On the integration of regional classification systems for the National Map

Thomas Bittner
Departments of Philosophy and Geography
National Center for Geographic Information and Analysis (NCGIA)
State University of New York at Buffalo
bittner3@buffalo.edu

Abstract

An ontology based methodology is used to analyze the classification and delineation systems of the USFS, the EPA, and the WWF from the perspective of their integration in the National Map. The envisioned ontology-based integration is focussed on geographic classification systems but it is consistent with the principles of the larger framework of the Open Biological Ontologies to ensure the possibility of data integration also from biology and the life sciences.
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1 Introduction

Categorial (digital or non-digital) display particular geographic regions and rely on a precise *delineation* of such regions. Precise delineation in turn relies on *local* qualities and quality pattern that distinguish neighboring regions (Omernik, 2004). For the integration of digital maps from different sources, *classification systems* for qualities of geographic regions and classification systems for the regions themselves are needed (Schuurman & Leszczynski, 2006; Bittner *et al.*, 2009). Classification systems for geographic regions are, by definition, general and *non-local*.

Thus, in the context of data integration there is a trade-off between local character of the precise delineation geographic regions and the non-local character of the classification of geographic regions. Moreover, due to the vagueness of many geographic categories, there is an additional fundamental trade-off between the possible preciseness of the delineation of particular geographic regions and the possibility of providing a unified classification system based on qualities that characterize geographic regions (Bittner, 2009).

Both trade-offs pose a fundamental challenge to the National Map and to the integration of geographic data from different sources in general: the need for maps with precise boundaries conflicts with the need for unified or at least compatible classification systems for integration purposes. I use the classification and delineation systems of the USFS, the EPA, and the WWF as a case study to determine how to integrate different systems in the presence of this trade-off. This paper is an application of an ontology-based framework for analysis of the ontological and methodological foundations of the classification and delineation of geographic regions proposed in (Bittner, 2009).

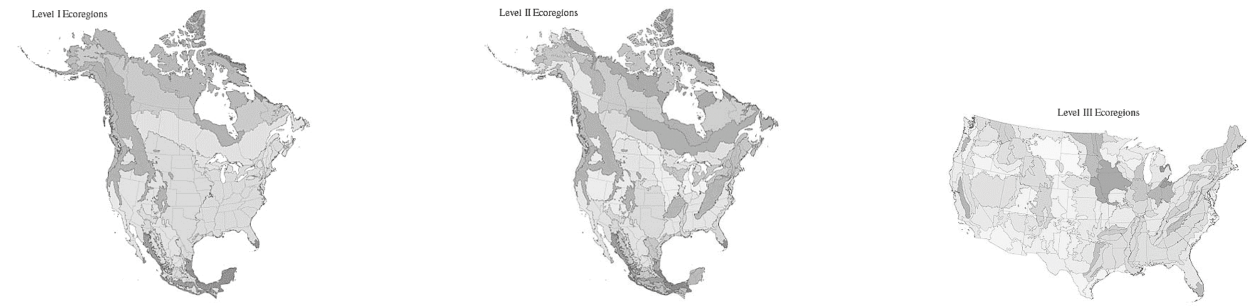
2 Ontological properties of classification and delineation systems

Within the underlying ontology-based framework, properties of classification and delineation systems need to be expressed terms of well-defined top-level categories and relations. An extended discussion of top-level terms can be found in (Bittner *et al.*, 2009; Bittner, 2009). Here those top-level terms are introduced in terms of examples from the classification and delineation systems of the USFS and the EPA. Some important definitions are also summarized in Table 1. To visualize the extensive use of those terms, they are marked using the Sans Serif font. The consistent use of these terms will ensure that the resulting integrated system will be ontologically sound. In addition this will ensure that the resulting system can also be integrated in the larger system of OBO ontologies (Smith *et al.*, 2007) and thus also facilitate data integration with the biological and the life sciences.

2.1 Delineation of geographic regions

Consider the three maps of ecoregions of North America (Figure 1). Each map represents a collection of ecoregion particulars of a certain size-range that are parts-of the North American continent (NAC). The symbols LI, LII, and $LIII$ are used to name the collections which members are depicted on the respective maps. The collection LI partitions the continent of North America (NAC): the members of LI jointly sum up to NAC and no two distinct members of LI overlap. Similarly, the collections LII, and $LIII$ are more fine-grained partitions of NAC. The collections LI, LII, and $LIII$ are hierarchically nested ($\uparrow$-p-included) within one another, i.e., every member-of LII is an part-of some member-of LI. Similarly, $LIII$ is $\uparrow$-p-included in LII, $LIII$ is $\uparrow$-p-included in LI, and so on.

In geographic delineation systems regions are assumed to be homogeneous with respect



(a) Level I ecoregions (b) Level II ecoregions (c) Level III ecoregions

Figure 1: Ecoregions of North America (EPA) at different scales (EPA, 2007)

to certain quality pattern (Table 1). Consider the geographic regions Central Great Plains (CGP) and Flint Hills (FH). (Labeled respectively '9.4.2' and '9.4.4' in in the system of the EPA as depicted in Figure 4.) CGP and FH are respectively homogeneous with respect to the quality pattern *Q-GCP* and *Q-FH* which are specified in Table 2 (Omernik, 1987).

All members of the collection $LIII$ are maximally homogeneous with respect to some quality pattern (Omernik, 1987; EPA, 2002, 2007): no neighboring members of $LIII$ are homogeneous with respect to the same quality pattern; no two distinct members of $LIII$ overlap; and jointly they sum-up-to the North American continent. In particular the regions Central Great Plains and Flint Hills are maximally homogeneous with respect to the quality pattern *Q-GCP* and *Q-FH*.

2.2 Quality pattern and classification

Maximal homogeneity with respect to quality pattern is critical for the delineation of ecoregion particulars. Classification of ecoregion universals can be based on two kinds of relations between such quality pattern: the sub-pattern relation and the genus-species relation (Table 1). For example, among the quality pattern listed in Table 3 the sub-pattern relation holds as indicated in the bottom of the left part of Figure 2 (pg. 4). Consider Tables 2 and 3. The quality pattern *Q-GCP* and *Q-FH* are both species quality pattern of the genus-pattern *Q-L*.

The ecoregion classification of Bailey (1983) can be considered as a prototypical example for the definition of ecoregion universals in terms of sub-pattern and genus-species relations between quality pattern: The quality pattern *Q-S* (Table 3) serves as the defining pattern for the ecoregion universal *Section*. The immediate sub-universals (roughly: immediate sub-classes – see (Bittner *et al.*, 2009)) of the universals of *Ecoregion* are defined in terms of sub-pattern of *Q-S* as depicted in the left part of Figure 2.

For example, the universal *Domain* is defined in terms of maximally homogeneity with respect to some proper sub-universal of *Climate regime*. That is, instances of *Domain* are maximally homogeneous with respect to *Polar Climate Regime*, or *Dry Climate Regime*, or .... The defining genus quality pattern of the universals *Domain*, *Division*, *Province* and *Section* stand in the sub-pattern relation as depicted in the left part of Figure 2.

Proper sub-universals of *Domain*, *Division*, *Province* and *Section* defined in terms of maximally homogeneity with respect to one specific species pattern of the pattern *Q-Do*, *Q-Di*, *Q-P*, and *Q-S*. For example, proper sub-universals of *Domain* are maximally homogeneous with respect to one specific species pattern of *Q-Do* (right part of Figure 2). More specifically, every instance of *Humid Temperate Domain* is maximally homogeneous with respect to the quality universal *Humid Temperate Climate Regime*.

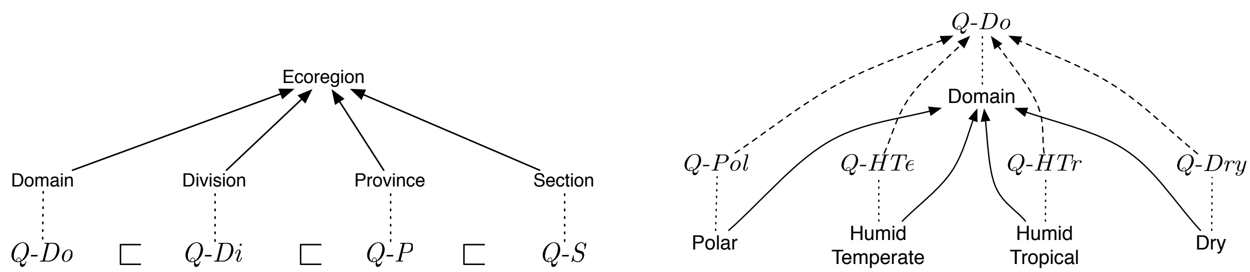


Figure 2: The ecoregion universals in Bailey's system. The solid arrows represent the relation sub-universal-of$_{_B}$. $Q_i \sqsubset Q_j$ represents that Q_i is a sub-pattern of Q_j. A dashed arrow between the quality pattern Q_i and Q_j indicates that Q_i is a species pattern of Q_j. A dotted line connecting a quality pattern to a universal indicates that this quality pattern is used as a differentia in the definition of the corresponding universal. The quality pattern *Q-Do*, *Q-Di*, *Q-P*, *Q-S*, *Q-Dry*, *Q-HTe*, *Q-HTr*, and *Q-Pol* were defined in Tables 3 and 2. (Bittner, 2009)

The hierarchical spatial nesting of ecoregion universals can be represented using the relation ↑-u-part-of$_{_B}$. For example, the relation ↑-u-part-of$_{_B}$ holds between the universals *Prairie Lowland Division* and *Humid Temperate Domain*: Every instance of *Prairie Lowland Division* is a part of some instance of *Humid Temperate Domain*. (See Figure 3.)

2.3 The trade-off between classification and delineation

Consider Figure 4. The delineations of members of *LIII* of the EPA and the instances of *Section* of the USFS are similar in some obvious but hard to specify way. This is due to the fact that the quality universals that characterize *Sections* in the system of the USFS (species pattern of *Q-S*) are compatible with the quality universals that characterize the members of the collection *LIII* of the EPA (Land surface qualities). However, clearly the delineation of

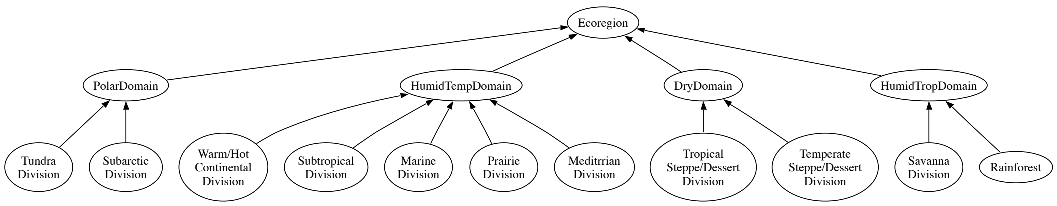


Figure 3: Graph of the relation ↑-u-part-of$_B$. (See (Bailey, 1983) for the complete graph.)

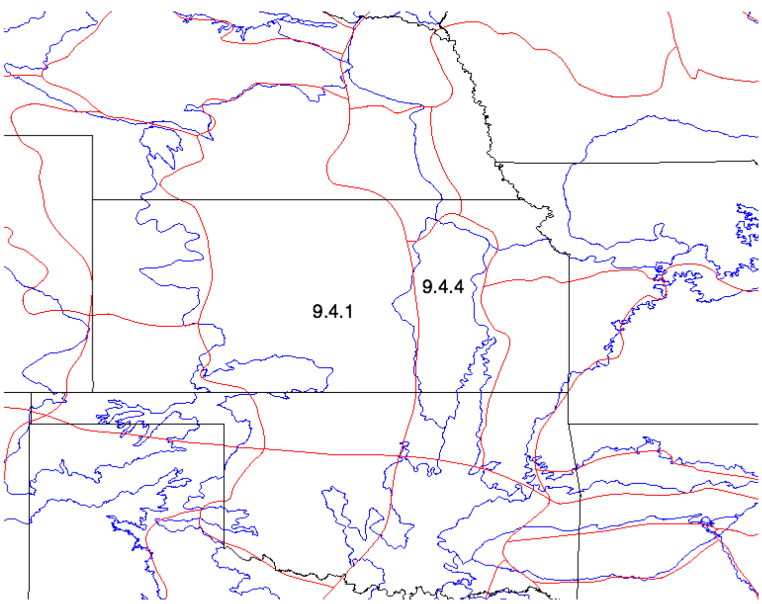


Figure 4: Delineation of instances of *Section* (red) and members of *LIII* (blue) in the Central Plains of the USA. (National Atlas of the United States, 2005, 2004)

the EPA is much more precise and detailed in comparization to the rather coarse delineation of the USFS.

The more precise and detailed delineation of the EPA is due to the more specific quality universals that characterize the members of the collection *LIII* of the EPA (2002): In addition to general land surface qualities, the local qualities of a given ecoregion are specified relative to the qualities of its neighbors (e.g., lower/higher precipitation, less relief, more irregular, etc.). In addition historical qualities of certain ecoregions are included in the quality pattern (e.g., 'Once a grassland ...'). Clearly, such quality pattern are very specific to certain ecoregion particulars. For this reason one cannot expect that there exists a classification system based on relations between general quality pattern similar to the one of the USFS (Figure 2). On the other hand, these very precise specification of qualities of particulars enable a much more precise (less vague) specification of boundary location as depicted in Figure 4. By contrast, in Bailey's system the focus is on a unified classification system (the universals and their sub-universal relations). The price for the unified system is that, due to the non-local character of the classification and the underlying vagueness, the delineation of ecoregion particulars is rather coarse and imprecise.

3 The classification and delineation system of the WWF

The classification and delineation system of the WWF (Olson *et al.*, 2001) is an example of a system that attempts to avoid the disadvantages of the two extreme positions of (i) the focus on classification based on non-local quality pattern as in Bailey's system (Aristotelian method of classification) and (ii) the focus on delineation based on local quality pattern as in the system of the EPA (weight-of-evidence methodology).

3.1 Local quality pattern for delineation at the most detailed scale

The WWF uses a collection of 825 geographic regions (*WWF_867*) which partitions the land surface of the Earth at the most detailed scale. In North America the collection *WWF_867* coincides with the collection *LIII* of the EPA system (i.e., *LIII* is a sub-collection of *WWF_867*). Since the WWF incorporates the collection *LIII* of *Level III ecoregions*, it seems to accept the focus on the precision of delineation based on local quality pattern at the most detailed scale. Due to the focus on local quality pattern, there are no relations between quality pattern that give rise to a (non-trivial) classification at this scale.

By contrast, the definitions of *Ecozone* and *Biome* universals are based on relations between non-local quality pattern. In addition, those non-local quality pattern provide *aggregation criteria* for defining coarser regions as sums or aggregates of the members of *WWF_867*.

3.2 Biome and Ecozone universals

The WWF uses two kinds of quality universals for the formation of quality pattern in its definitions of the universals *Biome* and *Ecozone*: *biomic* quality universals and *biogeographic* quality universals. The twelve immediate sub-universals of *Biomic quality* characterize geographic regions based on the distribution patterns of plants and animals corresponding to pattern of climatic, soil, and other qualities, e.g., *Taiga*, *Tundra*, etc. (Udvardy, 1975; Olson *et al.*, 2001). The eight immediate sub-universals of *Biogeographic quality* characterize geographic regions based on historic and evolutionary distribution patterns of plants and animals, e.g., *Nearctic Realm*, *Palearctic Realm*, etc. (Udvardy, 1975; Olson *et al.*, 2001). The quality pattern *Q-BG*, *Q-BI*, and *Q-238* (Table 3) are formed using these biomic and bio-geographic quality universals.

The universals *Ecozone* (also called *Biogeographic Realm*) and *Biome* can be defined in terms of homogeneity wrt. quality pattern as follows:

Definition 1 *Particular x is an instance of the universal* Ecozone *(respectively* Biome*) if and only if (a) x is a geographic region that is a sum of members the collection* WWF_867 *and (b) x is maximally homogeneous with respect to some species pattern of Q-BG (respectively Q-BI).*

Instances of proper sub-universals of *Ecozone* (respectively *Biome*) are sums of members of the collection *WWF_867* that are maximally homogeneous with respect to one specific immediate species pattern of *Q-BG* (respectively *Q-BI*). For example, every instance of *Nearctic Ecoregion* is a sum of members of *WWF_867* that, as a whole, is maximally homogeneous with respect to the quality pattern <*Nearctical distribution pattern*>. Similarly, every instance of *Tundra Ecoregion* is a sum of members of *WWF_867* that, as a whole, is maximally homogeneous with respect to the quality pattern <*Biomic Tundra quality*>.

At an intermediate scale one can identify the universal *EcoBiome*[1]:

Definition 2 *Particular x is an instance of the universal* EcoBiome *if and only if (a) x is a geographic region that is a sum of members the collection* WWF_867 *and (b) x is maximally homogeneous with respect to some immediate species pattern of Q-238 (Table 3).*

For example, the WWF regions called 'Alaskan North Slope Coastal Tundra' and 'Canadian Low Arctic Tundra' are instances of *EcoBiome*. Both are maximally homogeneous with respect to the quality pattern *Q-NaTu*, a species pattern of the genus pattern *Q-238*. Presently, the universal *EcoBiome* has 238 instances. For this reason the extension (i.e., the collection of the instances) of the universal *EcoBiome* is called '*WWF_238*'.

[1] The WWF does not use 'EcoBiome'. This name is intended to reflect the fact that every instance of *EcoBiome* is an instance of *Ecozone* and an instance of *Biome*.

3.3 Hierarchical nesting

The instances of the universal *EcoBiome* are smaller than the instances of the universals *Ecozone* and *Biome* but (in most cases) larger than the members the collection *WWF_867*. Let *EZC* be the extension of the universal *Ecozone* and let *BC* be the extension of the universal *Biome*. The collections *EZC*, *BC*, *WWF_238*, and *WWF_867* all partition the terrestrial surface of the Earth (Olson *et al.*, 2001). Moreover, *WWF_867* is immediately ↑-p-included in *WWF_238*, *WWF_238* is immediately ↑-p-included in both, *BC* and *EZC*. *BC* and *EZC* are not ↑-p-included in one another since some of their members partially overlap.

4 Towards an integrated system

The key insight of the WWF system is, that the trade-off between the need for non-local quality pattern for classification purposes and the need for local quality pattern precise delineation, can be overcome by using a single, sufficiently fine grained partition, as a basis (base level) as the most detailed scale. The geographic regions forming this partition are maximally homogeneous with respect to local quality pattern. The focus on local quality pattern at the base level ensures maximal possible precision and minimal vagueness of the resulting delineation. Geographic regions at coarser scales are defined as sums of regions from the base level. Local as well as non-local quality pattern can serve as criteria that determine which regions from the base level sum-up to (are aggregated to) regions at the coarser levels in partition-forming ways.

In principle any collection of geographic regions that partitions the terrestrial surface of the Earth (or some continent) in a sufficiently fine-grained way can be used as a basis for the aggregation of coarser geographic regions. To use the collection *LIII* of the EPA system as a basis of an integrated system in North America seems to be justified for the following reasons: Firstly. Several major systems agree on the location of the boundaries separating the various regions. (McMahon *et al.*, 2001; Olson *et al.*, 2001). Secondly. The USFS, the EPA, and the WWF agree on that land-surface quality universals are at least necessary for the the classification and delineation of geographic regions at this scale. In addition, land-surface quality universals are relatively well understood and seem to be more easily observable in reality than other qualities. Thirdly. At least in North America it was possible to minimize the vagueness of the location of the boundaries separating the various ecoregions at this scale by using local quality pattern and then crisping the remaining degree of vagueness by fiat.

Bailey's system can be integrated into the system of the WWF quite easily. The instances of *Section* in North America is identified with the members of *LIII*. The differentia used in Bailey's original definitions of the universals *Domain*, *Division*, and *Province* are pattern formed by climate and elevation qualities. In an integrated system the same quality patterns serve as criteria for the aggregation of base-level regions.

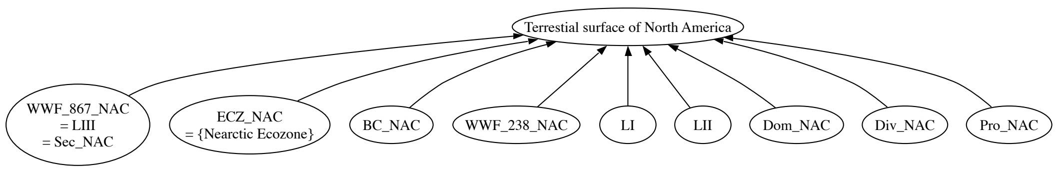
Definition 3 *Particular x is an instance of the universal* Province *(respectively* Division*,* Domain*) if and only if (a) x is the sum of members of the collection* WWF_867 *and (b) x is maximally homogeneous with respect to some species of the genus quality pattern Q-P (respectively Q-Di, Q-Do). All instances of* Province *are, in addition, self-connected.*

For example, every instance of the universal *Domain* is a sum of all the members of the collection *LIII* that are maximally homogeneous with respect to some proper sub-universal of *Climate regime*. Proper sub-universals of *Province*, *Division*, and *Domain* are defined as sums of members of *LIII* that are respectively maximal homogeneous with respect to a single species pattern of *Q-P*, *Q-Di*, and *Q-Do*.

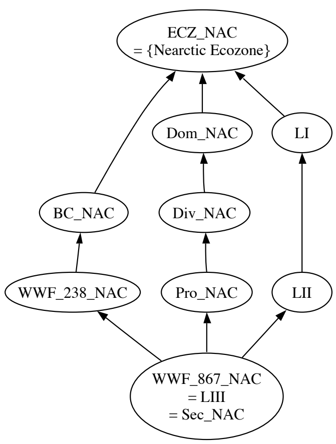
Let *EZC_NAC*, *BC_NAC*, *WWF_238_NAC*, and *WWF_867_NAC* be the collections of ecoregions that have as members respectively all those members of *EZC*, *BC*, *WWF_238* and *WWF_867* that are parts of the North American continent. Similarly, let *Dom_NAC*, *Div_NAC*, *Pr_NAC*, and *Sec_NAC* be the collections of ecoregions that have as members respectively all those instances of *Domain*, *Division*, *Province*, and *Section* that are parts of the North American continent. If the North American continent is identified with the Nearctic ecozone of the WWF system then the collection *EZC_NAC* has a single member – the Nearctic Ecozone. From the choice of the base level it follows that the collections *Sec_NAC*, *WWF_867_NAC*, and *LIII* are identical. In Figure 5(a) the graph of the relation partition-of$^{I}_{NAC}$ represents the fact that all these collections partition the North American continent.

The graph of the relation ↑-p-included-in$^{I}_{NAC}$ in Figure 5(b) shows that ecoregions of sub-regional scale form the basis of the delineation, i.e., *WWF_867_NAC*= *LIII* = *Sec_NAC*. Since the different systems form geographic regions at coarser scales using different kinds of quality universals, there are different hierarchical subdivisions that do not necessarily coincide. That is, each of the partitions *Pr_NAC*, *LII*, and *WWF_238_NAC* may have members which boundaries lie skew to the boundaries of members of the other two partitions. This is the reason for the lattice structure in Figure 5(b).

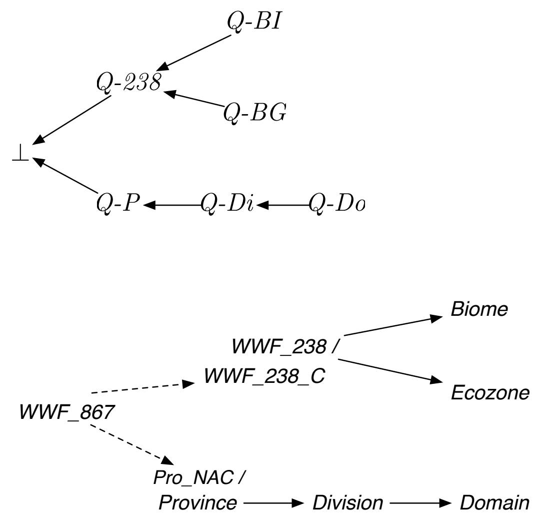
Consider the relationship that holds between the hierarchical nesting of ecoregion universals and the aggregation criteria that are used in their definitions. If ecoregion universal E_i is a ↑-u-part-of^{B} E_j then the quality pattern that serves as aggregation criterion in the definition of E_j is a sub-pattern of the quality pattern that serves as aggregation criterion in the definition of E_i. This can be verified in the quality pattern tree in Figure 5(c).



(a) Partitions of the terrestial surface of the North American Continent. (Graph of partition-of$^{I}_{NAC}$)



(b) Graph of ↑-p-included-in$^{I}_{NAC}$.



(c) Quality sub-pattern tree of the Classificatory part of the integrated system (top) and the corresponding combined ↑-p-included-in (dashed) and ↑-u-part-of tree (solid) (bottom).

Figure 5: Delineation,hierarchical nesting, and sub-pattern relations in an integrated system.

5 Conclusions

The use of the ontological terminology as an underlying framework (marked out by the Sans Serif font) makes it easy to represent the integrated system sketched in Figure 5 using OWL (Horrocks *et al.*, 2003). In this way it can facilitate automated reasoning which is important for computer-based data integration. In addition, although the focus is on geographic phenomena and the complexities of their integration, the resulting system will be immediately compatible with the system of OBO ontologies (Smith *et al.*, 2007) and in this way also facilitate data integration with the biological and life sciences.

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Defines	Definition
Particulars	Independent continuants, i.e., entities which endure through time while undergoing different kinds of changes. (you, me, ...)
Qualities	Specific properties or qualities which inhere in particulars. (your height, my weight, ...)
Collections	Group particulars in an arbitrary set-like manner. Collections are finite and non-empty. ({you, me}, ...)
Universals	Group particulars in more restricted ways that often result in tree-like structures. (human being, mammal, vertebrate, ...) Universals and collections have very different temporal properties. (Bittner *et al.*, 2009)
Quality universals	Group particular qualities in rather restricted ways that often result in tree-like structures. (weight, height, ...)
homogeneous	Let $Q_1, \ldots, Q_n$ be variables ranging over quality universals. Region x is homogeneous with respect to the quality pattern $Q =< Q_1, \ldots, Q_n >$ (Q-homogeneous) if and only if x is of at least of geographic scale and the sum of all parts of x that are regions of geographic scale and that do not have particular qualities that respectively instantiate $Q_1 \ldots Q_n$ is negligible in size with respect to the size of x.
maximally homogeneous	Region x is maximally homogeneous with respect to the quality pattern $Q =< Q_1, \ldots, Q_n >$ (maximally-Q-homogeneous) if and only if x is Q-homogeneous and all Q-homogeneous regions that overlap x are parts of x.
quality pattern	Let $Q =< Q_1, \ldots, Q_n >$ be a quality pattern. Then all m-tuples with $m \leq n$ that can be formed using $Q_1, \ldots, Q_n$ are sub-pattern of Q. (The order of the qualities forming the tuple does not matter.)
genus-species-pattern	Let $Q_S =< Q_1, \ldots, Q_n >$ and $Q_G =< Q'_1, \ldots, Q'_n >$ be quality patterns such that Q_i is an immediate proper sub-universal-of Q'_i for $1 \leq i \leq n$, then Q_G is a genus-pattern of Q_S and Q_S is a species-pattern of Q_G.

Table 1: Definitions for basic categories and for quality pattern and homogeneity (Bittner, 2009). All remaining definitions can be found in (Bittner *et al.*, 2009; Bittner, 2009).

quality pattern for the ecoregion	symbol	constituting quality universals	genus pattern
Prairie Division (of *NAC*)	*Q-Pra*	<*Humid Temperate Climate Regime*, *Prairie Climate Type*, *Lowland*>	*Q-Di*
Dry Domain (of *NAC*)	*Q-Dry*	<*Dry Climate Regime*>	*Q-Do*
Humid Temperate Domain	*Q-HTe*	<*Humid Temperate Climate Regime*>	*Q-Do*
Humid Tropical Domain	*Q-HTr*	<*Humid Tropical Climate Regime*>	*Q-Do*
Polar Domain	*Q-Pol*	<*Polar Climate Regime*>	*Q-Do*
Central Great Plains	*Q-GCP*	< *Irregular plains*, *Bluestem grama prairie*, *Cropland*, *Dry Mollisols* >	*Q-L*
Flint Hills	*Q-FH*	<*Open Hills*, *Bluestem prairie*, *Subhumid grassland*, *Mollisols* >	*Q-L*
Canadian Low Arctic Tundra	*Q-NaTu*	< *Nearctic Realm*, *Tundra* >	*Q-238*
Alaskan North Slope Coastal Tundra	*Q-NaTu*	< *Nearctic Realm*, *Tundra* >	*Q-238*

Table 2: Species quality pattern for some ecoregions of the North American Continent.

quality pattern type	symbol	constituting quality universals
Land-surface	*Q-L*	<*Land-surface form*, *Climax Plant Formation*, *Land use*, *Soil type*>
Climate	*Q-Do*	<*Climate regime*>
	Q-Di	<*Climate regime*, *Climate type*, *Elevation*>
	Q-P	<*Climate regime*, *Climate type*, *Elevation*, *Climax Vegetation*>
Climate + Land-surface	*Q-S*	<*Climate regime*, *Climate type*, *Elevation*, *Climax Vegetation*, *Land-surface form*, *Land use*, *Soil type*>
Biogeographic	*Q-BG*	<*Biogeographic ecoregion quality*>
Biomic	*Q-BI*	<*Biomic ecoregion quality*>
Biogeographic + Biomic	*Q-238*	<*Biomic ecoregion quality*, *Biogeographic ecoregion quality*>

Table 3: Genus quality pattern.