Conceptual Modeling for Environmental Niches and Potential Geographic Distributions Using UML GeoProfile

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***Abstract*— An ecological niche is defined by an array of biotic and abiotic requirements that allow organisms to survive and reproduce in a geographic area. Environmental data from a region can be used to predict the potential distribution of a species in a different region. Many formalisms for modeling geospatial information have been developed over the years. The most notable benefit of these formalisms is their focus on a high-level abstraction of reality, leaving unnecessary details behind. This paper presents a conceptual data schema for niches and potential geographic distributions using the UML GeoProfile formalism. The proposed data schema considers the geographic entities and environmental variables involved in the prediction of potential geographic distributions made with ecological niche data.**

Keywords-Geospatial database modeling; Ecological Niches; Potential Geographic Distributions.

I. INTRODUCTION

Conceptual models are formalisms that illustrate entities and relationships between them in a diagram representation. These representations are abstractions of the objects and associations of the real world, leaving unnecessary details out. Database design greatly benefits from conceptual modeling as it focuses on a high-level representation without taking into account implementation details [1][2].

Well-known approaches for modeling databases are the Entity-Relationship (ER) Model introduced by Peter Chen in 1976 [3] and Object-Oriented techniques such as the Object-Oriented Analysis (OOA), Object-Modeling Technique (OMT) and the standard Unified Modeling Language (UML) referred in [2]. These approaches help designers to model databases for almost every human activity.

As Computer Science and technology evolve, there is a necessity to model complex situations in which databases are essential. Databases for Geographic Information Systems (GIS) are a prime example of this. The work of Bédard and Paquette [4] was the first to attempt to include geospatial information in database modeling. They proposed an extension of the ER formalism for modeling spatial data. Since then, many researchers have proposed new formalisms for geospatial data [1][5].

Those formalisms are capable of representing, at the abstract level, geographic features such as roads, buildings or rivers. Moreover, they are also able to represent environmental variables such as temperature or vegetation. The representation and abstraction of geospatial data benefits professionals and scientists in areas, such as Civil Engineering, Agriculture and Ecology, among others.

The ecological niche and potential geographic distributions are fields of study in Ecology that have been of major research interest in the last years [6]. Ecological niches are defined by an array of biotic interactions and abiotic conditions in which a species can survive and reproduce [7]. An environmental niche is constructed only by abiotic conditions [8]. On the other hand, potential geographic distributions refer to areas or regions that have the appropriate set of conditions for a species to live and reproduce. Potential geographic distributions are usually calculated by mathematical algorithms. These algorithms use environment data and occurrences of a species to make predictions [9].

The aim of this paper is to model the entities, relationships and spatial phenomena of environmental niches and potential geographic distributions using a conceptual model for geospatial databases, providing a baseline for the design and implementation of repositories containing ecological niches and potential distribution data.

The rest of this paper is structured as follow: Section II reviews the related work. Section III overviews the basic concepts of ecological niche theory including potential distributions. Section IV offers a summary of geospatial databases formalisms, focusing on UML GeoProfile [2][10]. Section V presents a conceptual data schema for environmental niches and potential geographic distributions and briefly discusses an implementation of the data schema. Finally, Section VI provides some final considerations.

II. RELATED WORK

GIS applications work with geographical features (roads, rivers, buildings) as well as with environmental variables (temperature, humidity, soil). As mentioned in Section I, the aim of this paper is to model niche-based geographic distributions using a formalism for modeling geospatial databases. Previous works have attempted to provide means to model niche and geographic distribution information [9][11][12][13]. This section summarizes prior efforts found in the literature.

Although it does not involve conceptual modeling of geospatial databases, the work in [9] emphasizes the importance of databases in GIS applications stressing their storage capabilities. Moreover, it provides a six-step guide for using ecological niche to predict potential geographic distributions. Finally, it describes how environmental variables are handled in GIS applications, highlighting the selection of the appropriate GIS data types.

McIntosh et al. [11] developed a tool that helps ecologists design databases. The focus of their research is to simplify the design process for ecologists with no experience in database theory. They provided previously created templates that help overcome common errors in defining relationships between entities. Models created in their tool can later be exported to a Database Management System (DBMS). The major drawback is the lack of support for geospatial capabilities. Entities cannot be labeled as points, lines, polygons or fields; contrary to conceptual models like those mentioned in Section IV. Even if not directly related to ecological niches or potential distributions, the work in [11] is a valuable effort because it recognizes the importance of databases for ecologists.

Semwayo and Berman [12] presented the guidelines for representing ecological niches in a conceptual model. According to the authors, traditional ER and Object-oriented models fail to represent the granularity of an ecological niche. They propose an ontological engineering approach to model ecological data. Despite the fact that there is no reference to ecological niche theory, the focus of their study is modeling the relationships between humans and their environment. Again, there is no support for geospatial capabilities.

Finally, Keet [13] provides an overview of the principal concepts related to ecological niches and presents an Object-Role Modeling (ORM) diagram of the ecological niche. The proposed ORM diagram includes entities, such as species, fundamental niche, realized niche, hyper-volumes and conditions. The work in [13] is an attempt to model ecological niches based on the concepts first introduced by Grinnell [14] and Hutchinson [15] from a database conceptual standpoint.

Contrary to the described prior work, the data schema proposed in this paper is constructed around data used in niche-based geographic distributions, using a conceptual model with geographic and environmental capabilities. Ultimately, an implementation of the data schema in a DBMS would be capable of storing the necessary geographic and environmental data of ecological niches and potential geographic distributions. Before introducing the proposed schema, it is important to have basic concepts regarding ecological niches, potential geographic distributions and conceptual model for geographic data, which are discussed in Section III and Section IV.

III. ECOLOGICAL NICHE THEORY

According to [16], the term ecological niche was first introduced by Joseph Grinnell. Grinnell suggested that a species' niche is defined by its habitat requirements [14]. This means that a niche is determined by all the environmental variables that enable the survival and reproduction of a species.

A similar definition was given by Hutchinson, who introduced the concept of fundamental niche and defined it as an n-dimensional hypervolume determined by species requirements [7][9][15]. Hutchinson's definition is a quantitative approach that gives more clarity to the concept and leaves an open door for the development of mathematical techniques [16].

Although Hutchinson's definition is rather straightforward, an implementation is not a simple task. The amount of dimensions in a hypervolume is potentially infinite. Dimensions such as temperature and soil characteristics can be easy to collect, while other variables like the diet of an organism are, in some cases, not accessible. Additionally, certain dimensions can be irrelevant to determine the fundamental niche [7][15].

The dimensions of the hypervolume can be classified as conditions and resources. Resources are consumed or used, which might lead to competition between organisms of the same or different species. Differently, conditions are environmental (abiotic) variables, such as temperature, precipitation and terrain aspect, among others [8].

Depending on the dimensions considered, ecological niches can be classified as Grinnellian or Eltonian. Grinnellian niches (also referred as environmental niches) consider only environmental variables, which are, in most cases, considered scenopoetic, i.e., not affected by organisms. On the other hand, Eltonian niches focus on resources and relationships between organisms. The concept of n-dimensional hypervolume can be applied to both Grinnellian and Eltonian niches [8]. This paper, considers only environmental niches, as their data sets are becoming more available and data sets for Eltonian niches are still difficult to obtain [8]. Furthermore, data from environmental niches are more related to predictions of geographic distributions, which are also in the scope of this paper [9].

Others exploited concepts related to ecological niches are the realized niche and the geographic distribution of species. Hutchinson defined the realized niche as a subset of the fundamental niche restricted by species' biotic interactions [9][16]. According to Soberón, the realized niche occurs in the overlapping area between the geographic region with appropriate abiotic factors and the region in which there is a suitable combination of interaction between species [17]. The actual geographic distribution of a species would be the region that has the appropriate range of abiotic and biotic conditions, as well as being accessible to organisms [17][18]. The BAM Diagram (called BAM due to the labels in each circle of the diagram) [17] exhibited in Fig. 1 offers a graphic explanation of the concepts defined earlier. The circle A represents the area with the appropriate abiotic conditions (geographical expression of the fundamental niche). The circle B is the area with suitable combination of interacting species. The intersection of A and B denotes the geographical extent of the realized niche. Circle M holds the regions accessible to the species. Finally, the overlapping region of A, B and M represents the geographic distribution.

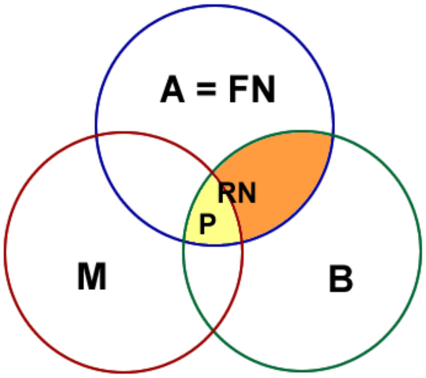

Figure 1. BAM Diagram for representing the fundamental niche [17]

Additionally to the actual geographic distribution, potential geographic distributions are regions with suitable conditions for species to survive, i.e., the geographical extent of the fundamental niche [9][19]. Usually, data from species distribution (occurrences and environmental variables) are used in mathematical algorithms to predict potential geographic distributions [9][19][20][21]. The inputs for these algorithms are a set of occurrence data and environmental variables for both occupied and evaluated area. Outputs, on the other hand, are either regions with suitable conditions in which species are present (the intersection P of the three regions of the BAM diagram), or regions with suitable conditions where organisms are not present (areas representing the fundamental niche A minus P in the BAM diagram) [17].

As mentioned in [6] and [22], since the 1990s, the methodologies based on Ecological Niche Modeling have increased significantly. There are several uses for niche related concepts in the literature including climate change projections, potential geographic distributions, species invasion projections, niche characterization, niche diversification, niche construction and habitat-suitability, among others [6][8][21][23][24][25].

IV. CONCEPTUAL MODELS FOR GEOSPATIAL DATABASES

Over time, computational systems have become more robust and sophisticated; hence, there is a necessity to handle complex data such as geospatial information. One of the major elements of a GIS is a database in which information is stored. Modern DBMS software, such as Oracle and PostgreSQL, have capabilities to manage geospatial data and provide additional benefits like security, redundancy or user control access.

Database designing has three basic stages [26]: conceptual, logical and physical. The conceptual stage produces data schemas that represent a high-level abstraction of entities and relationships between them. The major benefit of using conceptual models is their independence of implementation details, which is the reason of their usage in Computer Science fields such as Databases. Notable conceptual models used in database modeling are the ER Model, OOA, OMT and the UML [2][3].

The work in [4] was the first attempt to create a conceptual model (formalism) dedicated to model geospatial databases from a conceptual standpoint. Bédard and Paquette proposed a geospatial extension of the ER formalism. Thenceforth, many researchers and professionals have proposed new methods or extended previous ones. Conceptual models for geospatial databases assist in the process of modeling geographical features as they are modeled as perceived by humans [27]. Moreover, the studies in [28] and [29] state that geospatial formalisms allow reduction in the number of entities and relationships without losing semantics.

The studies in [1] and [5] present a timeline of the major geospatial formalisms and list their principal characteristics. According to Pinet [1], there are seven major goals shared by formalisms dedicated to model geospatial data:

1) Representing basic geospatial objects such as points, lines, polygons, multiple points, multiple lines or multiple surfaces.
2) Modeling geospatial relationships between objects. Examples of relationships are adjacency, overlap and disjoint.
3) Description of the evolution of objects over time.
4) Modeling objects that might have multiple representations depending of the geographical scale.
5) Description of objects with uncertain boundaries or positions, for instance floods or areas of pollution.
6) Representation of continuous geospatial data that can be measured in any location of the study area.
7) Modeling structured networks.

Usually, formalisms use pictograms to improve readability and to simplify the model [5]. A pictogram is a graphic symbol that resembles the real object that is being modeled. Fig. 2 shows the pictograms used in UML GeoProfile [10]. Notice that the pictograms cover most of the goals proposed in [1].

Comparing the various formalisms specialized in geospatial data is not in the scope of this paper. For a comparison and overview of different formalisms, refer to [1][2][5].

A. *UML GeoProfile Overview*

UML GeoProfile is an UML profile specifically designed as a formalism for modeling geospatial databases in a conceptual level. As noticed before, a conceptual model represents an abstraction of reality and does not involve implementation details. Being an UML extension, UML GeoProfile allows the use of classes, associations, packages and constraints, among other UML features [2]. Additionally, UML GeoProfile can be implemented in any Computer Aided Software Engineering (CASE) tool with UML profiles support.

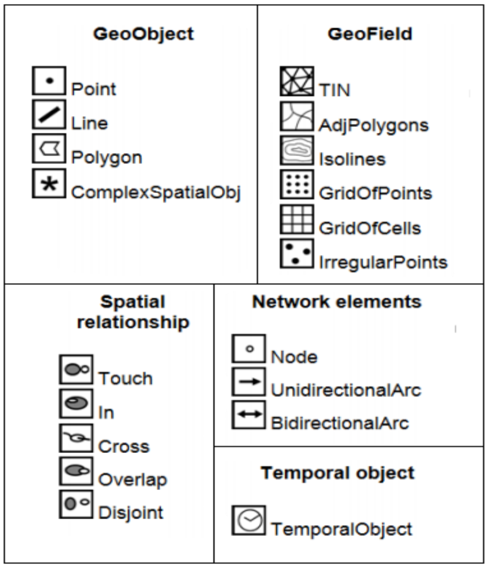

Figure 2. Pictograms used in UML GeoProfile [10].

The principal motivation behind UML GeoProfile was the standardization of previous models. To accomplish this, UML GeoProfile took the best offerings from different models and brought them together. As other formalisms, UML GeoProfile takes advantage of pictograms to simplify the model. In UML GeoProfile, pictograms are modeled as stereotypes. A UML stereotype allows designers to extend the terminology of UML in order to create new constructors [2][10]. Furthermore, UML GeoProfile takes advantage of UML packages to divide schemas in geospatial themes, e.g., vegetation, relief or hydrography. This characterizes related entities and provides better organization.

UML GeoProfile follows the international standards for Geographic Information of the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC) [10], which reduce inconsistencies between *de jure* and *de facto* standards [30]. Additionally, UML GeoProfile adopts a Model-Driven Architecture (MDA) approach. In MDA, models are first built in a Computation Independent Model (CIM); CIM models are later transformed to a Platform Independent Model (PIM). The third stage of the process is the Platform Specific Model (PSM), which is later converted to implementation code [10]. Further information on stereotypes, international standards and MDA can be found in [2][10][30].

V. REPRESENTING ENVIRONMENTAL NICHES AND POTENTIAL DISTRIBUTIONS USING UML GEOPROFILE

This section describes how to model environmental niches and potential geographic distributions using UML GeoProfile as an MDA's Computational Independent Model (CIM). First, we illustrate the representation of individual entities, and, then, we propose an approach to represent environmental niches and potential geographic distributions in three packages that form a single database schema.

A. *Basic representations*

As stated in Section IV, UML GeoProfile uses stereotypes to represent geospatial entities (classes in UML). For instance, the *Point* stereotype is used to represent trees or occurrence data while the *Polygon* stereotype represents geographic areas such as cities or forests. Moreover, UML GeoProfile provides stereotypes to represent continuous data such as humidity and temperature. Fig. 3 exhibits a representation of occurrence data of species (a), the occupied area in which organisms live (b) and temperature (c) employing UML GeoProfile.

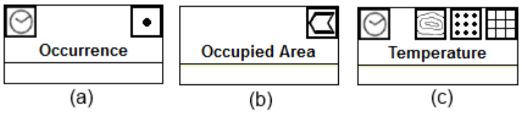

Figure 3. Representations of occurrence data of a species (a), occupied area (b) and multiple representations of temperature (c).

Additionally, UML GeoProfile supports multiple representations for geospatial entities. Depending on how data was initially collected, environmental variables can be represented in a diversity of GIS types. Fig. 3 (c) shows the representation of temperature displayed as Isolines, Grid of Points and Grid of Cells.

B. *Modeling Environmental Niches*

Predictive algorithms such as the Genetic Algorithm for Rule-Set Prediction (GARP) [31] work with a set of occurrence data and an array of environmental variables of a given area to predict geographic distributions. A range is defined for each variable (minimum and maximum values) to construct an n-dimensional hypervolume that restricts the conditions in which organisms can survive.

Being a generic modeling approach, it is necessary to build a schema that supports data from different species and multiple regions occupied by organisms of the same species. Each region has its own hypervolume defined by an array of environmental variables. Furthermore, the amount of variables can also vary from region to region.

Fig. 4 presents the proposed conceptual data schema for environmental niche data. Notice that the entities and their relationships are based on the literature for ecological niches and potential geographic distributions referenced in Section III. An occupied area (modeled with the Polygon stereotype) has one or multiple occurrences of a species. The relationship between the Occupied Area and Occurrence classes is modeled as a spatial relationship *In*, indicating that a species occurrence is inside a region. The term “occurrence” is preferred over “organism” because the schema does not consider particular characteristics of organisms such as weight or age. The organism's location (covered by the Point stereotype) is the most important piece of information. In addition, the schema does not take into consideration organisms' movement. For that reason, an occurrence is related to not more than one occupied area. However, an organism can be identified in two or more areas over a period of time. Although an occurrence can represent the same organism, it is still related to at most one region in a particular moment. To solve the relationship's lack of congruence, the Temporal Object stereotype is also assigned to the Occurrence class. This allows an organism to be related to other regions in a different moment in time.

Multiple environmental variables can be considered in an occupied area. In addition, a type of environmental variable can be analyzed in multiple regions as well. Here, the hypervolume is defined by the multiple instances of the Niche Axis (hypervolume dimension) association class, which cannot exist without the association between occupied areas and environmental variables.

An association class is defined for each association between the two classes, indicating the units (ratio, degrees, inches) and the minimum and maximum values of a particular variable in a specific area. This approach presents a limitation: it is incapable of modeling relationships between dimensions of the hypervolume, e.g., if the temperature is higher than 30°C, then the humidity must be between 90% and 99% [14]. These relationships depend entirely on the environmental variables and their variation. Consequently, it is difficult to predict and model them. Analytical tools or algorithms handle the relationships as rule sets used to predict geographic distributions [9][21].

Notice that in Fig. 4, a GeoField stereotype is not assigned to the Environmental Variable class as it was previously suggested. The reason behind this is that GeoObject classes (points, lines, polygons) and GeoField classes belong to different views of the reality and usually there are not topological relationships between classes of two different views [10]. That said, the lack of stereotype for the class is a non-issue. In order to construct a hypervolume it is only necessary to know the variable type and its range. Nevertheless, it is also important to provide a manner of including in the model the field from which the hypervolume data were extracted.

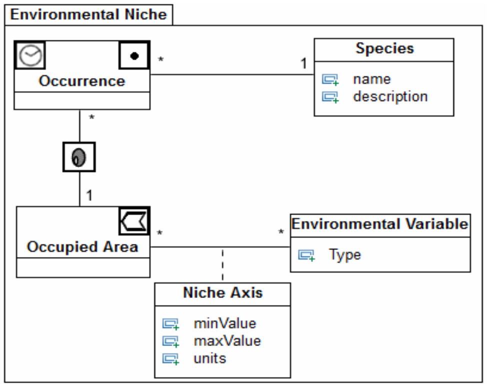

Figure 4. Representation of environmental niches

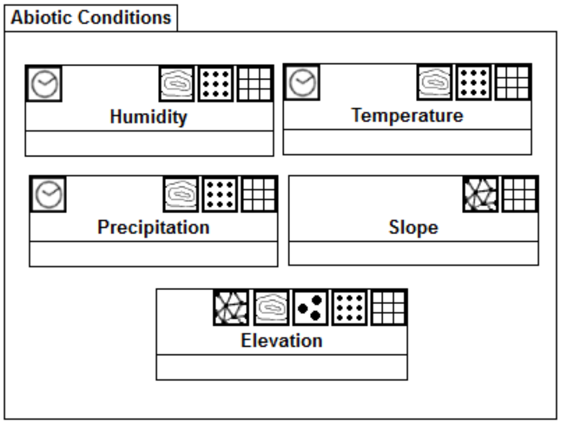

Figure 5. Possible environmental variables of an n-dimensional hypervolume. Multiple representations allow the use of different types of data sources.

As mentioned before, the amount of dimensions in a hypervolume is potentially infinite. Hence, the final model strictly depends on the study case. Fig. 5 provides an example of the possible representation of the environmental dimensions (abiotic conditions) of a hypervolume. Notice the presence of the Temporal Object stereotype in some classes, meaning that certain abiotic conditions can vary over time, e.g., the monthly average temperature of a region.

C. *Representing Potential Geographic Distributions*

Predictive algorithms and tools operate with occurrence data and environmental variables to produce potential geographic distributions of a species (regions where organisms can live or survive) usually in the form of a grid of cells [9][19]. Fig. 6 shows the classes related to the potential distribution.

The Evaluated Region class represents the boundaries of the area in which the distribution is projected; this is relevant to model because projections are usually done from a defined area to another. For example, the research in [9] used niche data of a pathogen from the United States (occupied area) and predicted distributions for Mexico (evaluated region); similar researchers are found in [19] and [21]. Evidently, environmental data from the evaluated region are also needed. These data are modeled in the same manner as the environmental dimensions of the niche hypervolume (refer to Fig. 5).

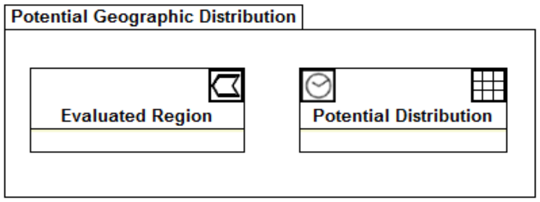

Figure 6. Potential Geographic Distribution. The evaluated region is modeled as polygon and the distribution as a grid of cells.

Notice that the Evaluated Region and Potential Distribution classes are not associated because they belong to different views. Additionally, there is no relationship between a species (or its organisms) and the evaluated regions. Even if organisms occupy the latter, there is no evidence of a topological relationship.

Finally, it is inevitable to acknowledge the necessity to link the field view classes (both abiotic conditions and Potential Distribution classes) to their corresponding region. This can be done through metadata that describes details such as coverage area or how and when data were obtained.

D. *Implementation of the data schema*

We implemented the conceptual data schema in PostgreSQL using the PostGIS geospatial extension and its *geometry* and *raster* data types to store geographic and environmental data. Non-geospatial entities were implemented using basic data types provided by the DBMS. To employ the data schema, first we took advantage of the software openModeller [32] to create the potential geographic distribution and ecological niche model of sample data (occurrences and environmental data) provided with openModeller.

The results generated by one of the algorithms included in openModeller were later stored in the data schema using basic SQL statements and tools designed to load geospatial information into a PostgreSQL database. QuantumGIS and other GIS software with geographic analytical capabilities can be used to retrieve the information stored in the database (information can be filtered by species, area of interest, among others). This provides the benefit of having data for multiple species stored in a single place instead of different files. Furthermore, our approach can exploit all the advantages of a DBMS.

VI. CONCLUDING REMARKS

This paper presented a conceptual data schema for environmental niches and potential geographic distribution of species. The complete schema consists of the components exhibited in Figures 4, 5 and 6. The major limitations of this approach are the lack of support for relationships between dimensions of the niche's hypervolume and the inability to model classification values such as vegetation type. Both limitations are handled by predictive algorithms in a form of rule sets generated from the abiotic layers.

The geospatial and temporal phenomena of the schema are modeled using UML GeoProfile stereotypes. UML GeoProfile was preferred over other formalisms for its capacity to model both object and field phenomena, as well as for the implementation of international standards, and MDA adoption. The proposed conceptual data schema represents no more than the CIM stage of the MDA. Future work includes implementation of the remaining MDA stages and development of a study case with real data.

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