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Remote sensing of water transparency variability in the Ibitinga reservoir during COVID-19 lockdown

Thaís Miike Contador a, Enner Alcântara a,*, Thanan Rodrigues b, Edward Park c

a São Paulo State University - Unesp, Department of Environmental Engineering, São José Dos Campos, SP, Brazil
b Federal Institute of Education, Science and Technology of Pará State, Castanhal, PA, Brazil
c National Institute of Education and Asian School of the Environment, Nanyang Technological University, Singapore

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ABSTRACT

As of October 8th: 2020, the number of confirmed cases and deaths in Brazil due to COVID-19 hit 5,002,357 and 148,304, respectively, making the country one of the most affected by the pandemic. The State of São Paulo (SSP) hosts the largest number of confirmed cases in Brazil, with over 1,016,755 cases to date. This study was carried out to investigate how the social distancing measures could have influenced the Ibitinga reservoir’s water transparency in São Paulo State, Brazil. We hypothesize that although the city’s drainage is the major reservoir’s input, as opposed to what has been reported elsewhere, the effect of extensive lockdown in the city of São Paulo due to COVID-19 is marginal on the water transparency. A time series of OLI/Landsat-8 images since 2014 were used to estimate the Secchi Disk Depth (ZSD). The COVID-19 cases and deaths (per 100,000 inhabitants), and social isolation index were used to find links between the ZSD and COVID-19. The results showed that the highest ZSD (higher than 1.6 m) occurred during the dry season (Austral autumn and beginning of Austral winter) and the lowest (0.4 - 0.8 m) during March 2020 (end of Austral summer). Paired sample t-Tests between images of 2020 and all the others showed that April 20th values were not different from that of June 14th, April 17th and March 18th. ZSD values from May 20th were not statistically different from May 14th and April 15th; June 20th values were not different from June 14th; and March 20th values were statistically different from all. We therefore conclude that, based on satellite data, the lockdown in SSP unlikely have influenced the water transparency in the Ibitinga reservoir.

1. Introduction

The year of 2020 has been marked by the international repercussions of the devastating coronavirus pandemic (COVID-19, WHO, 2020). Brazil had its first case reported on February 26th, in the State of São Paulo which then spread rapidly throughout the country (Alcantara et al., 2020; Brazil, 2020). In response to the rapid evolution of the pandemic, São Paulo’s leadership established restrictions on the State’s residents, imposing a partial lockdown starting on March 24th, 2020 (São Paulo, 2020).

While services considered to be essential for society, such as drugstores and supermarkets, were allowed to remain operational as long as social distancing protocols to reduce infection were correctly followed, most businesses were forced to adhere to the lockdown, limiting activities that required person-to-person interactions (São Paulo, 2020).

Since then, several scientists around the world have studied the effects of the recently implemented social distancing practices on the environment. Some effects reported include significant reductions of overall noise levels as well as air pollution in different countries (Zambrano-Monserrate et al.; Nakada and Urban, 2020). Braga et al. (2020) analyzed the influence of the lockdown on the water transparency in the Venice Lagoon; the influence was almost due to the reduction of the water traffic, with the decrease of wake waves. Mishra et al. (2020) analyzed the influence of lockdown on the phytoplankton biomass along Indian coastal waters and the results suggested a decline in the algae bloom. Garg et al. (2020) analyzed the turbidity variability in the Ganga River in India (using MSI Sentinel-2 images), during the lockdown and found that the turbidity was reduced.

Thus, although several studies reported the indirect link between the observed changes in the water quality and lockdown in different places, it often remains a challenge to establish a concrete relation between the two, mainly due to the complex nature of human-environment interactions.
interactions. This study was carried out to investigate how the social distancing measures could have influenced the Ibitinga reservoir’s water transparency in São Paulo State, Brazil.

The Ibitinga reservoir, the third largest in the Tietê River’s cascade system, is an organic matter dominated water along the middle portion of the Tietê River that receives both organic and inorganic waste from agricultural, urban and industrial activities. Therefore, the water quality and the level of pollution in the reservoir is dynamic and depends largely on the hydrological inputs from the surrounding drainages from the metropolitan region near the city of São Paulo (Rodrigues et al., 2018). Here we hypothesize that although the city’s drainage is the major reservoir’s input, as opposed to what has been reported elsewhere (e.g. Briga et al., 2020; Yunus et al., 2020), the effect of extensive lockdown in the city of São Paulo due to COVID-19 is marginal on the water transparency in the Ibitinga Reservoir.

2. Materials and methods

2.1. Study site

The Ibitinga Reservoir is a run-of-river and part of the Tietê River cascade system (21°45' S, 28°59' W), São Paulo State, Brazil (Fig. 1). Ibitinga reservoir was built for hydroelectric generation purpose lies in a transitional region between tropical and subtropical climate, specifically in a humid subtropical climate with flooded area around 114 km², and average flow of about 525 m³ s⁻¹.

The Tietê river has 1100 km of extension and is a challenging and relevant region to investigate, since its water attends to fishery activities, navigation, hydroelectric productivity, and supplies industrial, agriculture, and domestic demands. The Tietê’s waters are deeply affected by different non-natural contamination sources, such as discharges from pasture waste, wastewater from urban centers, and other agricultural activities developed in nearby areas, including sugarcane and citrus crops (Bernardo et al., 2019a; Rotta et al., 2021).

The river receives wastewater discharges from domestic and industrial sources along its course, in special huge amounts originating from São Paulo city, located upstream of the reservoir. The catchment area also comprises diffuse sources of pollution, as agriculture – notably sugarcane crops – and cattle breeding activities (Andrade et al., 2018). For the purposes of this study, the reservoir’s subwatershed was delineated through topographic data.

2.2. Data sources and collection

Radiometric data and water quality parameters data were measured during the fieldwork from 19–23 July 2016 (thirty samples), such as depth, Secchi disk depth, turbidity, pH, chlorophyll-a and reflectance. Details about the data collection protocol and processing can be accessed in Bernardo et al. (2018; 2019b) and Andrade et al. (2018).

Operation Land Imager (OLI)/Landsat-8, Level-2 satellite images from Ibitinga reservoir were downloaded at the USGS Earth Explorer website (https://earthexplorer.usgs.gov) from March 26th, 2014 to June 14th, 2020. Level-2 data is atmospherically corrected and generated from the LASRC (Landsat-8 Surface Reflectance Code), that yields

Fig. 1. Map showing the location of the Ibitinga reservoir’s subwatershed influence area in the State of São Paulo, and Metropolitan Region of São Paulo. Sampled location is also shown in inset map.
surface reflectance at a 30-m spatial resolution suitable for studying the dynamics of most inland water bodies (Zanter, 2019; Pahlevan et al., 2019). The surface reflectance was converted into \( R_{sp} \) by dividing it by \( s \) (Zanter, 2019). We selected the level-2 images because we have tested in our study areas and the results, if compared with other methods for atmospheric correction, showed the suitability of LASCSC over the other methods (Bernardo et al., 2017; Rotta et al., 2021).

Rainfall data for the subwatershed were made available by National Aeronautics and Space Administration’s GIOVANNI database (https://giovanni.gsfc.nasa.gov), with the following dataset: daily accumulated precipitation (combined microwave-IR) estimate (https://www.gov.br/ana/pt-br).

The reservoir’s water level data were downloaded from the Water National Agency of Brazil (https://giovanni.gsfc.nasa.gov), with the following dataset: daily

Aeronautics and Space Administration (Zanter, 2019). We selected the level-2 images because we have tested in our study areas and the results, if compared with other methods for atmospheric correction, showed the suitability of LASCSC over the other methods (Bernardo et al., 2017; Rotta et al., 2021).

The data about COVID-19 (per 100,000 inhabitants) and social isolation index from 1st March to May 8, 2020 was obtained from the São Paulo State Health Secretariat (https://www.seade.gov.br/coronavirus). The social isolation index, which uses geolocation data provided by the nation’s main telecom firms and shows the percentage of the population abiding by available social isolation advice. The shapefiles for municipal and state boundaries were provided by Brazilian Institute of Geography and Statistics (IBGE, 2020).

### 2.3. \( Z_{SD} \) modeling and statistical analysis

For the Secchi Disk Depth, \( Z_{SD} \) (m), estimation of the semi-analytical model from Lee et al. (2013, 2015) was performed based on the diffuse attenuation coefficient of downwelling irradiance \( K_d \) considering its applicability in a wide range of environments (Eq. (1)).

\[
Z_{SD} = \frac{1}{2.5 \times \text{Min}(K_d^s)} \ln \left( \frac{0.014 - R_{sp}}{0.013} \right)
\]

(1)

where \( \text{Min}(K_d^s) \) is the minimum value within the visible spectral domain (443–665 nm) of the attenuation coefficient of downwelling irradiance of the transparent water, and \( R_{sd} \) is the remote sensing reflectance at the same wavelength chosen for \( K_d^s \) (Lee et al., 2015). \( K_d(\lambda) \) can be estimated by (Eq. (2)):

\[
K_d(\lambda) = (1 + m_0 \times \theta_s \lambda(\lambda) + (1 - y b_y(\lambda)) \times m_1
\times (1 - m_2 \times e^{-\gamma_{\lambda} s d(\lambda)}) b_y(\lambda)
\]

(2)

where \( \theta_s \) is the solar zenith angle, here considered to be 30° and \( b_y \) is the backscattering coefficient for water molecules based on Smith and Baker (1981); \( m_0 \), \( y \) and \( \lambda \) are equal to 0.005, 4.26, 0.52, 10.8 and 0.265, respectively; \( a \) is the total absorption coefficient and \( b_y \) is the backscattering coefficient, obtained by the quasi-analytical algorithm (QAA) and here based on the version 5 (QAA_v5, Lee et al., 2009). The reference wavelength used in QAA_v5 was 561.41 nm.

The QAA_v5 was selected based on Rodrigues et al. (2017) results; the authors used data from Barra Bonita reservoir, which is near our study area. They tested the QAA_v5 and adjusted their own QAA (QAMM_v4) and find a better result using the QAA_v5.

A boxplot of \( Z_{SD} \) was used to compare the images through Two Sample t-Tests and confidence level of 0.05. The boxplot was based on 40 pixels selected manually in the reservoir taking care of avoiding the shallow areas; this is an important step to avoid the adjacency effects.

### 2.4. \( Z_{SD} \) model assessment and validation

Before validate the model, we tested the in situ \( Z_{SD} \) dataset for normal distribution using the Kolmogorov-Smirnov (K-S) test. The modeled \( Z_{SD} \) were assessed and validated using the in-situ collected data. The accuracy assessment of \( Z_{SD} \) algorithms was performed using Root Mean Square difference (RMSD, Equation (3)), Mean Absolute Percentage Error (MAPE, Equation (4)), Bias (Equation (5)), and Nash-Sutcliffe model efficiency coefficient (NSE, Equation (6)).

\[
\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i^m - y_i^o)^2}
\]

(3)

\[
\text{MAPE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_i^m - y_i^o}{y_i^o} \right|
\]

(4)

\[
\text{bias} = \frac{1}{n} \sum_{i=1}^{n} (y_i^m - y_i^o)
\]

(5)

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (y_i^m - y_i^o)^2}{\sum_{i=1}^{n} (y_i^o - \bar{y}_m)^2}
\]

(6)

where, \( y_i^m \) is the estimated value for the \( i \) observation; \( y_i^o \) is the measured value for the \( i \) observation; \( \bar{y}_m \) is the maximum measured value; \( \bar{y}_m \) is the minimum measured value, and \( \bar{y}_m \) is the average of measured values.

### 3. Results

#### 3.1. Water quality parameters

Water quality parameters for the reservoir are presented in Table 1. The mean depth is approximately 7 times higher than the \( Z_{SD} \) and the Chl-a concentration reveals that the trophic status ranged from Ultra-oligotrophic to Hypereutrophic; although the Chl-a reached 119.04 mg/m³ the turbidity can be considered low, with low standard deviation.

#### 3.2. \( Z_{SD} \) evaluation

The in situ \( Z_{SD} \), used to validate the model to estimate the \( Z_{SD} \), according to Kolmogorov-Smirnov (K-S) test were considered normally distributed, with S-D value of 0.18 and p-value of 0.22. Fig. 2a shows the comparison between estimated and in situ \( Z_{SD} \) values. Estimated values ranged between 1.12 and 1.80 m, and in situ values ranged between 1.33 and 3.20 m. The results from \( Z_{SD} \) estimation showed a MAPE, RMSD and bias values of 32.42%, 0.84 m and –0.75 m, respectively (Fig. 2b). The NSE was –5.03, which indicates that the mean value of the observed data would have been a better predictor than the model. However, we are more interested in the \( Z_{SD} \) time series variability than in to develop the most accurate model to estimate the \( Z_{SD} \).

The \( Z_{SD} \) is influenced by total suspended solids as well as dissolved and/or colloidal inorganic and organic substances. The Itibitinga watershed is mostly surrounded by shrubland with some areas of bare soil, reducing the runoff from rainfall to carry inorganic and organic matter into the water. According to Andrade et al. (2019) during the fieldwork in Itibitinga reservoir the absorption coefficient of dissolved organic matter (\( a_{CDM} \)) at 443 nm was higher than the other coefficients (mean = 1.95 m⁻¹, minimum = 1.24 m⁻¹, maximum = 5.93 m⁻¹ and coefficient of variation = 42.41%), that is, the light absorption in the water column by \( a_{CDM} \) represented 67.3% of the light budget. The absorption coefficient of phytoplankton showed the highest coefficient of variation (120.44%) with 17.7% of light absorption.

| Table 1 | Water quality parameters descriptive statistics (SD is the standard deviation) for the data used to assess and validate the \( Z_{SD} \) results. |
|---------|-----------------------------------------------------------------------------------------------------------------------------|
| Depth (m) | \( Z_{SD} \) (m) | Turbidity (NTU) | pH | Chl-a (mg/m³) |
| Min. | 9.50 | 1.60 | 2.82 | 5.50 | 1.37 |
| Max. | 21.60 | 3.20 | 8.87 | 6.95 | 119.04 |
| Average | 14.94 | 2.21 | 4.29 | 6.05 | 22.01 |
| SD | ±4.22 | ±0.35 | ±1.20 | ±0.48 | ±28.34 |
Rodrigues et al. (2017) applied the same method to estimate the $Z_{SD}$ in Nova Avanhandava reservoir (located in the same River as our reservoir) in three different dataset (three fieldworks: Nav1, Nav2 and Nav3) and the results showed a Nav1: RMSD = 0.55 m, MAPE = 12.86%, and bias = 0.35 m; Nav2: RMSD = 1.18 m, MAPE = 28.83%, and bias = 1.00 m; Nav3: RMSD = 0.99 m, MAPE = 31.17%, and bias = −0.90 m. The main difference between the two reservoirs is that Nova Avanhandava is classified as oligo-to-mesotrophic (with chlorophyll-a concentration ranging from 2.46 to 38.59 mg/m$^3$), dominated by the inorganic fraction with a low concentration of suspended particulate matter (ranging from 0.10 to 3.67 g/m$^3$).

The $Z_{SD}$ model was applied to a time series of OLI/Landsat-8 images,
from March to June of 2014–2020. We intended to compare March to June over different years to see the effect of the large-scale lockdown in Sao Paulo during these months in 2020. The spatiotemporal variability of $Z_{SD}$ is shown in Fig. 3.

Values higher than 1.6 m were found in a larger portion of the reservoir in April 2014, followed by May 2019 and June 2017. They all correspond to dry seasons (Austral autumn and beginning of Austral winter). On the other hand, the lowest values (0.4–0.8 m) were found in March 2020, followed by April 2016, and June 2018, corresponding to the end of Austral summer, beginning of Austral autumn and beginning of Austral winter, respectively. Tributaries showed lower values than the mainstream in all images except March 2020, in which mainstream values ranged between 0.4 and 1.2 m, and tributaries, between 0.8 and 1.6 m.

To analyze the trend of water transparency since 2014 and identify the effect of lockdown on water clarity (if any), the time series boxplots of $Z_{SD}$ were shown for each date (Fig. 4a), along with the rainfall variability in the study area and water level in the reservoir (Fig. 4b).

For $Z_{SD}$ values, images from April/20 (1.12 ± 0.09 m), May/20 (1.32 ± 0.16 m) and June/20 (1.07 ± 0.18 m) showed higher mean than March/20 (0.78 ± 0.11 m), in which the first one showed the least standard deviation of all. March/20 had the lowest mean of all. The highest value was in April/14 (1.58 ± 0.21 m), and the highest standard deviation was in June/14 (1.13 ± 0.29 m). Paired sample t-Tests between images of 2020 and all others showed that April/20 values were not different from June/14, April/17 and March/18. $Z_{SD}$ values from May/20 were not different from May/14 and April/15; June/20 values were not different from June/14; and March/20 values were statistically different from all.

As illustrated in Fig. 4b, rainfall data ranged from 1 mm (July/17) to 252 mm (January/2016), while the reservoir’s water level ranged from 403.67 m (December/16) to 403.97 m (July/14). Values obtained in 2020 were compared to 2014–2019 averages (Table 2) in order to analyze how rainfall in 2020 differed from previous years, during the months of interest. In 2020, rainfall values were much lower than 2014–2019, except for the month of June (18.45 mm higher). The same happened with water level data, in which the month of June showed a value 0.05 m higher in 2020 compared to the years 2014–2019. April and May showed similar rainfall values in 2020 (22.20 and 19.84 mm, respectively). However, while the $Z_{SD}$ median in April was 1.15 ± 0.09 m, in May it was 1.37 ± 0.16 m. June showed a value of 1.02 ± 0.18 m.

The seasonality of $Z_{SD}$ observed in 2020 was not much different from other years (2014–2019), that showed peak $Z_{SD}$ around May and started to fall in early June. This pattern is in phase with the rainfall that normally peaks around May to June on average. It should also be noted that majority of hydrological input received in the Ibitinga Reservoir is from the upstream cascade reservoirs, which is normally being effectively controlled to maintain a similar level of storage each year. Therefore, the variability of the $Z_{SD}$ observed in the Ibitinga Reservoir is likely related to the direct drainage from the surrounding metropolitan catchments. Thus, we speculate that the changes in the reservoir water quality related to the increased wastewater drainage and suspension of recycling program during the lockdown in the nearby cities (e.g. Urban and Nakada, 2020), may have been captured in the reservoir.

### 3.3 COVID-19 and social distancing assessment

The water quality improvement during the lockdown has been subject of studies (e.g. Yunus et al., 2020), and the social distancing can be

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**Table 2** Comparative values for rainfall and water level for March, April, May and June in 2020 and 2014–19.

| Years | March | April | May | June |
|-------|-------|-------|-----|------|
| Rainfall (mm) | 2014–19 | 2020 | 2014–19 | 2020 | 2014–19 | 2020 | 2014–19 | 2020 |
| Average (standard deviation) | | | | |
| 161.9 (36.04) | 62.62 | 22.20 | 64.80 |
| 59.55 (33.53) | 22.20 | 19.84 | 36.26 |
| 83.44 (49.48) | | | |
| 46.35 (36.26) | | | |

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**Fig. 4.** (a) $Z_{SD}$ data (boxplots) for satellite images and (b) daily average rainfall and water level on the respective dates.
used to measure the effectiveness of the lockdown in our study area.

Evolution of COVID-19 cases and social distancing measures in the Sao Paulo State are shown in Fig. 5. For the number of cases assessed (Fig. 5a–d), we used data by month since March, while for social distancing (Fig. 5e–h), it was considered the average of each month, starting on the day that quarantine officially started in the State (March 24th).

For COVID-19 confirmed cases, the city of Sao Paulo (capital of the State of Sao Paulo) showed the highest numbers since the beginning of the pandemic in Brazil. The following months showed a tendency of the cases to expand to the countryside, getting closer to the reservoir. At the end of March, cases in the capital ranged from 1000 to 5000, while the rest of the cities within the study area had less than 100. By the end of April, it had started to spread to other cities in the surroundings, and in the end of May and June it had spread to many other cities in the area.

Regarding social distancing rates, March (Fig. 5e) showed the highest values with only two cities with less than 50%, and none lower than 45%. The capital had values between 55 and 60%. In April (Fig. 5f), social distancing had a slight drop, but only one city presented values below 45% and the capital showed 50–55%. In May (Fig. 5g), social distancing was low for most cities, with a higher number of cities below 45%. In June, social distancing rates in the study area were the lowest of all, when social distancing measures had gone more flexible in the State. There was only one city with a rate between 50 and 55%, and none with values above that.

4. Discussion

As the Ibitinga Reservoir is located in the middle portion of Tiete River, it receives hydrological inputs such as non-treated water and surface runoffs from the metropolitan region of Sao Paulo city (Bernardo et al. 2018, 2019b). Its transparency is affected by organic and inorganic waste and pollutants from agricultural, urban and industrial activities in the watershed; the reservoir is characterized as a turbulent and eutrophic reservoir (Rotta et al., 2021). Its trophic state can also be affected by the seasonal rainfall, in which rainy seasons usually result in an intense eutrophication process through increased surface runoff and stormwater drainages (Rodrigues et al., 2018).

When the social distancing protocols were implemented in the state in order to contain the COVID-19 spreads in March 2020, several economic activities were halted for a while, possibly resulting in a reduction of their waste carried out by the river (Urban and Nakada, 2020). According to Urban and Nakada (2020), improper management of medical wastes and suspension of recycling program during the lockdown in Brazil have caused serious environmental damages across the country, which in sequence may potentially affect water quality of the reservoirs around the metropolitan SSP. In fact, Kulkarni and Anantharama (2020) showed that the increased volume of municipal solid waste and recyclables generated from the residences during the COVID-19 outbreak have negatively affected the reservoir water quality of the adjacent reservoirs.

Cases and social distancing rates during the pandemic in the study area presented that, even though the number of cases increased significantly and gradually from March to June 2020, social distancing rates dropped in most cities, showing that the social distancing measures were effective only during the first weeks. Meteorological assessment showed that months affected the most by the social distancing measures were the dry months, when compared to the previous 6 years average values. $Z_{SD}$ values showed that the months of May and June of 2020 had similar results to the respective months of 2014, when an extreme drought event occurred. The lowest median was observed in March 2020, the last image before social distancing started in the state. This decrease in the month of June can be related to the increase in average rainfall.

5. Conclusions

In this study, we investigate the link between social distancing measures due to COVID-19 and the Ibitinga Reservoir’s water transparency in the State of Sao Paulo, Brazil. We hypothesize that although the city’s drainage is the major reservoir’s input, as opposed to what has been reported elsewhere, the effect of extensive lockdown in the city of Sao Paulo due to COVID-19 is marginal on the water transparency. The comparison of $Z_{SD}$ estimated by OLI/Landsat-8 images from 2014 to 2020 (period of the lockdown) showed no significant difference and the lowest $Z_{SD}$ observed was related more with the rainfall behavior; which allowed us to accept the proposed hypothesis. Although the spatiotemporal resolution of OLI/Landsat-8 images might have limited accuracy of $Z_{SD}$ (MAPE of 32.42%), based on the current evidence we conclude that the lockdown has not significantly influenced the water transparency in the Ibitinga reservoir.

Fig. 5. (a) Cumulative cases in the last day of each month for COVID-19 cases; (b) Monthly average of social distancing rates. Blank spaces represent cities where social distancing data was not available.
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Ethical Statement
Hereby, I, Enner Alcântara, consciously assure that for the manuscript investigating changes of water transparency in the Ibitinga Reservoir detected using OLI/Landsat-8 images during COVID-19 lockdown the following is fulfilled:
1) This material is the authors’ own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors’ own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

I agree with the above statements and declare that this submission follows the policies of Remote Sensing Applications: Society and Environment as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement
Thaís Miiko Contador: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. Enner Alcântara: Conceptualization, Methodology, Formal analysis, Writing – review & editing. Thanan Rodrigues: Conceptualization, Methodology, Formal analysis, Writing – review & editing. Edward Park: Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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