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Spatial data for fungal specimens: retrospective georeferencing and practical recommendations for mycologists

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Abstract — The number of studies based on herbarium data for analyzing biogeographical patterns and environmental questions is increasing, as herbaria are making their collections available online. However, the quality of a specimen's spatial data still varies dramatically among records. Most historical specimen records either lack geographic information or have only vague textual descriptions about the locality, while contemporary records may exhibit unwarranted variation in spatial data quality, requiring increased awareness among mycologists about the importance of high quality primary spatial data for specimens. Georeferencing is the process of assigning geographic coordinates to a record linking it to a geographic location on Earth, and it can be processed retrospectively for records without geographical coordinates based on locality descriptions or directly collected in the field using GPS handheld units. Here we provide an overview of methods for georeferencing historical data retrospectively, discuss practical recommendations for collecting high quality spatial data for fungal specimens, and suggest decimal degrees as a standard form for citing geographic coordinates.

Keywords — biogeography, conservation, ecological niche modelling, GIS, phylogeography

Introduction

Fungal taxonomy aims to investigate the diversity of fungi on Earth, assigning names, and proposing phylogenetic relationships among species. Global estimates for fungi vary dramatically depending on the methods used (Blackwell 2011, Scheffers et al. 2012), ranging from 611,000 (Mora et al. 2011) up to 9.9 million species (Cannon 1997). Presently, there are almost

100,000 known fungal species (Kirk et al. 2008), which surely represent only a small fraction of extant species. Specimens harbored in herbaria represent occurrence records of a taxon at a given location on a specific date and provide a fundamental reference to morphological and molecular studies that are necessary to ascribe species names (e.g., Brock et al. 2009, Osmundson et al. 2013). They allow the delimitation and revaluation of a species identity when more taxonomic and molecular knowledge becomes available (e.g., Cabral et al. 2012). Herbaria throughout the world are increasingly making their collections available online, and consequently the number of studies based on herbarium data for analyzing biogeographical patterns and environmental questions is also increasing (Lavoie 2013). However, most biological specimen records either lack geographic coordinates or have only imprecise textual descriptions about the locality (Guralnick et al. 2006), severely limiting the comprehension of species distributions. Public databases containing fungal specimen data exist at global (e.g., Global Biodiversity Information Facility – GBIF, www.gbif.org/) and regional scales (e.g., *species*Link network, www.splink.org.br/), but the use of this data is still incipient among mycologists.

In the case of fungi, herbarium data have been explored to investigate biogeographical patterns (Wu & Mueller 1997, Mueller et al. 2001, Oda et al. 2004, Wollan et al. 2008, Geml et al. 2012, Wolfe et al. 2012) and climate change effects on sporocarp phenology (Kauserud et al. 2008, 2010, 2012), and to model the potential distribution of invaders (Wolfe et al. 2010, Wolfe & Pringle 2012). However, as we improve our knowledge about fungi, the quality of spatial data still varies dramatically among records. As expected, most historical records have vague textual descriptions of localities, and most labels lack geographical coordinates. Nevertheless, such unwarranted variation in spatial data quality can also be found in contemporary records, requiring an increased awareness by mycologists.

Halme et al. (2012) discussed the need to rethink data collection, database structure, and organization, stressing the importance for standardizing data collection practices. However, they did not emphasize the importance of spatial data quality for documenting species occurrence. The scarcity and variability of data related to geographic coordinates has severe implications for biodiversity and related life science research, including taxonomy, phylogenetics, ecology, biogeography, biological monitoring (Halme et al. 2012), and conservation planning (Dahlberg & Mueller 2011, Molina et al. 2011). Without specimen occurrence information, one cannot make inferences about spatial processes that influence the delimitation and distribution of species. Geographic Information Systems (GIS), which were designed to manage and analyze spatial information, can be used to integrate fungal databases with other variables such as land cover, protected areas, and climatic layers of present, past, and future scenarios. The development of ecological niche models (Peterson et al. 2011), which use known occurrence points to estimate potential species distribution based on the ecological niche to define suitable sites, is another promising avenue for mycological research. These models are an important biological tool for taxonomy, ecology, evolution, conservation, epidemiology, invasive species management, and protected area planning, as all research fields depend on accurate and precise coordinates for specimens.

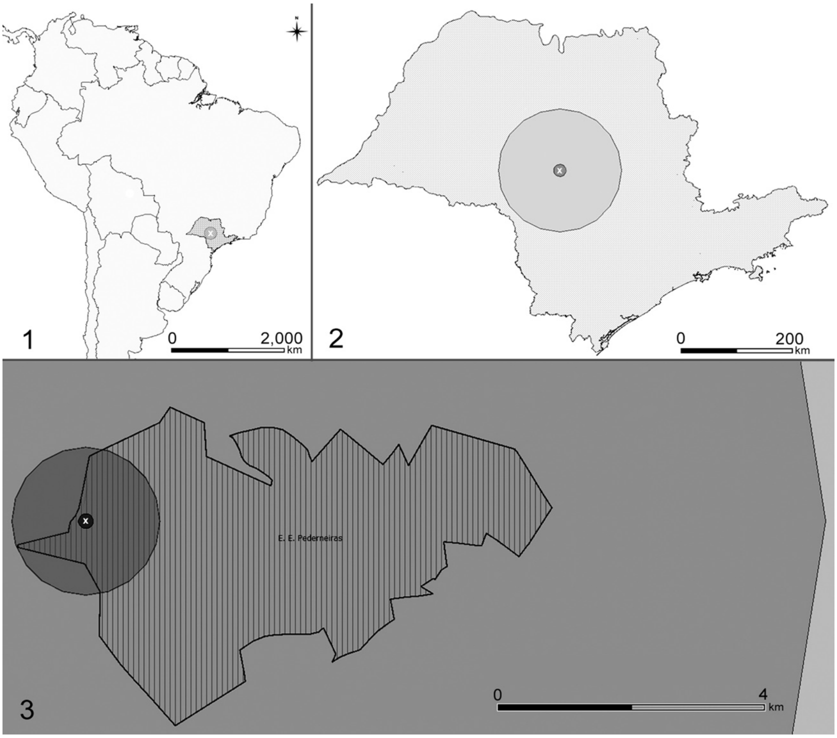
Georeferencing is the process of assigning geographic coordinates to a record, linking it to a geographic location on Earth (Chapman & Wieczorek 2006). Legacy specimens, which usually have only textual information regarding their locality, and recent collections made without geographic coordinates may be georeferenced retrospectively (Murphey et al. 2004), increasing the quality of specimen occurrence records. On the other hand, contemporary collectors could improve the accuracy and precision of their geographic coordinates by using Global Positioning System (GPS) handheld units.

As mycologists may not be well trained in georeferencing, we shall discuss how to improve georeferencing quality for fungal specimens. Our initial motivation came from practical experience, as most fungal specimens now available from the *species*Link network (http://splink.cria.org.br/) — a Brazilian initiative that integrates primary biodiversity data for the Brazilian Virtual Herbarium of Plants and Fungi (http://inct.florabrasil.net/) — lack geographical coordinates. For instance, *Schizophyllum commune* Fr., a widely distributed and quite abundant species, has 410 records in *species*Link network, but only 27 (~ 6.5%) could be selected to generate an ecological niche model. Record selection in this case took into account a number of quality criteria (Giovanni et al. 2012), but it is important to note that most records (85%!) were discarded because of the absolute lack of geographical coordinates. Due to the few records selected and their geographical bias, the generated model omits vast regions in the study area (Braga-Neto 2013a). Similarly, of the 594 records for *Pycnoporus sanguineus* (L.) Murrill available in *species*Link, only 47 (~ 8%) were selected (Braga-Neto 2013b). Therefore, so as to increase awareness about the importance of spatial data for fungal specimens, we provide an overview of methods to georeference historical data retrospectively, discuss practical recommendations for collecting high quality spatial data, and suggest a standard form for citing geographic coordinates.

Accuracy, precision, coordinate system and datum

Understanding the distinction between accuracy and precision is crucial, both for retrospective georeferencing of locality data and documenting localities (Murphey et al. 2004). Accuracy refers to how close a measurement of a quantity corresponds to its true value (whereas precision is the degree to which repeated measurements show the same results). Accuracy depends on how data is collected and processed. At the time of collection, accuracy refers to the quality of the location originally reported by the specimen collector, which may be accurately or inaccurately described, regardless the level of geographic detail recorded. In georeferencing, accuracy is related to correctly positioning the locality points based on available information and correctly entering the data into a spreadsheet or database. Precision, in the context of georeferencing, refers to the geographic extent potentially represented by the locality (Figs. 1–3). It is a product of the original locality description or measurement and the georeferencing method applied. A georeference can be accurate but not precise, precise but not accurate, neither, or both. A description of a locality containing only information about the county may be accurate, but because a county is a large geographic area, it is relatively imprecise. On the other hand, a locality described retrospectively by latitude and longitude coordinates may be precise because only a small geographic area is involved, but inaccurate if the georeferencer assigned the values erroneously. Furthermore, a georeference can be inaccurate and imprecise if the coordinate measurement in the field contains a systematic error and the datum was specified incorrectly. The georeferencing process was designed to assign accurate and precise locality data to specimen records, but as all measurement involves some kind of error, it is very important to document uncertainties as they can determine the suitability of data for particular analyses (Rocchini et al. 2011).

Also important is the geographic coordinate system, which enables every location on Earth to be specified unambiguously. The most common global systems are Latitude/Longitude (preferentially expressed in decimal degrees) and the Universal Transverse Mercator (UTM), which uses a metric-based Cartesian grid to locate positions on the Earth's surface. The UTM system is not a single map projection but a series of map projections (known as zones), one for each of sixty 6-degree bands of longitude. On the other hand, the earth's surface is not perfectly round, so it is necessary to correct these undulations. The datum is a mathematical model of the size and shape of the earth, and of the origin and orientation of coordinate systems. Coordinates without a horizontal datum do not uniquely specify a location, so failure to record the correct datum associated with coordinates can result in positional errors of hundreds to thousands of meters on a global scale (Wieczorek et al. 2004). Given its impact on precision, it is essential to provide information about the datum used as an essential part of the coordinate description. Datum shifts must be taken into



FIGURES 1–3. Geographical projections of estimated errors as a function of the number of decimal places in the decimal degree format (Wieczorek et al. 2004). The most precise coordinate was used as a reference point around which errors were depicted as buffer zones; the darker the buffer the more precise. A specimen recorded originally with 5 decimal places (e.g., Latitude –22.33214, Longitude –48.87189) has very precise spatial data, because it includes an error radius of only 1.51 m estimated for this latitude. **1**. If the coordinate chosen as an example did not contain any decimal place (e.g., Latitude –22, Longitude –49) the error dramatically would increase 100,000-fold. This error is depicted as the light gray 151 km radius buffer within São Paulo State, Brazil. **2**. Close-up of São Paulo State showing the same buffer and a smaller and darker one that represents the 15.1 km expected error if the coordinate contained only one decimal place (e.g., Latitude –22.3, Longitude –48.9). **3**. A closer view shows that a coordinate with two decimal places (e.g., Latitude –22.33, Longitude –48.87) is expected to embody an error of 1.51 km, which decreases to 150 m if the coordinate included three decimal places (e.g., Latitude –22.332, Longitude –48.872). The dashed polygon in FIG. 3 represents a Protected Area where the original point was obtained.

account when comparing data of different datum or re-projecting data to avoid the inclusion of errors. The most common global horizontal datum is WGS84 (World Geodetic Survey 1984), but there are some regional datums frequently used, such as NAD83 in North America, and SAD69 in South America.

Retrospective georeferencing of specimen records

Most herbaria that house fungal specimens collected over the past centuries currently face the task of georeferencing a vast amount of historical records, inevitably complicated by imprecise text descriptions, inconsistent formatting, misspellings, old names that have changed, different languages, and even contradictory information about collection sites. Traditionally, herbarium specimen labels have included several levels of text information specifying the site where the collection was made (such as country, county, city, and/or a reference to a place or geographic feature using some measure of distance and direction) but rarely including geographic coordinates. Essentially, retrospective georeferencing is a hypothesis that interprets quantitatively a locality description based on best available geographic information, along with associated uncertainty (Wieczorek et al. 2004). It attempts to define a standardized process by minimizing subjectivity, but it is a time consuming process (Murphey et al. 2004, Guralnick & Hill 2009, Hill et al. 2009), especially if carried out on a specimen-by-specimen basis (Guralnick et al. 2006).

There are some methods being developed to georeference locality descriptions objectively, some of which can be widely implemented even if GIS expertise is lacking (Chapman & Wieczorek 2006). Basically, the methods classify the locality descriptions, determine coordinates and extents, calculate uncertainties, and document the georeferencing process. The Wieczorek et al. (2004) point-radius method provides a relatively easy, practical solution for georeferencing localities and estimating uncertainties. It takes into account aspects of the precision and specificity of the site description, as well as the map scale, datum, precision, and accuracy of the sources used to determine coordinates. Each locality is described as a circle, with a point marking the position most closely described by the site description and a radius describing the maximum distance from that point within which the site is expected to occur. However, the Wieczorek et al. (2004) method tends to overestimate the uncertainty, since it is essentially additive and does not consider the probability distribution for each uncertainty source (Guo et al. 2008); some other methods have developed more complex estimates of uncertainties as probability surfaces (Guo et al. 2008, Liu et al. 2009).

Along with setting appropriate methods, there is a general concern for developing processing tools to increase the rate for georeferencing locations by focusing on automated methods and batch processing (Guralnick et al. 2006, Hill et al. 2009). These initiatives apply documented data standards and provide essential information about the data processing steps to ensure the process is replicable and may be improved upon, as the methods are still being developed (Hill et al. 2009). Even so, Wieczorek et al. (2004) recommend checking automated results to ensure that they were interpreted correctly. Development of these integrative tools will reduce redundancy of effort by returning assigned coordinates directly to the data curators, increasing efficiency along the process (Guralnick et al. 2006, Hill et al. 2009).

Depending on the data volume to be processed and the world region, another promising and increasingly adopted approach to retrospective georeferencing is based on Google Earth© (Garcia-Milagros & Funk 2010, Năpărus & Kuntner 2012, Weirauch et al. 2012). This convenient and freely available popular software offers a friendly interface that easily allows information visualization, accepts data imported from different sources and formats (including decimal degrees), includes uncertainty and datum, overlays maps, creates paths, points, and polygons, measures linear distances or paths, checks point elevations, manages points and associates them with notes and photos, shares data, and exports to other software. However, the time needed to georeference each specimen may be considerable (Garcia-Milagros & Funk 2010).

Georeferencing specimen records today

Collecting data in the field is the first step towards good georeferencing procedures (Chapman & Wieczorek 2006). The most important improvement in georeferencing practices stems from the Global Positioning System (GPS), a satellite-based navigation system which determines location points anywhere on Earth and in all weather conditions and is freely accessible to anyone with a GPS receiver. Given the high accuracy and precision of GPS devices in recording locality data, we strongly recommend GPS use in the field. All GPS devices provide latitude and longitude, and some also calculate altitude. Since the end of the 'Selective Availability' period on 1 May 2000, the accuracy of hand-held GPS units improved from more than 100 m (McElroy 1998) to less than 1 m.

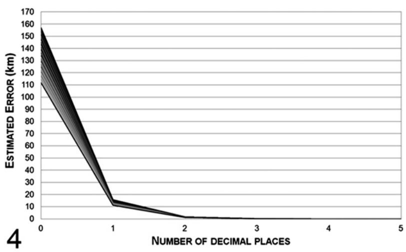
The most useful devices for biological surveys are hand-held GPS units, which are relatively cheap, small, and effective. Most modern units have a colorful screen that displays map features and allows fast handling, along with 12 parallel channels for acquiring GPS satellite signals faster and more accurately. It is best to choose waterproof or at least water-resistant models with replaceable batteries for collecting specimens in the field. Currently, GPS units do not have basemaps by default, but it is possible to transfer maps and increase their usefulness. For instance, the BirdsEye Satellite Imagery service offers high-resolution color satellite imagery of surrounding environments that at an additional cost can be uploaded to Garmin handheld GPS units. The highest resolution images can help mycologists navigate, find trails, avoid edges in forest fragments, and estimate spatial coverage, among several potential applications. Halme et al. (2012) demonstrated how to estimate sampling effort by recording tracks produced by GPS during an inventory of wood-inhabiting fungi in Finland. All these data require memory space, so devices with a USB connection are highly recommended.

However, GPS data should not replace text descriptions of localities, which are essential for validating the points. In contrast to legacy records, modern collectors have the advantage of being directly responsible for specimen data quality and can use many techniques and tools to ensure accurately georeferenced locations. Hence, site descriptions should be as specific, unambiguous, complete, and accurate as possible (Chapman & Wieczorek 2006). Collectors should avoid using vague terms such as 'near', 'along' and 'center of' without providing an offset distance estimate. To reduce uncertainty, localities to be used as reference points should be permanent sites covering small areas. If the site can only be tracked down by distances measured along a path, road, or river, it is important to be accurate.

If no GPS device was available in the field, coordinates should be assigned as soon after collection as possible from online maps (e.g., Google Earth) or gazetteers (e.g., Alexandria Digital Library, Fuzzy Gazetteer). Some tools are available globally (e.g., Geonames; www.geonames.org/), while others focus on particular regions (e.g., GeoLoc, a web service for finding localities in Brazil; http://splink.cria.org.br/geoloc). Various online maps carry more or less detailed text information, such as forest district names that are often cited by collectors. Such maps are available at the national level (e.g., France: www.geoportail.gouv.fr/accueil; Australia: www.aus-emaps.com/topo.php) or sub-national level (e.g., Bavaria, Germany: http://geoportal.bayern.de/bayernatlas/). Other useful tools are GEOLocate (www.museum.tulane.edu/geolocate/), a platform dedicated to georeferencing natural history collections data, and MaNIS Georeferencing Calculator [(http://manisnet.org/gc.html], mostly helpful in calculating offset distances and errors. It is important to assign the coordinates while the information is still fresh, so you can easily and accurately locate the geographical references.

How to improve accuracy and precision of GPS data

GPS accuracy depends mostly on the type of GPS unit used, the number of satellites visible to your receiver, the strength of satellite signals, the geometric positioning of the satellites in the sky, and atmospheric conditions. There is always a degree of uncertainty that should be associated with any coordinate. A GPS unit uses four or more satellites to calculate your latitude, longitude, and altitude on Earth. However, handheld GPS altitude measurements are usually inaccurate, so the most reliable measurements are horizontal. Maximizing



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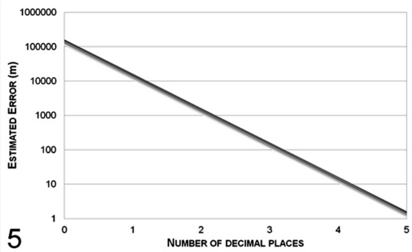

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FIGURES 4–5. The precision of geographic coordinates depends on the number of decimal places in the decimal degrees format. **4**. A geographic coordinate expressed in decimal degrees lacking decimal places is expected to embody an error of hundreds of kilometers. However, errors vary with Latitude; regions at the Equator are expected to include up to 35% more error than the ones near the Poles. **5**. The magnitude of the error, expressed in meters in a semi log scale, is negatively related to the number of decimal places. The error is expected to decrease 10-fold for every increased decimal place, so we recommend recording the most complete available information. The inclusion of five decimal places in all measurements ensures enough precision for most applications.

signal strength and the number of satellites available when measuring will produce the best horizontal accuracies. Ensure that your device reads the signal of at least four satellites, but if possible wait for more satellites to be detected. Most GPS units express signal strength and horizontal accuracy, so wait a few minutes or move to an area with better signal reception, taking note of the distance and direction from the original point. GPS satellite signal may be impaired by solid objects, such as mountains and dense forest canopy, causing errors and even no reading at all. If you are working in a closed canopy area, it is useful to turn on the GPS while still in an open area.

It is essential to configure the GPS coordinate system and datum in advance. We recommend Latitude/Longitude in decimal degrees as the coordinate system, and the datum WGS84 as a standard, as it is geocentric and globally consistent. Since this configuration is followed by most systems, it will also facilitate data exchange. A measurement in decimal degrees to five decimal places is recommended (FIGS. 4–5). Most GPS devices do not directly record accuracy with the waypoint data but provide it in the interface showing current satellite conditions. As the importance of estimating uncertainties also applies to GPS-derived data, we recommend noting the accuracy of each point. To forestall problems, it is a good practice to record GPS coordinates and associated data (decimal latitude, decimal longitude, and accuracy) in a notebook. Most importantly, document your data with proper metadata. Metadata is data about data, describing the data with information about who, what, when, where, why, and how; including the model of the device used is important.

Standard form for geographical coordinates

One of the most critical georeferencing steps (and a major source of error) is data entry. Reduce errors by adopting good practices. The most convenient format for storing and managing geographic coordinates is DECIMAL DEGREES (Wieczorek et al. 2004), which relies on just two attributes (decimal latitude, decimal longitude) and does not include extra symbols, minimizing the chances of transcription errors. Using different variations of the unit symbols in the classical degrees, minutes, and seconds input format may produce errors of more than 1 km (Hans Otto Baral, pers. comm.). Decimal latitude is expressed by positive values to the North and negative values to the South of the Equator, varying from 0 to 90 to the North Pole, and 0 to −90 to the South Pole. Decimal longitude is expressed by positive values to the East and negative values to the West of the Greenwich Meridian, varying from 0 to 180 in the East and from 0 to −180 in the West. If possible, record the coordinates in decimal degrees to five decimal places, as insufficiently precise coordinates can result in uncertainties (FIGS. 1–3). Error is expected to increase 10-fold every decimal place lost (FIG. 5), so we recommend to record the most complete available information. It is essential to provide information about the datum used (e.g., Latitude: −26.92856, Longitude: −49.04896, Datum: WGS84). There are online tools that can help convert different formats to decimal degrees, as Converter (http://splink.cria.org.br/conversor), an open access web-based service developed by the Reference Center on Environmental Information (CRIA) that converts different types of geographic coordinates and datums commonly used in Brazil, and GeoCalc (www.geocomp.com.au/geocalc/), a free software that converts coordinate data files between commonly-used mapping systems in the world.

Final comments

Providing high quality geographic coordinates is an essential step in creating species distribution maps, either by simply plotting the occurrence points on the map or by modelling and projecting the ecological niche to depict its potential distribution (Peterson et al. 2011). The adoption of simple practices guarantees the collection of high quality primary spatial data for fungal specimens. Data quality could be increased even further if herbarium curators and editors of taxonomic, ecological, and conservation journals emphasized the importance of providing geographic data for all specimens. Currently, most fungal taxonomic journals do not require geographic coordinates as essential information of specimens examined, leaving the responsibility of providing locality data to collectors and herbarium curators. We encourage researchers to obtain high quality data in the field and editors and curators to encourage geographic coordinates for specimens, greatly improving data availability and maximizing their usefulness.

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