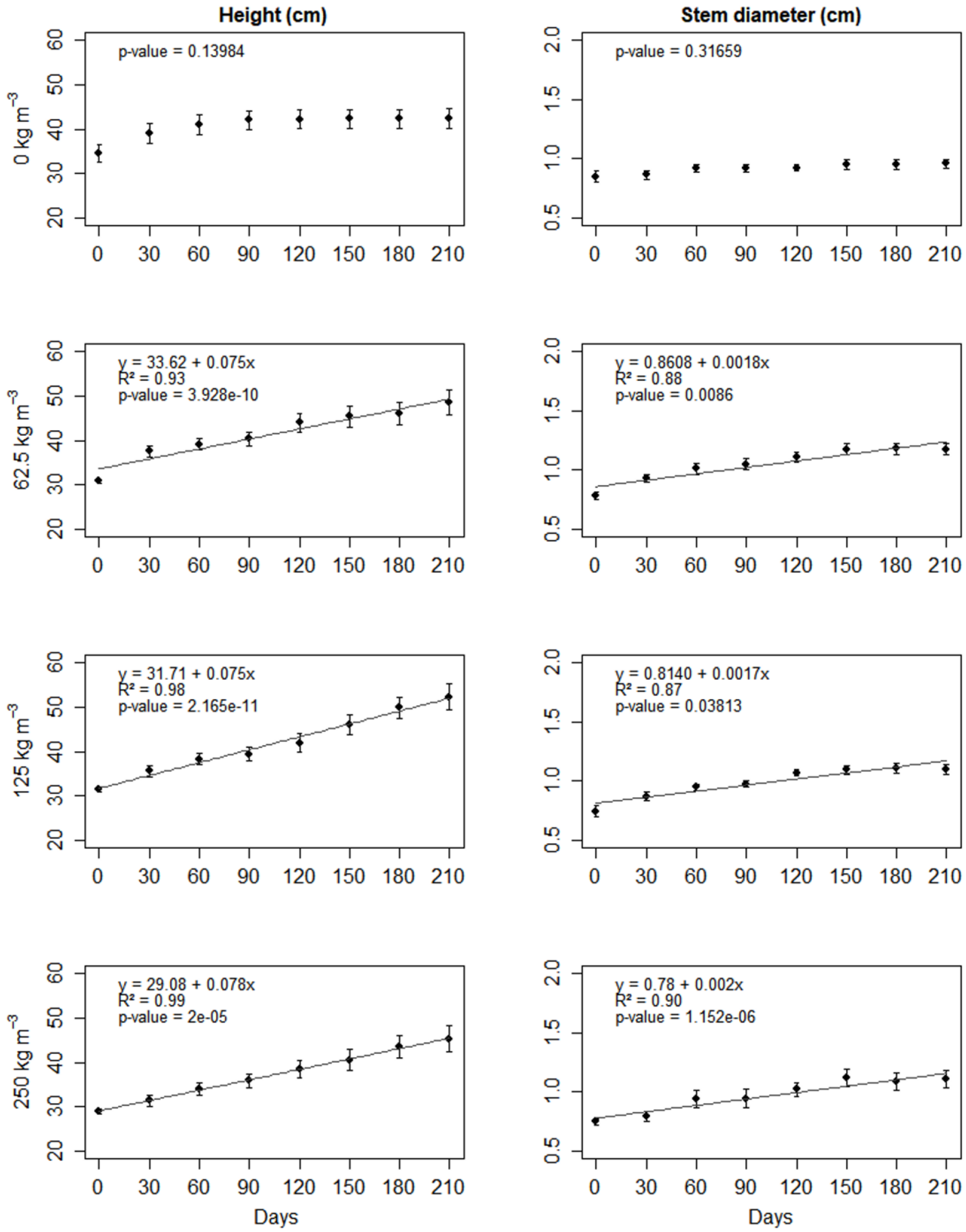

Fig. 3 Height and stem diameter means (± SE) of *Euterpe edulis* seedlings along 210 days of growth in pots with 0, 62.5, 125, and 250 kg·m^{-3} of sewage sludge organic fertilizer (SSOF). When *p*-value < 0.05, we used linear regression

Our study demonstrated that the use of SSOF increases the growth of *E. edulis*, being a potential fertilizer for its cultivation. This practice could assist in reducing the threat of decreasing *E. edulis* population in native forests and encourage its cultivation as a crop in other regions besides its original distribution (including regions of nutrient-poor sandy soils), using the SSOF instead of chemical fertilizers. Additionally, this is a suitable alternative to avoid discarding sewage sludge without treatment, which causes severe damage to the environment (Campbell 2000; Bertoncini et al. 2008). However, sewage sludge origin and processing must be carefully considered before its use as a fertilizer, as it may also contain heavy metals that may influence its efficacy and negatively affect the environment (Alvarenga et al. 2015; Kchaou et al. 2018) or the products obtained from *E. edulis*.

Conclusion

Our study showed that *E. edulis* has its initial growth increased when cultivated with SSOF. *E. edulis* exhibited greater height RGR, diameter RGR, and biomass, and higher N and P concentrations in the shoot when fertilized with SSOF at concentrations between 120 and 250 kg·m^{-3}. The present study demonstrated the potentiality of using a sewage sludge-based fertilizer in *E. edulis* cultivation. Therefore, it can be further developed as an alternative to sewage sludge disposal and contribute to *E. edulis* conservation. Nevertheless, continuous long-term field studies are recommended to better understand the effects of sewage sludge organic fertilizer on the edible products of *E. edulis* and on cultivated soil.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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