



# Linking remote sensing and soil properties to model mercury spatial patterns in a natural reserve in the Amazon rainforest

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Received: 17 October 2025 / Accepted: 23 December 2025 / Published online: 29 December 2025  
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**Abstract** Mercury (Hg) accumulation in Amazonian soils is influenced (governed) by atmospheric deposition, hydrological processes, and the rapid turnover of organic matter. Understanding its spatial distribution is critical for assessing ecosystem vulnerability and informing conservation strategies in tropical forests. We collected thirty surface soil samples within a 5×5 km grid in a protected area of the Amazon rainforest to investigate spatial relationships of total mercury (THg) concentrations. Variogram analysis and geostatistical interpolation—Ordinary Kriging (OK) and Co-Kriging (CK)—were applied to characterize spatial autocorrelation. Remotely sensed

variables, including Gross Primary Productivity (GPP) and Height Above Nearest Drainage (HAND), were integrated alongside soil classification and soil organic matter (SOM) to improve predictive accuracy. THg concentrations, determined by cold vapor generation atomic absorption spectrophotometry, averaged  $60.51 \pm 18.16 \mu\text{g kg}^{-1}$ , with Oxisols and Ultisols showing comparable means ( $\sim 62 \mu\text{g kg}^{-1}$ ). CK models incorporating GPP and HAND achieved the lowest mean absolute error (MAE=0.027), with similar spatial ranges for THg, GPP, and HAND supporting their joint predictive capability. GPP alone was a significant predictor (MAE=0.04), consistent with links to atmospheric Hg deposition, terrain morphology, and sediment redistribution. Spatial patterns revealed Hg hotspots in intermediate topographic zones where

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10661-025-14941-3>.

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organic and inorganic leaching (podzolization) and high humic activity occur, while Hg losses were associated with transport from upland plateaus and seasonally flooded areas. These results demonstrate that coupling geostatistical modeling with remote sensing products provides a robust approach for predicting Hg distribution in Amazonian soils and can inform environmental monitoring and management efforts in sensitive tropical ecosystems.

**Keywords** Amazon soils · Gross primary productivity · Height above nearest drainage · Soil organic matter · Geostatistical analysis · Remote sensing

## Introduction

Mercury (Hg) is a globally distributed neurotoxic pollutant that poses significant risks to ecosystems and human health. Natural processes such as volcanic activity and rock weathering, alongside anthropogenic sources including fossil fuel combustion, mining, and industrial emissions, release Hg into the atmosphere where it can be transported over long distances (Amos et al., 2015; Chen et al., 2018). Once deposited in aquatic systems, Hg can be transformed by sulfate-reducing bacteria into methylmercury (MeHg), a bioavailable form that bioaccumulates and biomagnifies through food webs, threatening food security and human nutrition (Morel et al., 1998; UNEP, 2002). Global annual atmospheric Hg<sup>0</sup> emissions are estimated at ~7.8 kt<sup>-1</sup>, underscoring the urgency of understanding Hg pathways and impacts (Outridge et al., 2018).

The Amazon rainforest is a globally significant Hg reservoir and plays a dual role as both a sink and a source of Hg in the Southern Hemisphere (Schneider et al., 2023). Its soils store pedogenic Hg<sup>2+</sup> and also receive substantial atmospheric Hg<sup>0</sup> inputs from forest fires and artisanal gold mining (Pinto et al., 2019; Sexauer et al., 2008). Total mercury (THg) concentrations in Amazonian soils result from both atmospheric deposition and the weathering of Hg-bearing geological substrates. Within the forest canopy, litterfall and throughfall are primary pathways transferring Hg<sup>2+</sup> to the soil surface (Figueiredo et al., 2018; Guedron et al., 2006; Driscoll et al., 2013; Wang et al., 2016; Teixeira et al., 2018; Crespo-Lopez et al., 2021). Soil mineralogy, particularly the presence of iron and aluminum

oxyhydroxides and clay minerals, strongly influences Hg retention (Do Valle et al., 2005; Harris-Hellal et al., 2011; Roulet & Lucotte, 1995). Pedogenic processes such as podzolization and spodosolization further affect THg distribution (Roulet et al., 1998; Grimaldi et al., 2008; Guedron et al., 2006). Seasonal flooding enhances Hg mobilization via ion exchange and particle transport, with soil saturation accelerating adsorption–desorption dynamics (Almeida et al., 2014; Azevedo et al., 2019; Du Laing et al., 2009; Gu et al., 2011).

Remote sensing technologies now provide unprecedented opportunities to characterize the environmental drivers of Hg cycling across broad spatial scales. For example, considering the pathways of Hg accumulation in soils via particulate deposition and litterfall, areas with denser forest canopies are expected to contain larger soil Hg pools (Qin et al., 2025). In this context, global estimates of gross primary productivity (GPP) derived from the MODIS sensor (Moderate Resolution Imaging Spectroradiometer) can serve as a key variable for representing vegetation productivity and the potential for Hg capture through canopy-mediated processes (Running & Zhao, 2015). The Height Above the Nearest Drainage (HAND) algorithm, derived from digital elevation models, also stands out as a remote-sensing-based tool for predicting hydrological dynamics and flood-prone areas in the Amazon (Rennó et al., 2008). This algorithm is particularly relevant for assessing Hg cycling in Amazonian environments because topography exerts strong control over key biogeochemical processes that directly influence Hg retention and mobility in soils, such as redox conditions, organic matter preservation, and sediment redistribution (Guédron et al., 2018; Oliveira et al., 2001).

Geostatistical approaches such as Ordinary Kriging (OK) and Co-Kriging (CK) are powerful tools for modeling spatial patterns and identifying contamination hotspots. OK minimizes estimation variance, while CK incorporates auxiliary variables with spatial autocorrelation to improve predictions (Yamamoto & Landim, 2013). In Western Amazonia, near our study area, kriging has been used to assess the spatial distribution of Hg and organic matter in soils of a lowland open ombrophile forest (Bernardi et al., 2015). Geostatistical methods have additionally been applied to investigate the influence of gold mining on Hg distribution in soils from Pará State (Teixeira et al., 2021) and the Peruvian Amazon (Ramírez et al., 2021). In aquatic ecosystems, indicator kriging and cokriging were used to evaluate

the distribution of Hg and organic matter in bottom sediments of the Puruzinho Lake, identifying priority deposition zones and the influence of the seasonal hydrological cycle (Almeida et al., 2014). Despite these advances, the use of remote sensing data in predictive geostatistical models remains limited in the Amazon to date, constraining our ability to detect and interpret complex biogeochemical patterns.

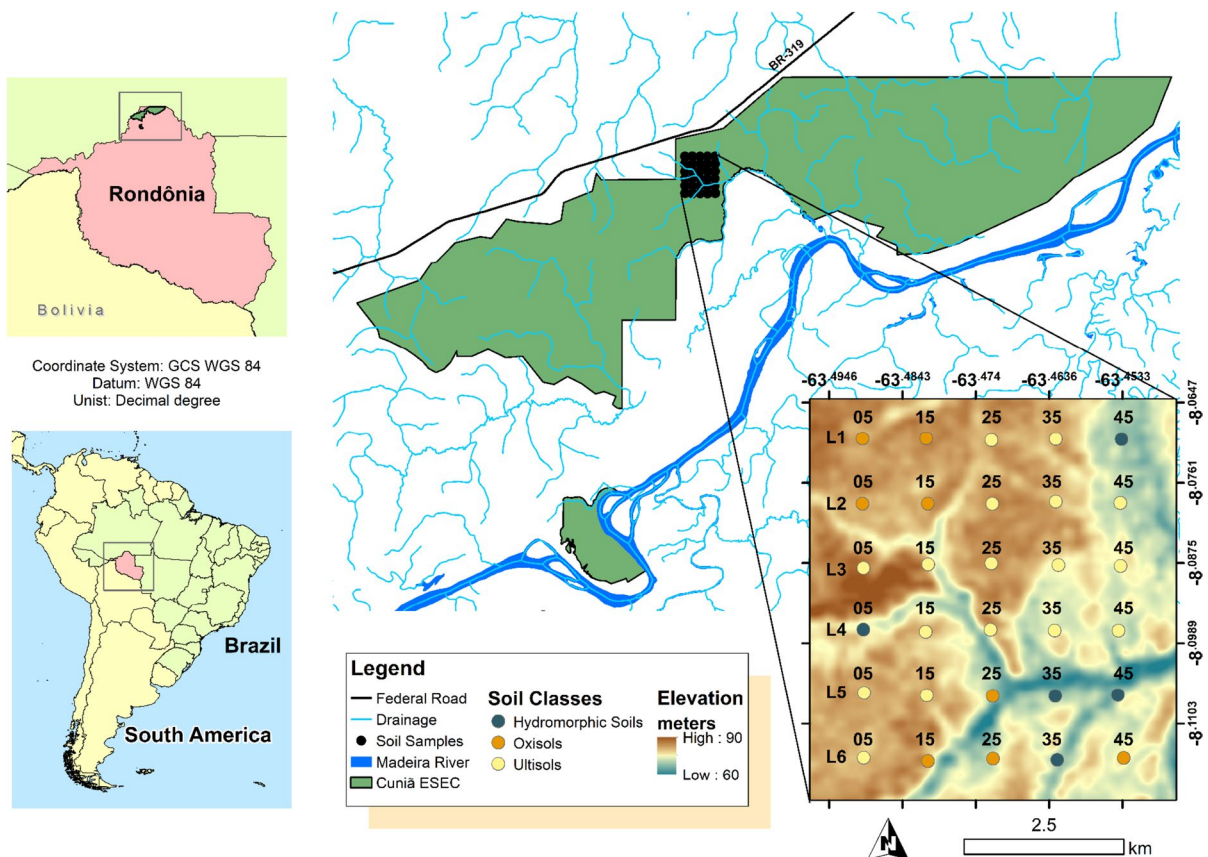
This study applies OK and CK geostatistical models, incorporating GPP, HAND, and soil organic matter (SOM), to predict THg spatial patterns in a protected area of the Amazon rainforest. We evaluate the relative contribution of each variable, identify environmental drivers of Hg hotspots, and highlight the roles of carbon stocks and seasonal flooding in Hg cycling. By linking remote sensing products with soil geochemistry, this research demonstrates a scalable approach for improving regional Hg risk assessment in tropical forest ecosystems

## Materials and methods

### Study area

The study was conducted at the Cuniã Ecological Station (Cuniã ESEC), located in the interfluvium between the Madeira and Purus rivers (Western Amazon) (Fig. 1). Cuniã ESEC is situated approximately 70 km from Porto Velho, the capital of the state of Rondônia, and 60 km from the municipality of Humaitá, in the state of Amazonas. It is a strictly protected conservation unit dedicated exclusively to the indirect use of its natural resources through scientific research and educational visitation (Brasil, 2000).

Covering an area of 125,000 ha, Cuniã ESEC is characterized by lowland open ombrophilous forest with palm trees. The climate is Tropical Monsoon (Am) according to Köppen's classification, with heavy summer rainfall and a prolonged winter dry season (Alvares



**Fig. 1** Sampling design showing the 1 km-interval regular grid used for topsoil collection in Cuniã ESEC

et al., 2013). Geologically, Cuniã ESEC comprises two primary units: Alluvial Deposits and Fluvial Terraces (Quadros & Rizzotto, 2007). Alluvial deposits result from meandering river systems and are primarily composed of unconsolidated sediments. Fluvial terraces contain ferruginous gravels with variable organic matter content. The dominant soil types are well-developed Ultisols with podzolization, while Oxisols occur in seasonally flooded depressions (ICMBio, 2018). Hydromorphic soils occur on a smaller spatial scale, typically following the narrow drainage lines associated with small streams (“igarapés”). These soils are acidic ( $\text{pH H}_2\text{O}=3.74\pm0.17$ ) and have relatively high aluminum ( $332\pm129\text{ mg kg}^{-1}$ ) and iron ( $195\pm104\text{ mg kg}^{-1}$ ) contents.

#### Soil sampling and processing

Thirty topsoil samples (0–20 cm) were collected at 1 km intervals within a 25 km<sup>2</sup> grid (Fig. 1) during September–October 2010, corresponding to the onset of the flood period. The sampling design followed the Biodiversity Research Program (PPBio) protocol to maximize environmental heterogeneity and capture variability in topography, vegetation, and land use. Samples were collected using a stainless-steel shovel, placed in plastic bags, and transported to the laboratory. In the laboratory, samples were freeze-dried, pulverized in a porcelain mortar and pestle, and sieved to 200 mesh. The soil organic matter (SOM) content was determined following the methods described in the Brazilian Agricultural Research Corporation manual (Teixeira et al., 2017). Briefly, dried soil samples were oxidized with 10% hydrogen peroxide, which decomposes organic matter into carbon dioxide and water. The SOM content was calculated from the mass difference before and after oxidation.

#### Total mercury (THg) quantification

Freeze-dried subsamples (~0.5 g) were digested with 1 mL ultrapure water (Milli-Q Plus, Millipore, Bedford, USA) and 5 mL aqua regia ( $\text{HCl}:\text{HNO}_3$ , 3:1) in a digestion block at 50 °C for 30 min. After digestion, 6 mL potassium permanganate (5% w/v) was added, and the samples were heated for an additional 20 min. Samples were left overnight, treated with 1 mL hydroxylamine hydrochloride (12% w/v), and filtered through 3 µm Whatman filters. Final volumes were adjusted to 15 mL

with ultrapure water. THg concentrations were determined using a Flow Injection Mercury System (FIMS-400, Perkin Elmer, Norwalk, USA) with cold vapor atomic absorption spectrometry (CVAAS). Analytical quality control included reagent blanks to verify glassware decontamination and reagent purity. Method accuracy was assessed using the certified reference material EnviroMAT SS-2 (Soil Standard, SCP Science, Quebec, Canada), yielding a recovery rate of 80.7% ( $n=4$ ).

#### Remote sensing data

Gross Primary Productivity (GPP) was derived from the MODIS MOD17 product (MOD17A2H), which provides consistent 500-m spatial-resolution estimates of vegetation productivity at 8-day intervals (Nemani & Glassy, 2000; Running & Zhao, 2015). A total of 724 images from February 2000 to November 2015 were compiled to ensure robust long-term averages. Outliers in the time series were minimized using the minimum noise fraction transformation (Couto Junior et al., 2013).

Height Above the Nearest Drainage (HAND) was calculated to represent vertical distance to the nearest channel and assess drainage potential. HAND was computed from a 30 m Shuttle Radar Topography Mission digital elevation model (SRTM-DEM) obtained from NASA Earth Explorer (October 2010), with corrections using IceSAT-2 ground control points (Li et al., 2022). Processing was conducted in ArcGIS 10.8.1 (ESRI) using the “Hydrology” module.

#### Statistical analysis

Data distributions for THg ( $\mu\text{g kg}^{-1}$ ), SOM ( $\mu\text{g kg}^{-1}$ ), 15-year average GPP ( $\text{g C m}^{-2}\text{ 8-day}^{-1}$ ), and HAND (m) were tested for normality using the Shapiro–Wilk test. All variables met normality assumptions, allowing comparison between soil types (Ultisols, Oxisols, and Hydromorphic) via one-way ANOVA followed by Tukey’s HSD post hoc test. Significance was set at  $p<0.05$ . All statistical analyses were performed using STATISTICA 12.

#### Geostatistical modeling

Ordinary kriging (OK) was applied to interpolate THg, SOM, GPP, and HAND. Co-kriging (CK) was used to model THg distribution using SOM, GPP, and HAND as covariates. Kriging estimates values for unsampled

locations by weighing nearby observations according to the spatial autocorrelation structure described by an experimental variogram (Webster & Oliver, 2007). Unlike deterministic interpolation methods, kriging provides statistically optimal and unbiased predictions with minimum variance, thus yielding more robust estimates (Cressie, 2015; Cintrón et al., 2024). Here, the spherical model was adopted for both OK and CK systems, as expressed by the Eq. 1, where,  $\gamma(h)$  is the semi-variance,  $c_0$  is the nugget effect,  $c$  is the sill, " $h$ " is the lag, and " $a$ " is the range (Lourenço & Landim, 2005). Detailed OK and CK computation steps and cross-validation results are provided in the Supplementary Material (Text S1).

$$\gamma(h) = \{c_0 + c \left( \frac{3h}{2a} - \frac{1}{2} \left( \frac{h}{a} \right)^3 \right) \text{ if } h < ac_0 + c \text{ and if } h \geq a \quad (1)$$

The nugget effect represents small-scale variability or measurement error, the sill corresponds to maximum spatial variance, and the range is the distance of spatial dependence. Spatial dependence is classified as strong (<25%), moderate (25–75%), or weak (>75%) based on the nugget-to-sill ratio (Cambardella et al., 1994). Geostatistical analyses were performed using the Geo-statistical Wizard in ArcGIS 10.8.1 (ESRI).

## Results

Table 1 summarizes descriptive statistics for all variables by soil class and overall mean. The mean THg concentration across all soil classes was  $60.51 \pm 18.16 \mu\text{g}\cdot\text{kg}^{-1}$ . Oxisols and Ultisols exhibited comparable and relatively higher THg concentrations ( $62.27 \pm 20.01$  and  $62.72 \pm 18.43 \mu\text{g}\cdot\text{kg}^{-1}$ ,

respectively), while hydromorphic soils recorded the lowest mean value ( $50.2 \mu\text{g}\cdot\text{kg}^{-1}$ ).

ANOVA results indicated a significant difference only for HAND across soil classes ( $F=6.3385$ ,  $df=27$ ,  $p=0.0056$ ). Tukey's HSD test revealed significantly lower HAND values in hydromorphic soils compared to Ultisols ( $p=0.0045$ ) and Oxisols ( $p=0.0226$ ). Ultisols and Oxisols occurred at mean HAND values of  $18.66 \pm 4.2$  m and  $17.93 \pm 5.2$  m, respectively. Hydromorphic soils were associated with the highest mean GPP ( $491.36 \pm 22.83 \text{ gC}\cdot\text{m}^{-2}\cdot\text{8 days}^{-1}$ ) and lowest HAND ( $11 \pm 2.54$  m).

Ordinary kriging (OK) analysis revealed strong spatial dependence for THg, SOM, GPP, and HAND (nugget-to-sill ratio < 25%). Remote sensing variables exhibited no nugget effect, whereas THg and SOM displayed minor discontinuities (Table S1). SOM had shorter spatial ranges, suggesting greater local heterogeneity, while THg, GPP, and HAND showed regional-scale autocorrelation.

Figure 2 presents OK-derived spatial distributions of THg, SOM, GPP, and HAND, with respective semivariograms. The MAEs for THg, SOM, GPP, and HAND were 0.067, 0.15, 0.065, and 0.029, respectively; all models achieved RMSE = 1. The southeastern grid area corresponded to intermediate HAND values (15.5–20.6 m), while the eastern sector was dominated by flood-prone zones (HAND < 15.5 m). Lower THg levels were observed in higher HAND zones (> 21.6 m) near Ultisols and Oxisols, and also in the central-western sector where hydromorphic soils occurred at low HAND values (< 15.5 m). Hotspots of THg coincided with elevated SOM in ecotone topographic positions (HAND 15.5–20.6 m).

The co-kriging (CK) analysis of THg against single covariates showed predictive performance in the

**Table 1** Summary of the THg, SOM, GPP, and HAND values to the 30 soil samples in Cuniã ESEC

| Variables                | Mean $\pm$ SD                            |                                          |                                                        |                  |
|--------------------------|------------------------------------------|------------------------------------------|--------------------------------------------------------|------------------|
|                          | THg ( $\mu\text{g}\cdot\text{kg}^{-1}$ ) | SOM ( $\mu\text{g}\cdot\text{kg}^{-1}$ ) | GPP ( $\text{gC}\cdot\text{m}^{-2}\cdot\text{8 day}$ ) | HAND (m)         |
| Ultisols (N=17)          | $62.72 \pm 18.43$                        | $37.18 \pm 18.43$                        | $485.92 \pm 24.61$                                     | $18.66 \pm 4.2$  |
| Oxisols (N=8)            | $62.27 \pm 20.01$                        | $36.92 \pm 9.27$                         | $497.16 \pm 20.6$                                      | $17.93 \pm 5.2$  |
| Hydromorphic Soils (N=5) | $50.2 \pm 13.07$                         | $29.28 \pm 8.53$                         | $500.58 \pm 17.75$                                     | $11 \pm 2.54^a$  |
| Total (N=30)             | $60.51 \pm 18.16$                        | $36.36 \pm 7.46$                         | $491.36 \pm 22.83$                                     | $17.19 \pm 5.02$ |

<sup>a</sup> statistically different in the Tukey HSD post hoc test ( $F=6.3385$ ,  $df=27$ ,  $p<0.0056$ ); The average GPP corresponds to a 15-year data set (2000–2015)

order  $SOM < HAND < GPP$  (Table S2). THg–GPP and THg–HAND models achieved lower MAEs (0.04 and 0.06, respectively) than THg–SOM (0.23) (Fig. 3), though the latter reduced spatial discontinuity. When all covariates were integrated in CK (Fig. 4), predictive accuracy improved markedly (MAE = 0.02) relative to SOM-only CK (MAE = 0.23) and THg–remote sensing CK (MAE = 0.027). Incorporating multiple sensing variables reduced stochastic variability, enhanced hotspot delineation, and amplified spatial thresholds (Table S3).

THg dependent on GPP and HAND, one at a time, showed the best MAE results in Fig. 3 and exhibited greater regionality. However, these combinations did not considerably modify the THg distribution and increased the *nugget effect*. Furthermore, although SOM did not have the best model, it was the only variable capable of reducing discontinuity (Table S2). The THg spatial distribution with SOM generalized the prediction to the regions with higher SOM pools, displaying minimal hotspot influence.

All CK models in Fig. 4 exhibited a high spatial dependence (*nugget-to-sill* ratio < 25%) and RMSE = 1. In addition, THg CK with SOM yielded less favorable results (MAE = 0.23) compared to THg soil OK with remote sensing data, which exhibited more satisfactory outcomes (MAE = 0.027) (Fig. 4). The CK model integrating all variables achieved excellent and the best results (MAE = 0.02) with hotspot dependence. The sensing variables acting simultaneously on the distribution of THg minimized the randomness of THg to the point of surpassing THg CK only with SOM. These sensing variables amplified the thresholds and, consequently, the influence of hotspots on the distribution of THg (Table S3).

## Discussion

Our findings emphasize the significant roles of vegetation carbon pools, represented by gross primary productivity, and flood dynamics, represented by the Height Above the Nearest Drainage metric, as key drivers of the regional variability in THg distribution in Amazon surface soils. This conclusion is reinforced by the autocorrelation analysis from the co-kriging results. The high degree of dependence observed between THg in soils and all variables suggests a strong spatial correlation with local environmental

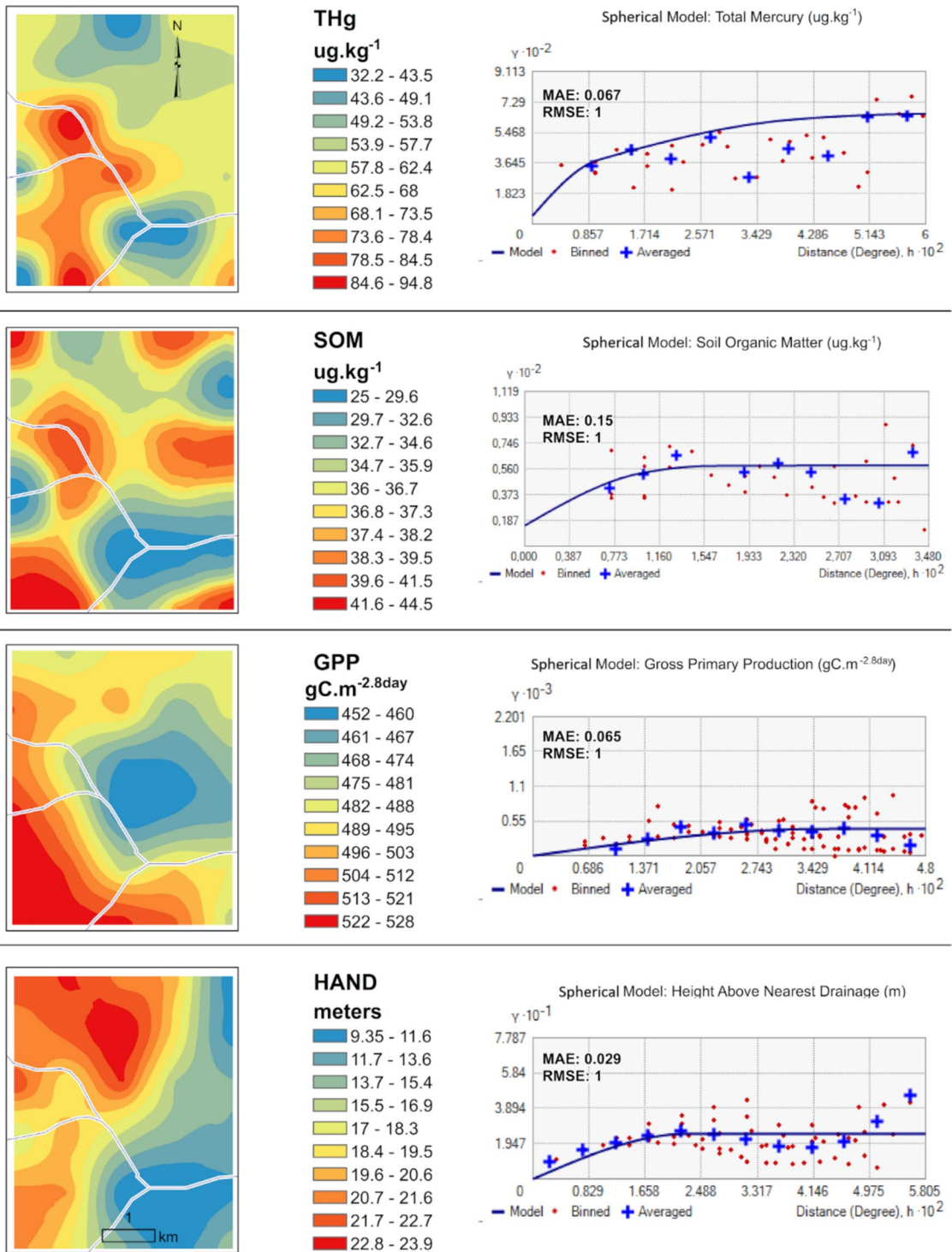
factors, including soil processes, properties, carbon pools, and topography (Crespo-Lopez et al., 2021).

Oxisols and Ultisols in flood-prone settings exhibit low Hg retention capacity under reducing conditions, leading to toposequence-driven THg adsorption patterns (Guedron et al., 2006; Roulet & Lucotte, 1995). In such conditions, Amazonian soils often exhibit an eluvial horizon, indicating a loss of minerals from the surface or subsurface. Directly below the eluvial horizon is the illuvial horizon, which receives the minerals leached from the eluvial horizon, as demonstrated by Schaefer et al., (2023).

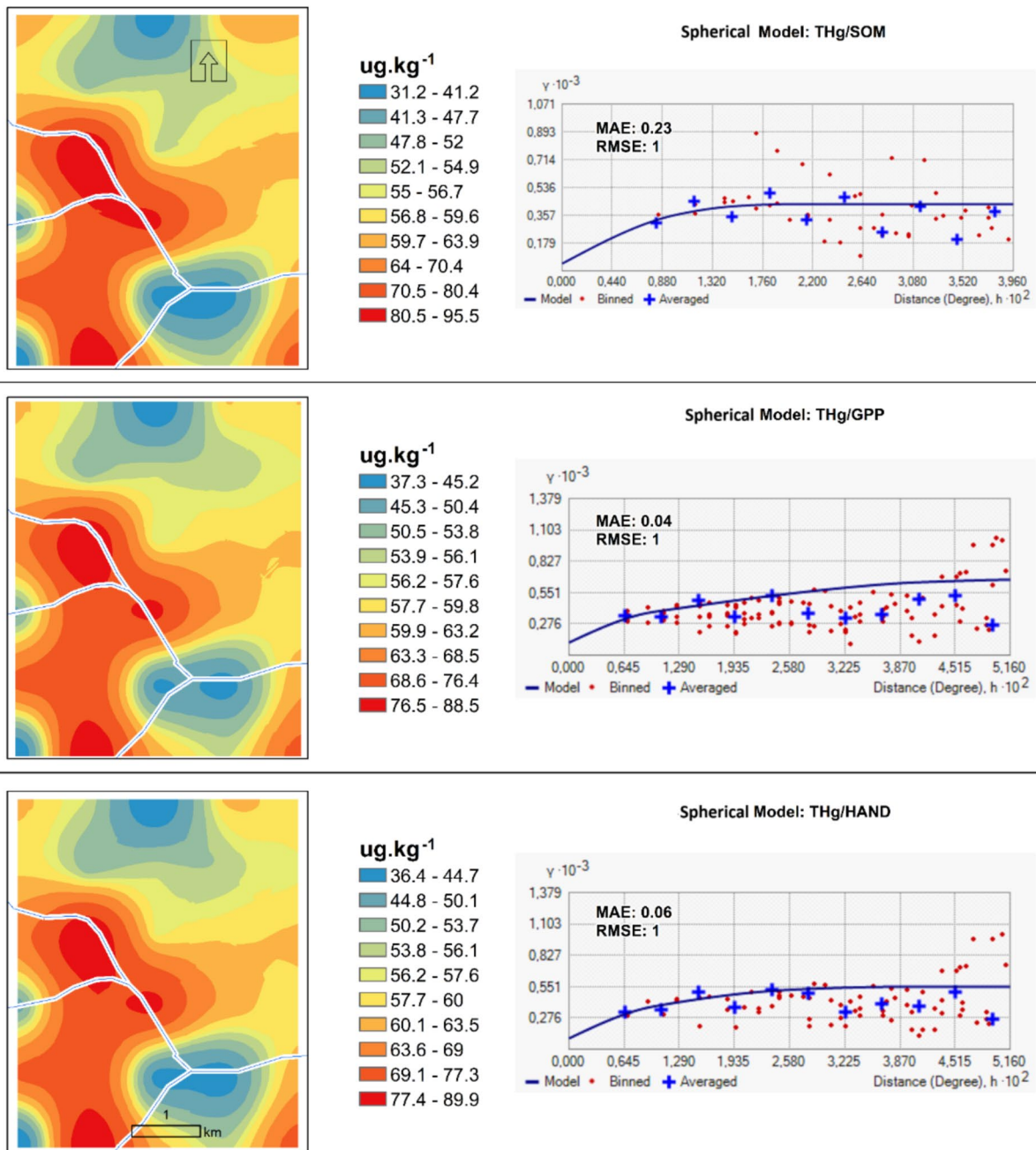
Although THg and SOM exhibit similar distributions (Fig. 2), geostatistics reveal distinct autocorrelation distances, indicating local influences on THg spatial dynamics related to humic activities (Roulette & Locute, 1995; Do Valle et al., 2005). The low concentrations of THg and SOM in certain areas of soils, despite higher average GPP (Fig. 2), are linked to water availability and material transport by desorption, resulting in THg and SOM losses (Roulet & Locute 1995; Xia et al., 2022). Additionally, regions with low SOM and high THg in ecotone areas indicate the importance of clay minerals oxy-hydroxide aggregates in Hg retention (Roulet et al., 1998).

The presence of THg in surface soils is closely linked to wet and dry depositions, and the litter-soil interface plays a fundamental role in cation exchange in the soil surface (Gu et al., 2011; Wang et al., 2016). Long-term studies have shown that 60 to 70% of Amazon rainforest species shed old leaves during dry months due to increased solar radiation (Brando et al., 2010; West, 2014). This increase in new leaf production contributes to higher GPP because young leaves have greater photosynthetic capacity and water-use efficiency (Restrepo-Coupe et al., 2013; West, 2014). However, in some Amazonian forests experiencing water stress, there is a change in leaf area dynamics (Smith et al., 2020), with a decrease in new leaf development and an increase in litter on the soil surface.

The potential accumulation and interaction of Hg in forest carbon reserves, facilitated by forest fires and the interception of atmospheric Hg emissions, highlight litter as a source of Hg for surface soils (Lindberg et al., 1995; Yu et al., 2016). In this context, THg from natural and anthropogenic emissions that enter litter interact with terrain configuration and sediment and bed transport, particularly in the Amazon region (Louis et al., 2001). Our findings suggest that



**Fig. 2** Spatial distributions of THg, SOM, GPP, and HAND with drainage line and their respective experimental semivariograms on the regular grid in the Cuniã ESEC

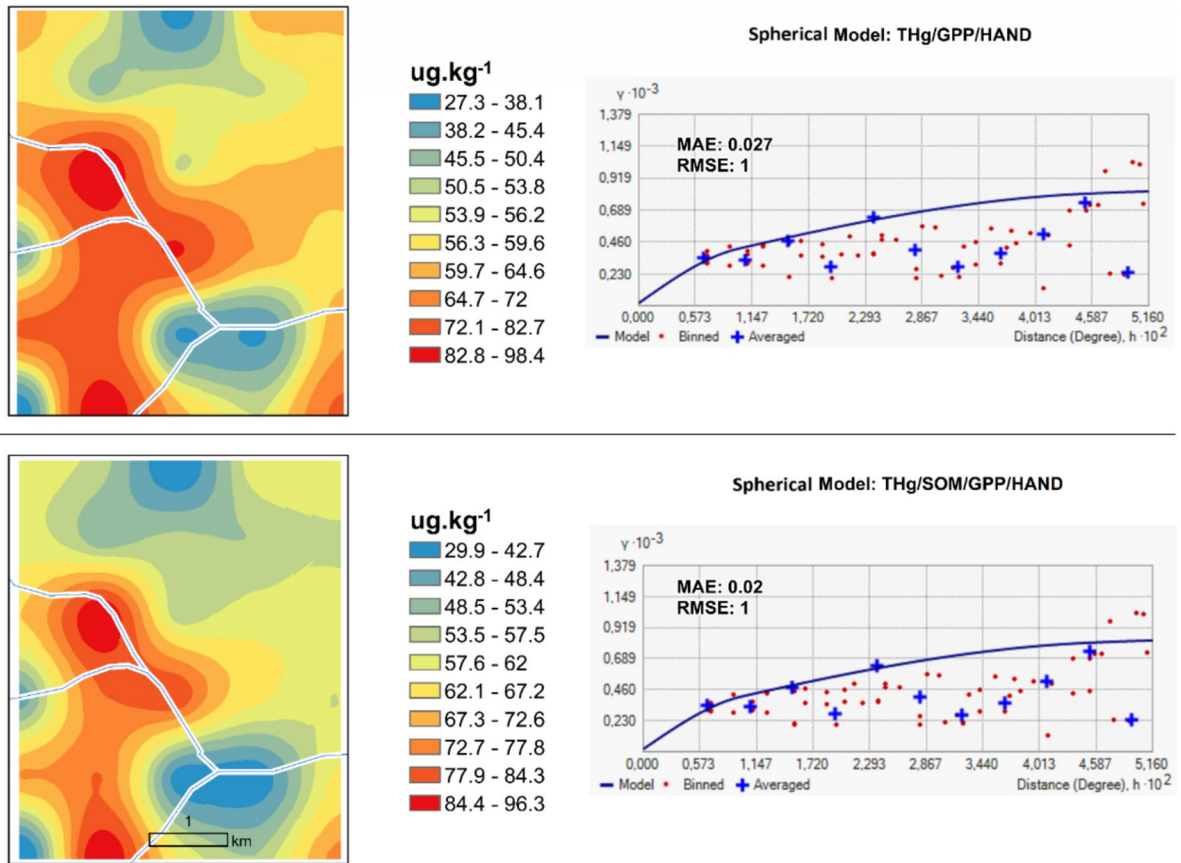


**Fig. 3** Spatial distribution of THg with the drainage line as a function of the environmental variables SOM, GPP and HAND one at a time in the regular grid of the Cuniã ESEC

THg mineralization from litterfall/throughfall reaches ecotone soil zones, indicating leaching of organic and inorganic materials from plateau areas associated with high GPP (Fig. 2). This observation aligns

with studies conducted by Roulet and Lucotte (2001), Guedron et al. (2006), and Xia et al. (2022).

Table 2 summarizes studies on THg concentrations in various classes of forest soils in the Amazon rainforest.



**Fig. 4** Spatial distribution of THg with drainage line depends on SOM, GPP and HAND on the regular grid in the Cuniã ESEC

**Table 2** Comparison of mean Hg ( $\mu\text{g kg}^{-1}$ ) concentrations in superficial forested amazon soils

| Soil Class   | Regions                               | Hg concentrations | Reference                 |
|--------------|---------------------------------------|-------------------|---------------------------|
| Hydromorphic | Madeira River Basin, Rondônia, Brazil | 50.2              | This study                |
| Oxisols      | Madeira River Basin, Rondônia, Brazil | 62.3              | This study                |
| Ultisols     | Madeira River Basin, Rondônia, Brazil | 62.7              | This study                |
| Hydromorphic | French Guiana                         | 166.6             | Roulet and Lucotte (1995) |
| Hydromorphic | Madeira River Basin, Rondônia, Brazil | 53.5              | Almeida et al. (2014)     |
| Oxisols      | French Guiana                         | 249.8             | Roulet and Lucotte (1995) |
| Oxisols      | Tapajos River Basin, Pará Brazil      | 134.1             | Roulet et al. (1998)      |
| Oxisols      | Amapá, Brazil                         | *203              | Oliveira et al. (2001)    |
| Oxisols      | Alta Floresta, Brazil                 | 61.9              | Lacerda et al. (2004)     |
| Oxisols      | Tapajos River Basin, Pará Brazil      | 245.4             | Figueiredo et al. (2018)  |
| Ultisols     | Tocantins Basin, Pará Brazil          | 71                | Aula et al. (1994)        |
| Ultisols     | Tapajos River Basin, Pará Brazil      | 98                | Roulet et al. (1998)      |
| Ultisols     | Negro River Basin, Amazonas, Brazil   | 132               | Fadini and Jardim, (2001) |

\*Median

In French Guiana, Roulet and Lucotte (1995) described deeply weathered tropical soils under dense forest, including both hydromorphic and ferralitic (Oxisol) profiles. Hydromorphic soils showed low Hg concentrations ( $166.6 \mu\text{g kg}^{-1}$ ), whereas Oxisols exhibited substantially higher values in the surface horizons ( $249.8 \mu\text{g kg}^{-1}$ ), corroborating the data obtained in our study. Fadini and Jardim (2001) reported relatively high mean Hg concentrations ( $132 \mu\text{g kg}^{-1}$ ) in soils from the Negro River Basin, despite the absence of major anthropogenic sources. Elevated mercury concentrations in these soils are primarily controlled by pedogenetic processes, notably intense weathering and the accumulation of Fe- and Al-oxyhydroxide minerals, which effectively bind Hg and shape its spatial distribution (Fadini & Jardim, 2001; Roulet & Lucotte, 1995). However, gold mining activities in the watershed and regional and long-range atmospheric deposition also contribute to increased Hg concentrations in the soil (Oliveira et al., 2001). This emphasizes the interplay of the atmosphere-canopy-soil relationship in the spatial distribution of THg, primarily linked to the dynamics of litterfall mineralization, pedogenesis, and leaching in toposequence (Gu et al., 2011; Teixeira et al., 2018; Wang et al., 2016).

## Conclusions

The spatial distribution of THg in Amazonian forest soils is strongly influenced by carbon production and the interactions between Fe/Al oxyhydroxides and humic substances. These patterns are further shaped by toposequence-driven leaching and sediment transport during seasonal flooding. The Amazon rainforest plays a pivotal role in the global Hg cycle, acting as a major filter for both anthropogenic and natural emissions. Mercury entering the dense canopy is deposited onto plateau soils, from where it can be mobilized downslope. These slopes function as both sinks and secondary sources of THg, while floodplains facilitate Hg transport into aquatic systems. Integrating remote sensing metrics with kriging geostatistical models proved highly effective for characterizing Hg spatial dynamics in tropical forest soils. This combined approach enhances our understanding of regional processes and contributes to a broader comprehension of Hg accumulation, redistribution, and re-emission within the global cycle.

**Acknowledgements** We would like to thank the Biodiversity Research Program (PPBio) for setting up the collection stations in the Cuniã ESEC (ICMBio).

**Author contribution** Conceptualization: Y.O.S.R. and J.V.E.B. Formal analysis: Y.O.S.R., L.C.M. and R.A. Investigation: Y.O.S.R. and R.A. Validation: C.T.C.N. Project administration: A.G.M. Resources: W.R.B. Writing – original draft: Y.O.S.R. and J.V.E.B. Writing – review & editing: L.C.M., R.A., A.G.M., W.R.B., and C.T.C.N.

**Funding** This work was funded by the PPBio Amazônia Ocidental (CNPq, processes no. 441260/2023–3 and 441228/2023–2), INCT-CENBAM (CNPq, process no. 406474/2022–2), and CAPACREAM (CNPq, process no. 444350/2024–1).

**Data availability** Data will be made available on request.

## Declarations

**Competing interests** The authors declare no competing interests.

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