Ontology-Based Topological Representation of Remote Sensing Images

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This article aims to propose an ontology-based topological representation of remote sensing images. Semantics, especially related to the topological relationships between the objects represented, are not explicit in remote sensing images. Our aim is to provide an explicit definition in ontologies of the topological relations between objects in the image using the Quadtree data structure for spatial indexing. This structure is explicitly defined in an ontology allowing the automatic interpretation of the obtained representations taking into account the topological relations. This representation has been validated by a case study of semantic retrieval based on the Normalised Vegetation Index (NDVI), taking into account the topological relations between NDVI regions in images. This representation can be used to develop applications in Geospatial Semantic Web.

Keywords: Geo-ontology, Semantic Representation, GIS, Remote Sensing Images, Spatial Relations

1. Introduction

Remote sensing images are used in various decision-making areas. The addition of semantics to geographical information management is imperative for the improvement of semantic interoperability and the usability of this type of images. An important step towards strengthening the semantic interoperability of these images involves making explicit the semantics associated with geographical information. The semantic representation of geographical data provides a formal semantic description that cannot be expressed in current models of geographic data.

Currently, there are problems with representing the semantics, including a lack of a formal and explicit support (Kuhn 2005). Several ontology-based approaches for remote sensing image retrieval and segmentation have been developed (Hashimoto et al. 2011, Wiegand and García 2007, Larin Fonseca and Garea Llano 2011) but have not included a formalised integration of geographic data and knowledge. In fact, the research problem addressed in this paper is that there are no theoretical proposals of semantic representations of remote sensing images to take advantage of explicit topological relations between geographical objects and the required elements to verify this type of relations.

The data structures used for the spatial index in Geographic Information Systems (GIS) can be formally defined in ontologies. In this sense, we propose a new semantic representation that explicitly organises objects represented in an image. The purpose of this representation is to define a spatial indexing structure that reflects the topological relationships between the objects and allows spatial analysis. Furthermore, the overall use of ontologies in our proposal allows for the explicit definition of both the objects and the organising data structure, resulting in an improved semantic analysis.

The main aim of this paper is to propose a topological representation to complement the remote sensing images in the process of information retrieval considering the topological relationships. A key component in the designed solution is the use of ontologies to support the integration process for semantic enrichment of remote sensing image representations.

The remainder of this paper is organised into four sections. The background works are discussed in the next section. Section 3 provides a general description of the topological representation of remote sensing images and the main ideas behind computational implementation. We present a case study as an experiment to illustrate the feasibility and soundness of the proposal in section 4. Finally, section 5 presents concluding remarks.

2. Related Works

The management of geographical knowledge has focused primarily on the use of ontologies (Kuhn 2001). Ontologies allow the representation of concepts, instances, relationships and axioms and permit the inference of implicit knowledge. The concept of a Semantic Reference System was proposed by Kuhn (2003) as an abstract model to solve the problem of interoperability and several processes were associated with ontologies as part of the system design. Similarly, a methodology for geographical domain conceptualisation using ontologies was proposed by Torres Ruiz et al. (2011). Different results have been produced using ontologies as the main foundation of theoretical proposals in Ontology Driven Geographic Information Systems (Fonseca and Egenhofer 1999, Fonseca and Egenhofer 2009, Fonseca et al. 2002). Likewise, we assume that ontologies are feasible for supporting the semantic representation of remote sensing images. Fonseca et al. (2000) expressed the need to find a suitable structure for ontologies related to geographical information.

In the geographical information representation, an ontologies-based approach that is structured to allow feature and event attributes to represent meaning in class rules and relationships is required (Grossner, Goodchild, and Clarke 2008). In this sense, there is experience related to the capture of ontologies operational at the time of data production (Comber, Fisher, and Wadsworth 2005).

The first approaches to the semantic representation of images have been from the perspective of semantic annotations. According to Kiryakov et al. (2003), an annotation can be considered to be the link between the instances and concepts of an ontology. Semantics are defined by the behaviour, the role and the functional relationship of the annotated elements and are usually performed by the intuition of the user. With the Semantic Web emerging, the use of semantic annotations to describe Web resources has become an important goal for the scientific community (Handshuh and Staab 2003). In this context, knowledge representation and ontologies have proved be essential.

The semantic annotation concept was defined by Handshuh and Staab (2003) as the association between data schema elements and domain ontology elements. Grcar and Klien define semantic annotation as “the task of matching an arbitrary word or term with the most appropriate concept in the corresponding domain ontology” (Grcar and Klien 2007). Klien and Lutz (2005) proposed a method to automate the semantic annotation process based on spatial relations, using the specific characteristics of geographical information. Automating this process facilitates the transition to managed semantic representations (Grcar and Klien 2007). Klien (2007) presented a rule-based strategy for the semantic annotation of geographical data that combines Semantic Web and Geospatial Web Services technology.

Klien and Lutz (2005) proposed an automatic method of semantically annotating geographic data based on spatial relationships, taking advantage of the specific characteristics of geographic information. Automating this process facilitates the transition towards semantically managed representations (Grcar and Klien 2007). The Data-Representation Ontology (DRO) proposed by Larin Fonseca and Garea Llano (2011) is a special type of ontology to describe the semantics embedded in geographic data. In addition, the authors proposed an automatic method based on classification techniques of patterns for the generation of the DRO and its relationships with other ontologies. In the process of the generation of the DRO, the topological relationships between the objects represented in the data, which are declared explicitly, are calculated. These proposals are positive steps in the semantic representation of geographical data but do not consider ways to verify spatial relationships taking into account their geographical nature.

Jiang and Zhou (2012) proposed an ontology-based remote sensing information service description model to provide semantic supports for the intelligent discovery and composition of spatial relationships. Their results indicated that the use of ontologies is valid for realising intelligent remote sensing information discovery and composition.

Huang, Tian, and Chang (2011) considered various types of knowledge related to remote sensing image understanding and presented a knowledge representation architecture analysing each knowledge type and its representation, especially task knowledge and integrated knowledge. This proposal considered the relationships between the objects represented in the images but did not delve into any relationship types or into the explanation of the elements necessary for the consistent representation of the relationships.

Nagai, Ono, and Shibasaki (2011) presented a method with the stated purpose to supersede human inductive learning and reasoning in complex scene understanding and characterisation by automatically adding high-level ontology to the image. The authors propose an algorithm with the aim to provide high-level semantic classifications for image content. The topological information related to similar object configuration is defined through a k-means classification. This proposal makes explicit the necessary elements for the consistent representation of the relationships in the ontology.

The discussed proposals use ontologies as conceptual supports of geographical knowledge representation, but they do not properly formalise the topological relationships. In addition, the representation of the required elements is insufficient to infer and validate the topological relationships between geographical objects in ontologies, thus precluding a more effective spatial and semantic analysis.

3. Topological Representation of Remote Sensing Image

Given that ontologies are formal representations of knowledge and have been widely used in the discovery and management of geographic information, we propose an ontology-based semantic representation of remote sensing images. The association between geographic objects represented in the image and knowledge takes into account the recovery process and the topological relationships between the objects represented.

3.1 Conceptual Representation

Our proposal of semantic representation of remote sensing images is based on the interrelation of several ontologies for representing topological relations between geographical objects. The domain concepts and instances that represent geographical objects such as the definition of data structure are elements that exist autonomously and independently of the execution of the integration process for the semantic representation. Because all of these elements can be part of different image representations and in order to enhance reuse, we consider the semantic representation as three related ontologies: Main Ontology (MO), Domain Ontologies (DO), and Data Structure Ontology (DSO). In Figure 1, we present a scheme of the proposed representation.

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Figure 1

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The most important ontology is the Main Ontology (MO), which contains the semantic representation. This ontology is organised into a data structure for spatial search so that the retrieval of information and knowledge exploit the topological relationships between nodes. In other words, the represented geographical objects are organised into a suitable data structure for spatial search because this type of organisation allows for the inference and validation of topological relationships between the represented objects. To contribute to the conceptual proposal with the aim of enhancing the spatial search, the chosen data structure must be conceptualised in an ontology, termed data structure ontology (DSO). This ontology will be imported into the main ontology. Once the spatial relationships are explicit in the MO, the geographical object organisation expressed in Data Structure Ontology allows for the verification of these ontologies.

The Domain Ontologies (DO) provide the conceptual basis that enables the semantic representation and grants a common understanding of the scenario, ensuring semantic interoperability. In the Main Ontology, the required Domain Ontologies will also be imported during the data and knowledge integration process.

Indeed, the MO can be expressed by Equation (1).

$$\boldsymbol{MO} = < \boldsymbol{I}, \boldsymbol{L} > \tag{1}$$

In the Equation (1), I are the instances of chosen data structure nodes and L are the links to the instances of the concepts. The fact that MO adopts spatial indexing logic through Data Structure Ontology enables heterogeneous systems management and analysis of whole semantic representations of geographical objects in a remote sensing image and the performance of inference processes without prior knowledge of the physical organisation of implicated ontologies: MO, DSO and DO.

Formalisation of the links between geographical objects and instances of the data structure concepts is achievable in the main ontology if and only if the geographical objects concepts are previously defined. On the contrary, it is necessary to create the appropriate concepts in the MO or in a different ontology. If these concepts do not exist, it is necessary to create them in the MO or in some other Domain Ontologies. Instances that represent geographical objects in the geographical data must be imported from the DO to the MO.

The proposed representation can be computationally designed in a single ontology but it would then be necessary to define all the elements of this ontology for each image, which would be redundant and computationally expensive.

In summary, the integration process carried out for the semantic representation includes importing the DO and DSO to the MO and determining relations between instances of the concepts of these ontologies. The Data Structure Ontology is reused for each semantic representation of a remote sensing image. Particular spatial relations between geographical objects in the image are semantically represented in the MO, which is unique for the integration process.

The semantic representation of remote sensing images is characterised by the semantic definition of geographical objects presented in the image and respective relations. Their definitions will be formalised in the MO by the instances of concepts present in the DSO, organised and interconnected by the relations established between them.

In order to describe the geographical objects represented in an image in terms of the chosen data structure, we define three general properties for DSO concepts:

- *contains*: this property includes geographical object instances completely contained in the data structure node area,
- *partOf*: this property includes geographical object instances, each of which has areas completely contained in the data structure node area,
- *partialOverlap*: this property includes geographical object instances partially but not completely contained into the data structure node area.

To index a geographical object in the data structure, the polygon coordinates that define the object are used. In fact, data structure nodes are links between spatial knowledge and geographical objects.

The steps to carry out the semantic representation are the following:

(1) Create the Main Ontology
(2) In the MO, import Domain Ontologies for geographical objects conceptualisation and Data Structure Ontology for spatial indexing.
(3) If necessary, create the instances of relevant geographical objects on the image in the MO.
(4) Index geographical object instances and set the respective properties (*contains*, *partOf*, and *partialOverlap*) with nodes in the data structure.
(5) Semantically enrich the representation by incorporating the necessary knowledge to better use the images represented.

To facilitate implementation, we suggest choosing any spatial indexing data structure. The potential types of spatial relations might be represented or implied in the DSO and the indexing process details depend on the chosen data structure. Organising geographical objects using this type of data structure not only reflects the spatial relations but also takes advantage of the spatial nature of relations in information retrieval. After all, proposed semantic representations support both spatial and semantic searches.

3.2 Computational Representation

Computational implementation of the integration process for the semantic representation of remote sensing images has two main components: geographical object management, according to object oriented paradigm, and ontology management, the persistence component.

Due to the matrix nature of remote sensing images, a suitable data structure should allow information cell organising and searching by points. In this sense, one of the simplest and more applied methods uses Quadtree, a multidimensional data structure. The use of a hierarchical representation based on a rectangular decomposition as of this structure favours the verification of topological relations between the indexed objects (Winter and Bittner 2002, Dean 2005). Quadtree structure uses multiple nodes for the indexing of a geographical object given the level of detail required to represent the borders. (Zhou, Chen, and Wan 2009) introduced a data model that ensures the validity of the topological relationships using a Quadtree structure in the MAPGIS7.4 system. Indexing geographical objects in a Quadtree supplies spatial searches from regions or semantic searches based on concepts formalised in ontologies. Likewise, it is possible to find geographical object instances and spatial related objects under any given criteria.

Data Structure Ontology formalises Quadtree and respective spatial searches. The matching elements of both implementation components are established as follows. For each concept in the ontology a class was implemented, and variables or class methods were respectively assigned to attributes or properties of the concept. Thus, each class will be persistent in the corresponding concept. Data Structure Ontology contains the concept *quadtree*, the properties that link a node with its four child nodes and the properties *contains*, *partOf* and *partialOverlap*. The concept *quadtree* has an envelope property containing the information about the associated rectangle region. Link between data and formalised knowledge is given by geographical object representation as an instance, which also allows the definition of relations with Domain Ontologies concepts and instances. Furthermore, these instances can be related to any node of the *quadtree* by the properties *contains*, *partOf* and *partialOverlap* during the indexing process. Semantic representation persistence is achieved by the Main Ontology.

The indexing process starts by determining which area farthest from the root node completely contains the minimum bounding box, i.e., coordinates of the minimum rectangle enclosing the object. In this case, the *contains* property is instantiated by the obtained node as domain and the geographical object instance as range. If the node area is completely covered by the object area, *partOf* properties of the obtained node descendants are instantiated by the geographical object instances as range. If any descendant node area partially covers the semantic representation area, *partialOverlap* property is instantiated by the geographical object instance as range. The indexing process continues until the node area is totally covered by the object area or the object area covered by the node reaches a threshold set as resolution. The threshold can be given by a fixed value for one of the two dimensions of the rectangular region associated with the node or by setting the maximum height the *quadtree* could reach.

To illustrate, we will index the main campus of the University of Havana (UH) and the surrounding facilities that are also part of the institution. Figure 2 a) shows a start-index region and Figure 2 b) exhibits the set of rectangles covering the given region. The rectangles can be associated with indexed *quadtree* nodes. Nodes related by *contains* property to objects are represented by shaded rectangles. In this case, the *quadtree* maximum height is 8.

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Figure 2

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Each level of the *quadtree* represents the indexed geographical objects with a given accuracy. The greater the level height in the *quadtree* implies the greater accuracy with which the level represents the indexed geographical objects. Figure 3 a) shows the rectangles associated with the first four levels of the *quadtree*. Figure 3 b) exhibits the rectangle identifiers arranged in a tree.

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Figure 3

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In *quadtree* presented in Figure 3, the indexed region is linked by a *contains* property to node A, by a *partialOverlap* property to nodes B, E, G, J and L, and by a *partOf* property to the nodes F, H, I, K, N, P, Q, R, S, T, V, W and X.

Management component was implemented in Java, and persistence component was implemented in OWL (Ontology Web Language).

4. Experimental Results

The aim of this experiment was to validate the conceptual proposal for the semantic representation of satellite images through a case study oriented to retrieve information on the vegetal cover using the Normalised Difference Vegetal Index (NDVI) (Tarpley, Schneider, and Money 1984). NDVI computation is a commonly used technique to improve the distinction between two covers with a different reflective behaviour in two or more spectral channels. The use of these types of indices to identify vegetal masses is based on the exclusive radiometric behaviour of vegetation.

NDVI is quite effective in normalising the vegetation spectral response and diminishing the topographic effect of the scene. Using the NDVI values obtained with Equation (2), it is possible to define different categories of earth covers (Crippen 1990).

$$NDVI = \frac{IRed - Red}{IRed + Red} \quad (2)$$

We used a database composed of multispectral satellite images obtained from the Landsat 7 sensor (NASA 2011). The database contains 41 scenes from the Caribbean area with spatial resolution of 30 m and 2 channels of spectral resolution red (Red) and infrared (IRed).

The integration processes described above were developed for the semantic representation of database images:

- Four categories of earth covers (Crippen 1990) were conceptualised in Domain Ontologies to be used in the semantic representation.
- The instantiation of category concepts was conducted by computing NDVI. The domain ontologies were imported to the Main Ontology and the instances were indexed by the process described in 3.2. Finally, 41 semantic representations of remote sensing images were obtained as a result.

In order to reveal the effectiveness of our proposal, we compared our information retrieval and image classification results with the results of analogous process performed using Remote Sensing Software ENVI 3.6 (Environment for Visualizing Images, version 3.6) (RSI 2002).

We compared the results obtained by the retrieval process using the DO without considering the spatial relations between NDVI regions and the created semantic representation, taking into account the spatial relations between NDVI regions applying SPARQL (W3C 2010). In addition, we compared the results against traditional supervised image classification of NDVI images using four algorithms implemented in ENVI: Parallelepiped, Maximum Likelihood, Binary Encoding and Neural Net.

Table 1 show the results for eight different queries, where the last four consider spatial relations. For each query the effectiveness of the retrieval process is measured by R-precision (Aslam and Yilmaz 2005), which represents precision when the number of retrieved elements is equal to the number of relevant elements. In other words, the precision represents retrieved relevant NDVI regions percentage.

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Table 1

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The results shown in the first four columns of Table 1 reveal that the supervised image classification process from patterns of NDVI regions fails to identify any type of region when combining two types of regions in queries. Retrieval is not successful due to the nature of the classification process, which is based on the comparison between the pixels of the images to classify and the pattern pixels without taking into account spatial relationships (see Figure 4).

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Figure 4

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The last two columns of Table 1 illustrate the results of the retrieval process using ontological representation and SPARQL as a query language. In the fifth column, results are obtained using only Domain Ontologies. The sixth column shows results using the semantic representation proposal, in which DO values are integrated. The last four queries were not successful only using DO because the ontologies do not include the representation of topological relationships between different NDVI regions in the image. The observed difference between the results of the supervised image classification process and the DO was not significant. However, the retrieval using the semantic representation proposal was effective (see Figure 5). The explanation for this result is that the explicit nature of the topological relationships allows them to be considered consistently in the recovery of topologically related geographical objects.

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Figure 5

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The results of this experimental indicate the validity of the proposed semantic representation for remote sensing images and the advantages of taking into account the topological relations between image regions for information retrieval. This study confirms that the proposed representation could be used as a semantic complement of the original remote sensing image, thus extending its use.

5. Conclusions

In this work, we have proposed a topological representation of remote sensing images based on the use of ontologies as a conceptual platform for persistence and geographical information retrieval. Semantic definitions of objects presented in the image compose the semantic representation, which is formalised in the *Main Ontology* by the instances of *Data Structure Ontology* concepts. The use of Quadtree encourages the spatial recursive subdivision for the semantic organisation and management of geographical information. Semantic representation, once created, could be reused in different processes of spatial and semantic analysis and could be subsequently semantically enriched.

The experimental results seem to highlight the feasibility of the proposal as a support of the image retrieval process, encouraging information exchange between providers and users and providing a semantic complement to the remote sensing images. The results can be extrapolated to different types of regions. Moreover, spatial relationship types implied in the queries might be increased according to the chosen data structure.

Further research should be performed to investigate the new methods to automatically identify the geographical objects and to attempt to use the proposed representation with other types of remote sensing images such as aerial images and hiperspectral images, considering more appropriate data structures for the ordering of geographical objects.

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Table 1 Comparison of the results of supervised image classification methods of NDVI regions process

Methods / Queries for NDVI Region	SC Parallelepiped	SC Maximum Likelihood	SC Binary Encoding	SC Neural Net	An instantiated *DO*	Semantic representation
Area of social natural elements	60	65	78	90	100.0	100.0
Earth cover without vegetation	68	70	86	95	100.0	100.0
Open vegetation	57	64	73	78	100.0	100.0
Dense vegetation	70	77	90	95	100.0	100.0
Area of social natural elements **completely containing** *Dense vegetation.*	1.9	2.1	2.4	2.6	2.7	100.0
Dense vegetation **disconnected from** *Area of social natural elements.*	2.3	2.6	3.0	3.1	3.2	100.0
Open vegetation **inside of** *Earth Cover without vegetation.*	2.2	2.3	2.9	3.0	4.6	100.0
Earth cover without vegetation **completely contained into** *Open vegetation*.	2.0	2.2	2.6	3.0	8.1	100.0

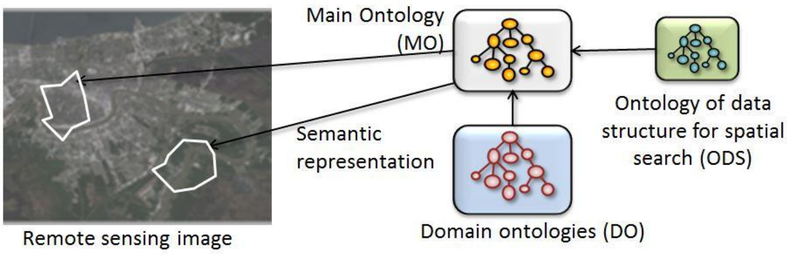

Figure 1. Scheme of the proposed semantic representation

(a) (b)

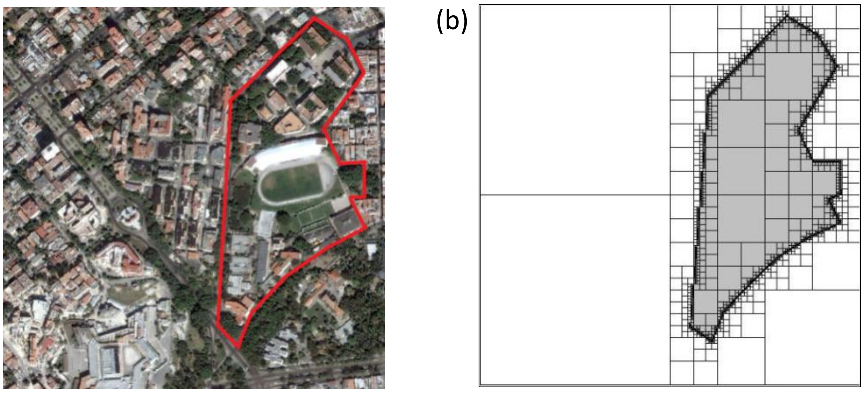

Figure 2. Quadtree representation of the region occupied by the UH facilities

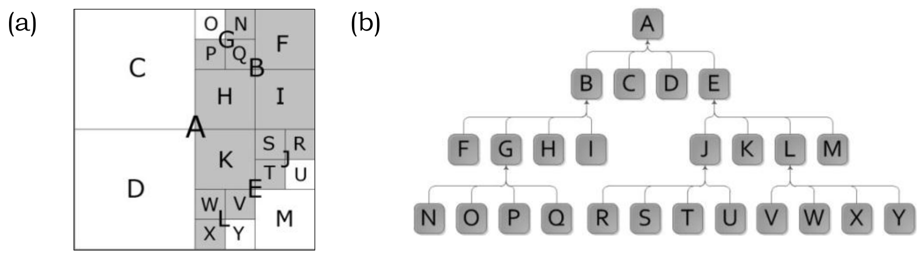

Figure 3. Indexing the region occupied by the UH facilities in a *quadtree* of height 4

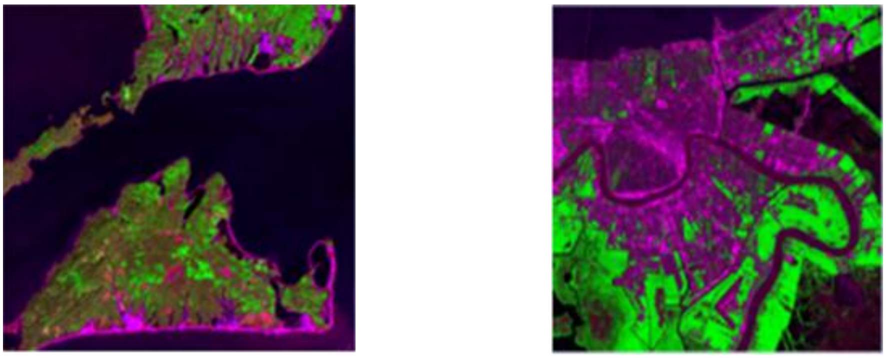

Figure 4. Examples of the response to the semantic retrieval for the case of a query that related two concepts (Open vegetation inside of Earth Cover without vegetation) using NDVI images

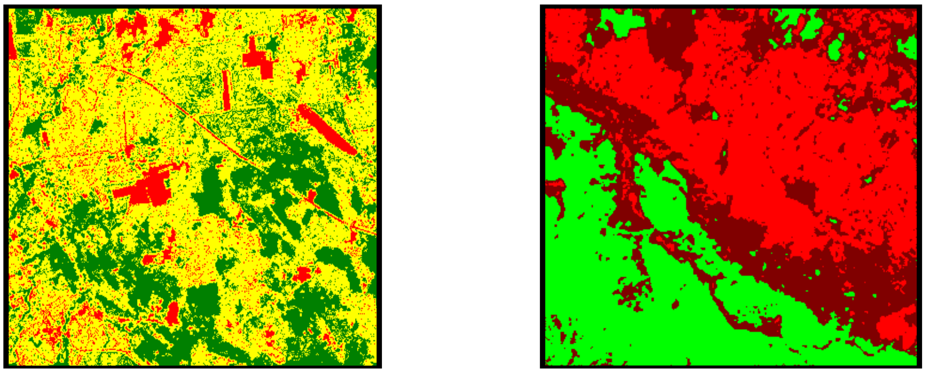

Figure 5. Example of a response to the retrieval for the case of two queries (Dense vegetation and Open vegetation) using classified NDVI images, on the left image classified by the Maximum Likelihood method and on the right other image classified by the Neural Ned method