The forensic potential of a pedological spatial database in predicting the provenance of soil evidences: building dynamic probabilistic models based on multidisciplinary data

Matheus Pereira Nogueira e Silva
matheuspnsilva@gmail.com
Advisor: Carlos Conforti Ferreira Guedes, Ph.D. (Department of Geology/UFPR)

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Introduction

The purpose of studying and developing new tools on Forensic Science arises from the growing need to create new investigative methods that aid in criminal justice and prosecution. Over the years, criminal proceedings require increasingly sophisticated evidence and greater technical-scientific background. There are two main objectives of any investment in forensic researches: (a) to prevent and tackle crime, (b) reduce impunity and (c) contribute to a fair and uncontested procedure. According to the Brazilian Association of Criminalistics (ABC), Brazil solves, annually, 5 to 10% of all murders (62.517 violent deaths counted in 2016, near 30.3 casualties per 100 thousand population), while at USA, France and UK this rate reaches 65, 80 and 90%, respectively (CNMP, 2012). Thus, there is an urgency to invest in infrastructure, scientific researches and real applications of Forensic Science.

When it comes to Forensic Geosciences, numerous topics can be studied and improved. Forensic geoscientists adopt several tools from Classic Geology in order to find a solution for their cases. Historically, the first modern records of the application of Forensic Geology dates back from the 19th century, when a few scientists analyzed soil or sediment evidences to make inferences about the dynamics of a crime under investigation (Ehrenberg, 1856 *apud* Wells et al., 1856; Gross, 1893; Popp, 1904 apud Murray, 2004). Despite the isolated caseworks, no systematic textbook was ever published until Murray & Tedrow (1975).

As stated by Donnelly (2011), Forensic Geology faced a renaissance since 2002, manly driven by both the media and enthusiastic geologists from many universities or law enforcement departments around the world. Therefore, several papers have been published in the last two decades showing the innumerable applications of soil science in the elucidation of murders (Bull et al., 2006; Fitzpatrick & Raven, 2012; Petraco et al., 2008), theft (Salvador et al., 2019), hit-and-run (Fitzpatrick et al., 2009), exhumation (McPhee, 1996) and rape (Horrocks & Walsh, 1999). Through Forensic Geophysics, authors have demonstrated how to detect forensic targets like burial sites (Nobes, 1999) and hidden tunnels (Sloan et al., 2015). The list goes on: human geographic provenance estimation by teeth analysis (Holobinko et al., 2011), airplane crash investigation (Daugherty, 1997) and even wildlife crimes such as rhinoceros poaching in South Africa (de Bruin, 2015).

Two main problems can occur during a forensic soil analysis: a small amount of evidence and the (often) absence of samples for comparison. The first one is inevitable and intrinsic to all forensic activities; the second, on the other hand, can be, depending on the circumstances, attenuated. Knowing that it is not possible to precisely geolocate an unknown soil sample, a well-built spatial database can point-out areas of high likelihood and, thus, great probability of provenance. Thereby, during an inquiry, investigators can reduce the search area by excluding certain places and focusing on specific sites, optimizing resources and time.

A soil spatial database for forensic purposes must consist, primarily, of samples collected, stored and analyzed following high quality standarts and a solid chain-of-custody. Besides, the sampling area should be covered in a way that all units (litostratigraphic and pedologic) end up well represented, avoiding geostatistical misleadings. However, this effort has never been done in Brazil.

In this research, a 100 km² area just north of Curitiba, between Almirante Tamandaré and Colombo Brazilian cities (Figure 1), was chosen by a high murder rate/low urban interference criteria, in order to evade from transported soils and to aim in sites with propensity to serve as body disposals. Through remote sensing and the geological background, 150 sampling points were designated, which is expected to result in 200 soil samples, from both the surface (0-5 cm) and the B pedological horizon, when not the same.

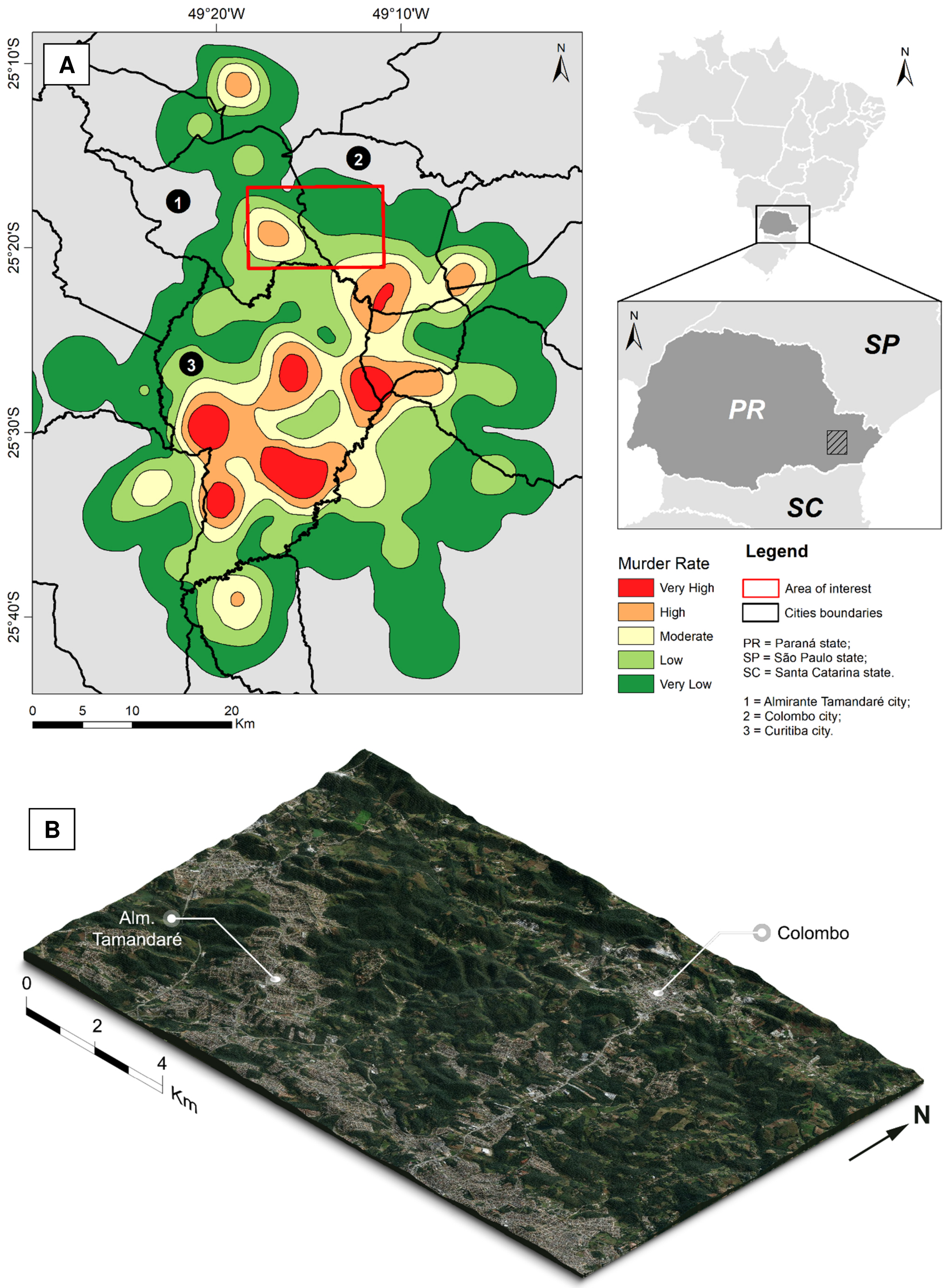

Figure 1. Location of the study area. (a) Spatial distribution of murder rate in Curitiba Metropolitan Region (RMC) – red circles indicate the most violent areas. (b) 3D-model of the study area, taking place along the Almirante Tamandaré and Colombo cities border. Urbanized zones sums up a third of the space.

For each sample, at least four different parameters will be analyzed and stored in a geographic database, totaling at least 30 variables and, thus, 170 degrees of freedom. Along with Bayes' Theorem, probabilistic models will be generated for input samples to evaluate the ability to predict its provenance or at least the litostratigraphic unit of origin (Figure 2). Principal Component (PCA) and Discriminant Analysis will be tested as well. The approved algorithms will be inserted in a dynamic web map application with a graphic user interface (GUI) and presented to the Brazilian police authorities for further investigations.

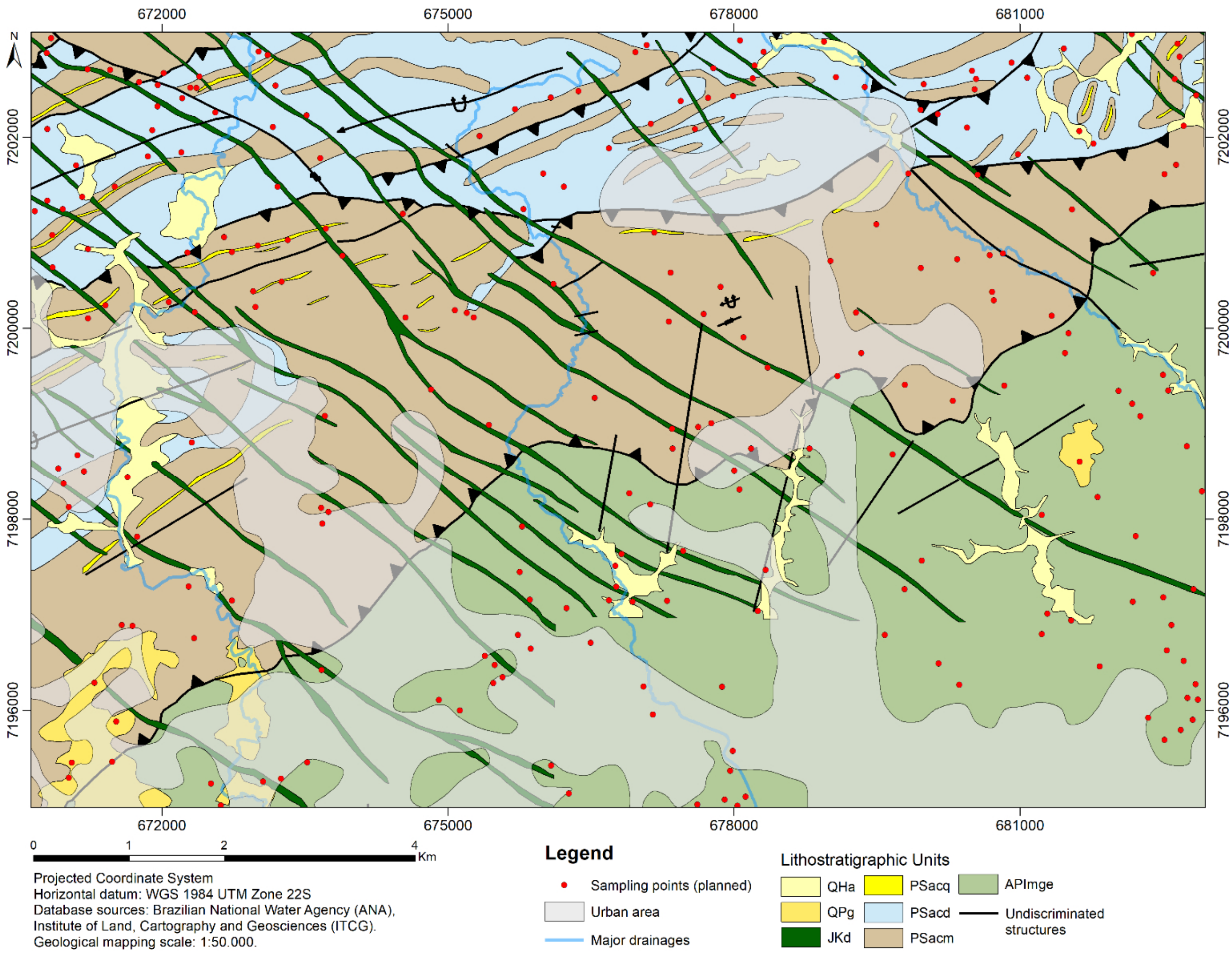

Figure 2. Geological map of study area. As shown above, three geological domains predominate in this region: low-grade limestones (PSacd) and metapelites (PSacm) from Capiru Formation (Açungui Group, Ribeira Belt, Mantiqueira Province) and migmatitic gneisses (APImge) from the Atuba Complex. Quartzites (PSacq, Capiru Fm.), alluvial sands (Qha) and unconsolidated sediments (QPg) from Curitiba Basin (Guabirotuba Fm.) are also present, but in small quantities. Mafic dykes (JKd) from the Paraná Magmatic Province segment the whole area along the NW-SE axis. Red dots stands for the selected sites for sampling soil, based on remote sensing data. The light gray cover represents the urbanized areas, which will be avoided for sampling due to the presence of transported soils. Data from Institute of Land, Cartography and Geosciences of Paraná and Curitiba Metropolitan Area Coordination.

State-of-the-art

Not many authors have focused on studying the predictive ability of a soil property database to geolocate samples for forensic purposes – most of them explore the many forms of sampling and characterizing soil for comparison analysis between evidences from inside the corpus delicti (suspects, crime scene or alibi sites) (Dawson & Hillier, 2010; Fitzpatrick, 2008; Fitzpatrick & Raven, 2005; Guedes et al., 2011; Lee et al., 2012; Parikh & Suneetha, 2016).

Rawlins et al. (2006) were the first to demonstrate how to connect multiple source sites to primarly-transferred soil traces, by joining and interpreting XRD, SEM, palynology and organic matter data from different locations. When dealing with a bigger spatial soil database, Lark & Rawlins (2008) deeply studied likelihood and probability functions for soil provenance inferences, even achieving a perfect match for a validation sample. Based on that purpose, Nakai et al. (2014) started developing a nationwide database containing XRD data of heavy minerals and heavy elements from stream sediments all over Japan island, that could provide great information about probable origin of earth-related forensic samples (Bong et al., 2012). Besides geochemical composition from bulk samples, several types of data can be inserted into a spatial database to improve the predictive geolocation script, as microfossils, man-made particulates, biogenic components and single grain morphology (Pirrie et al., 2017).

Menchaca et al. (2018) collected surface soil samples inside a perimeter in California and evaluated its colour, magnetic susceptibility and particle-size distribution. The variability pattern and discriminant analysis allowed them to closely match 22% of the blind samples within the first choice, and 44% as the second or third. Connecting informations from different multidisciplinary soil databases in USA, Stern et al. (2019) made a GIS-based Bayesian approach on a burial site investigation by assigning relative likelihood index to cell grids over multiple layers and generating a raster with gradation in probabilities of provenance. Even with the inaccuracy from low mapping scales, satisfying results were obtained.

Material and Methods

The 200 soils samples will be submitted to colour identification by Munsell chart (and later converted to CIE L*a*b format), magnetic susceptibility analysis through Satisgeo KT-6, gammaspectrometry (eU, eTh, K and Total Count), granulometric separation and analysis by laser granumeter CILAS 1094 (0.05 to 500 µm range). Geochemical characterization will be done through x-ray flourescence, either by a handheld Olympus Innov-X Delta – following Bergslien (2019) recommendations – and a bench-top Panalytical Axios Max. The soil chemical structure will be obtained by Thermo Scientific Nicolet 380 Smart Orbit Fourier Transform Infrared spectroscopy (FTIR) and DeltaNu ReporteR Raman spectroscopy. When CO_2 is detected in a sample, its isotopic signature will be determined through $\delta^{18}O$ and $\delta^{13}C$ analysis by Thermo Scientific Delta Advantage mass spectroscopy with Gas Bunch system. The sediment samples collected from the alluvial units will be submitted to heavy minerals analysis through densimetric and magnetic separations, then identified and quantified under polarized light microscopy.

All results obtained from these methods will be converted to double data type and inserted into a spatial database managed by pgAdmin 4 and based on a PostgreSQL server with PostGIS extension. Through the Psycopg adapter, a webmap application will be developed through Python and Javascript programming, along with Leaflet, OpenStreetMap and Mapbox open-source libraries. Every soil property will be geostatisticaly evaluated for its spatial variability. For a new questioned input, probabilistic models will be constructed following Bayes' Theorem.

Every applied method will be tested according to its ability to highlight the influence from the underlying bedrock (as done by Rawlins et al., 2003) and to differentiate a sample from others, leading to the exclusion or addition of a new parameter. Furthermore, the same will be done for either the surface or the B pedological horizons, when not the same.

Expected Results

Through the mentioned methods, it is expected that different areas can be distinguished and delimited mostly by the litostratigraphic contacts, since there is a great contrast between the source rocks (metapelites, low-grade limestones and migmatitic-gneisses). Also, we aim to the possibility of isolating specific areas of high likelihood from unknown soil samples, after the comparison of its geophysical, geochemical, pedological and sedimentological properties to the database. The probabilistic model will demonstrate presumable sites of origin. After analyzing its effectiveness, this research can serve as a model for any other region, as long as exist a suitable soil database.

Future Activities

As stated above, it is planned to occur a three-week field trip for sampling. The samples will be later submitted to multi-parameters analysis (geochemical, geophysical, pedological and sedimentological). Along with the geostatistical analysis of the dataset, a GIS tool for geographic provenance will be programmed. Besides the dissertation, at least two scientific papers will be written.

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