An ontological system based on MODIS images to assess ecosystem functioning of Natura 2000 habitats: A case study for Quercus pyrenaica forests

ARTICLE *in* INTERNATIONAL JOURNAL OF APPLIED EARTH OBSERVATION AND GEOINFORMATION · MAY 2015

Impact Factor: 3.47 · DOI: 10.1016/j.jag.2014.09.003

4 AUTHORS, INCLUDING:

Antonio Jesús Pérez Luque
University of Granada

Ramón Pérez Pérez
University of Granada

Francisco Javier Bonet
University of Granada

International Journal of Applied Earth Observation and Geoinformation 37 (2015) 142–151

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

An ontological system based on MODIS images to assess ecosystem functioning of Natura 2000 habitats: A case study for *Quercus pyrenaica* forests

A.J. Pérez-Luque[a,b,*], R. Pérez-Pérez[a,b], F.J. Bonet-García[a,b], P.J. Magaña[c]

[a] Laboratorio de Ecología (iEcolab), Instituto Interuniversitario Sistema Tierra, Universidad de Granada, Avda. del Mediterráneo s/n, Granada 18006, Spain
[b] Departamento de Ecología, Facultad de Ciencias, Universidad de Granada, Avda. Fuentenueva s/n, Granada 18071, Spain
[c] Grupo de Dinámica de Flujos Ambientales, Instituto Interuniversitario Sistema Tierra, Universidad de Granada, Avda. del Mediterráneo s/n, Granada 18006, Spain

ARTICLE INFO

Article history:
Available online 26 September 2014

Keywords:
Ontology
NDVI
Snow cover
(satellite) Earth observation
Sierra Nevada

ABSTRACT

The implementation of the Natura 2000 network requires methods to assess the conservation status of habitats. This paper shows a methodological approach that combines the use of (satellite) Earth observation with ontologies to monitor Natura 2000 habitats and assess their functioning. We have created an ontological system called *Savia* that can describe both the ecosystem functioning and the behaviour of abiotic factors in a Natura 2000 habitat. This system is able to automatically download images from MODIS products, create indicators and compute temporal trends for them. We have developed an ontology that takes into account the different concepts and relations about indicators and temporal trends, and the spatio-temporal components of the datasets. All the information generated from datasets and MODIS images, is stored into a knowledge base according to the ontology. Users can formulate complex questions using a SPARQL end-point. This system has been tested and validated in a case study that uses *Quercus pyrenaica* Willd. forests as a target habitat in Sierra Nevada (Spain), a Natura 2000 site. We assess ecosystem functioning using NDVI. The selected abiotic factor is snow cover. *Savia* provides useful data regarding these two variables and reflects relationships between them.

Introduction and rationale

European Union has developed a set of environmental directives focused on nature conservancy (Evans, 2012). Their main aims are: (1) to halt the biodiversity loss according to the Convention on Biological Diversity (CBD, 2005), (2) to promote the implementation of policies for achieving sustainable development in a context of global change.

The Birds (79/409/EEC; 2009/147/EU) as well as the Habitats Directives (92/43/EEC) seek a favourable conservation status for all listed habitats and species all throughout the European territory (Louette et al., 2011). For these objectives, it is mandatory to implement methods to assess the conservation status of habitats and species. This is a challenging task that requires taking into consideration the concept of monitoring (Lindenmayer and Likens, 2010; Pereira and Cooper, 2006). According to Lindenmayer and Likens, the protocols used to satisfy legislation requirements must be focused on identifying trends in structural and functional features of habitats. These authors assert that "mandated monitoring" (required by legislation) can help in assessing the changes in the conservation status of habitats (Lindenmayer and Likens, 2010, p. 1325).

Satellites gather huge amounts of information that could be useful to monitor and to assess the conservation status of habitats (Vanden Borre et al., 2011). Such information would be adequate to assess both structural (distribution) and functional changes (productivity, phenology, etc.) in the Natura 2000 habitats. For example, a wide set of products derived from MODIS (Moderate Resolution Imaging Spectroradiometer) sensor are useful for monitoring ecosystem function at a landscape scale (250–1000 m resolution) (Hall et al., 2002; Huete et al., 2002; Justice et al., 2002). Other satellites such as Quickbird or IKONOS provide information at a finely detailed spatial resolution (0.5–4 m resolution), which is useful to monitor habitat distribution and structure (Förster et al., 2008; Hyde et al., 2006; Wang et al., 2004). The most important

* Corresponding author at: Laboratorio de Ecología (iEcolab), Instituto Interuniversitario Sistema Tierra, Universidad de Granada, Avda. del Mediterráneo s/n, Granada 18006, Spain. Tel.: +34 958249748; fax: +34 958137246.
E-mail addresses: ajperez@ugr.es (A.J. Pérez-Luque), ramon@ugr.es (R. Pérez-Pérez), fjbonet@ugr.es (F.J. Bonet-García), pmagana@ugr.es (P.J. Magaña).

http://dx.doi.org/10.1016/j.jag.2014.09.003
0303-2434/

advantage of satellite Earth observation in relation to habitat monitoring could be its capacity to allow comparisons among different locations (Vanden Borre et al., 2011). The temporal homogeneity (the same information is gathered with a predefined periodicity) is also a key feature to implement monitoring protocols using (satellite) Earth observation. However, the information collected from satellites cannot be processed and interpreted straightforwardly by most scientists and decision makers (Kalluri et al., 2003). Both the overwhelming amount of data to process/analyse as well as the inherent complexity of the variables measured make it difficult to create an operational system for assessing habitat functioning (Xue et al., 2011).

Ontologies are knowledge-representation techniques defined as a specification of a conceptualization (Gruber, 1993) within a domain of interest (habitat functioning in our case). A conceptualization is "an abstract, simplified view of the world that we wish to represent for some purpose" (Gruber, 1993, p. 199). A computer can "understand" an ontology, because ontologies are structured according to concepts and relationships on which a computer can "reason", as opposed to unstructured files like documents (Antoniou and van Harmelen, 2004). The use of ontologies can foster comprehensive data discovery and integration (Gruber, 1993; Jones et al., 2006), adding semantic meaning to data. Thus, these techniques can promote the use of remote sensing by environmental managers and ecologists (Silva et al., 2005).

While ontologies help to represent the domain, knowledge bases are used to store facts and complex information defined according to ontologies. Consequently, an inference engine, a software tool that applied logical rules to the knowledge base, can reason about those facts, deduce implicit facts, or resolve semantic queries (Hayes-Roth et al., 1983). Although ontologies are commonly used in different disciplines (Bard and Rhee, 2004; Renear and Palmer, 2009), they are not common in Ecology (Madin et al., 2007, 2008; Williams et al., 2006), or Earth observation (Arvor et al., 2013; Fallahi et al., 2008; Hashimoto et al., 2011; Larin Fonseca and Garea Llano, 2011; Oliva-Santos et al., 2014; Wiegand and García, 2007).

In this work, we describe the design and implementation of an ontological system (called *Savia*, http://obsnev.es/ontologia/index) that combines the advantages of (satellite) Earth observation with the knowledge-representation capabilities of ontologies to create a tool that displays indicators and trends regarding habitat functioning. This work had two objectives: (a) to assess the functioning of a Natura 2000 habitat and its relationships with abiotic factors (thematic objective), and (b) to use ontologies to create a operational system that satisfies the first objective (methodological objective). Our work provides a novel case study to the body of knowledge regarding the use of ontologies in Earth observation. It is also of value because we compute temporal indicators and trends to assess the conservation status of habitats. Finally, we show how ontologies can help to bridge the gap between ecologists and remote-sensing experts.

Study area and data

Study area

Sierra Nevada (SE Spain) is a mountainous area (ranging from 860 m to 3482 m a.s.l.) covering more than 2000 km^2 (Fig. 1b). The climate is Mediterranean, characterized by cold winters and hot summers, with a pronounced summer drought.

Sierra Nevada is considered one of the most important biodiversity hotspots in the Mediterranean region (Blanca et al., 1998) and has several types of legal protection: Biosphere Reserve, National and Natural Park, and Nature 2000 site. Sierra Nevada is also a LTER (Long-Term Ecological Research) site.

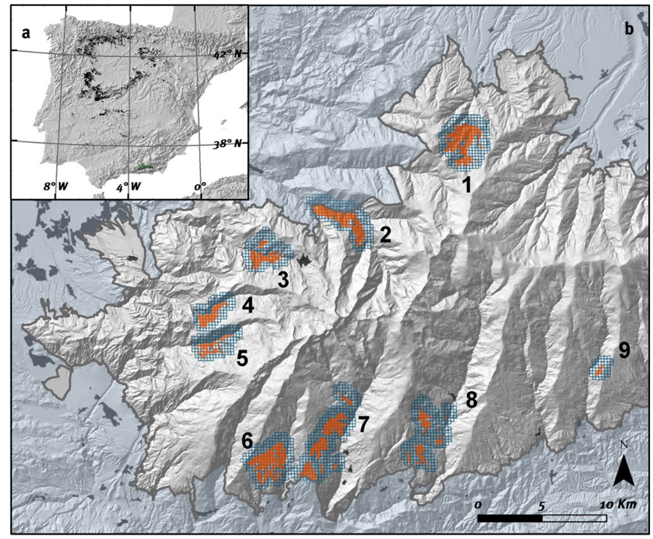


Fig. 1. Location of Sierra Nevada mountains. The distribution of *Q. pyrenaica* in the Iberian Peninsula is shown in black (a). The nine patches of *Q. pyrenaica* in Sierra Nevada are shown in orange (b). The grey line shows the boundary of the natural protected area of Sierra Nevada. The pixels used to compute the vegetation and snow indicators are included (blue grid).

We have focused this work on one habitat of Sierra Nevada: forests dominated by *Quercus pyrenaica* Willd. This habitat (EU habitat code 9230) is included in the Annex I of the Habitats Directive and its conservation status is not well known (EIONET, 2013), partly due to lack of detailed ecological studies (García and Jiménez, 2009). The Pyrenean oak forests extend from southwestern France to the Iberian Peninsula (Franco, 1990) (Fig. 1a), reaching their southernmost European limit in Sierra Nevada, where nine oak patches (2400 ha) have been identified (Fig. 1b), ranging between 1100 and 2000 m a.s.l.

Q. pyrenaica is considered as vulnerable in southern Spain (Blanca and Mendoza, 2000) and the populations inhabiting Sierra Nevada are considered relict forests (Melendo and Valle, 1996). They have undergone intensive anthropic use in recent decades (Camacho-Olmedo et al., 2002). They are also expected to suffer the impact of climate change, due to their climate requirements (wet summers): *Q. pyrenaica* requires between 650 and 1200 mm of annual precipitation and minimal summer precipitation between 100 and 200 mm. Thus, simulations of the climate-change effects on this habitat point to a reduction in suitable habitat for Sierra Nevada (Benito, 2009; Benito et al., 2011).

Data sets and derived information

We have selected two MODIS products: MOD13Q1 to assess the habitat functioning and MOD10A2 to study the behaviour of an abiotic factor (snow cover). MOD13Q1 provides information on vegetation indices NDVI (Normalized Difference Vegetation Index). The spatial resolution of this product is 250 m and the temporal resolution is 16 days. MOD10A2 provides information about snow cover extent (Hall et al., 2002). It has a periodicity of 8 days and a spatial resolution of 500 m. Each MOD10A2 pixel is labelled as snow if it has had snow on one of the previous 8 days. We selected MODIS products because both their spatial resolution and temporal resolutions are appropriate for the scope of this study.

We homogenized the different spatial and temporal resolutions in these two products to produce the final data at 500 m of spatial resolution and 16 days of temporal resolution. For the spatial resolution, we intersected the two grids to assign the identifier of any MOD10A2 pixel to its overlapping one in MOD13Q1. For

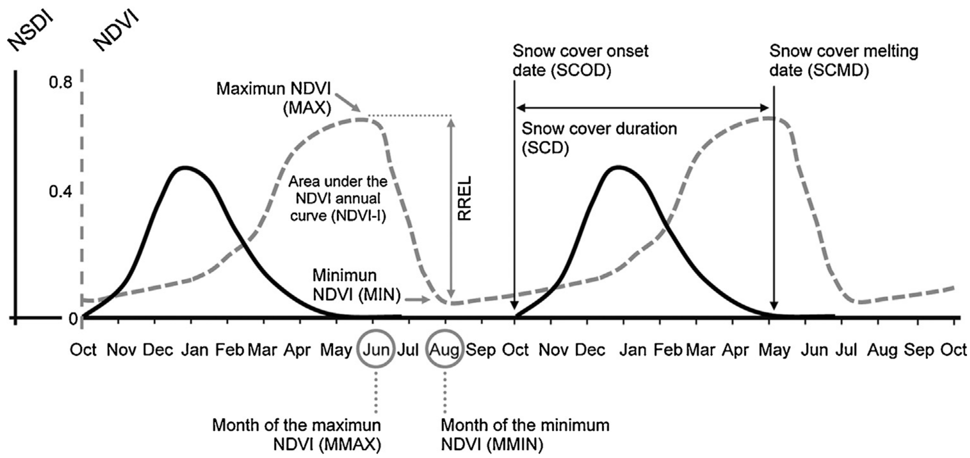


Fig. 2. Attributes derived of Normalized Difference Vegetation Index (NDVI) and snow-cover profiles
Modified from Alcaraz-Segura et al. (2009) and Wang and Xie (2009).

temporal homogenization, we aggregated the data from MOD10A2 (8 days) to gain information regarding at least MOD13Q1 scale (i.e. more than 16 days). We used the MODIS time series from 2000 to 2012.

NDVI seasonal measurements (aggregation of NDVI values by season) are suitable tools to quantify productivity and biomass (Running et al., 2004; Turner et al., 2006), seasonality (Piñeiro et al., 2006; Potter and Brooks, 1998) and other phenological measurements (Cleland et al., 2007). These measurements have been used to characterize ecosystem functioning (Cabello et al., 2012). We have calculated indicators regarding these ecological functions using the mean NDVI profiles provided by MODIS (Fig. 2) *sensu* Alcaraz-Segura et al. (2009):

- *Annual and seasonal mean (NDVI-I)* which can be used to estimate fAPAR (Fraction of Absorbed Photosynthetically Active Radiation) (Sellers et al., 1996) and thus net primary production (Paruelo et al., 1997; Sellers et al., 1992; Tucker et al., 1985).
- *Annual relative range (RREL)*; difference between maximum and minimum NDVI divided by annual mean. This variable provides an indicator of the seasonality of the photosynthetic activity (Paruelo and Lauenroth, 1995).
- *Maximum and minimum NDVI values (MAX and MIN) and months (MMAX and MMIN)* in which they occur. They provide an additional description of phenology, indicating the intra-annual distribution of the periods with maximum and minimum photosynthetic activity (Hoare and Frost, 2004; Lloyd, 1990).

NDSI (normalized difference snow index) is a "spectral band ratio that takes advantage of the fact that snow reflectance is high in the visible wavelengths and low in the shortwave infrared region" (Salomonson and Appel, 2006, p. 351). This index has proven to be a robust indicator of snow cover using MODIS images (Rittger et al., 2013). We have calculated several indicators from MOD10A2 images (Wang and Xie, 2009) (Fig. 2):

- *Snow-cover duration (SCD)* is defined as the number of days covered by snow per hydrological year (describe a time period of 12 months for which precipitation totals are measured).
- *Snow-cover onset dates (SCOD)* is defined as the first date in the hydrological year that the pixel has snow. This indicator is useful to identify shifts in the starting of snow season.
- *Snow-cover melting dates (SCMD)* is the last date in the hydrological year that the pixel has snow. This indicator provides useful information about the melting process.
- *Snow-cover melting cycles (SCMC)* is the number of melting cycles in each pixel per hydrological year.

Knowledge retrieval: ontologies and semantic processing

Savia was designed taking into account a client–server architecture (Fig. 3). The system contains different modules that extract relevant knowledge from the raw data. These modules act in a user-transparent way and are detailed in the following subsections, highlighting image processing, the development of the ontology, how instances are generated, and the final query system.

Embedding MODIS images in a database and calculating thematic indicators

HDF (Hierarchical Data Format) files are downloaded from NASA servers and processed using a workflow that makes the process automatic and reproducible. This workflow is stored and documented in a model repository called ModeleR (Bonet et al., 2014; Pérez-Pérez et al., 2012). The workflow extracts information contained in any HDF files and stores it in a relational database (see structure in Fig. 4). NDVI and NDSI values are stored in a table that is linked to a vector layer containing the centroids of MODIS pixels. These raw data are used to aggregate and calculate the different indicators in *Savia*. The results are integrated again into the relational database, that is part of the Sierra Nevada LTER site information system (Bonet et al., 2011).

The indicators described in the "Data sets and derived information" section were calculated for each pixel and temporal stage (by hydrological year, i.e. the period between October 1st of one year and September 30th of the next; and by season) using SQL queries. The temporal trend for each pixel was calculated using the non-parametric Mann–Kendall trend test (Kendall, 1975; Mann, 1945). The analyses were computed in R (R Core Team, 2013) with Kendall package (McLeod, 2011). We set 0.05 the alpha level for the test, and slopes with p values >0.05 were considered significant.

Creating the ontology

The ontology must represent both the information (MODIS products, indicators, and temporal trends) and the concepts used to add ecological meaning to the data (Fig. 5). To build the

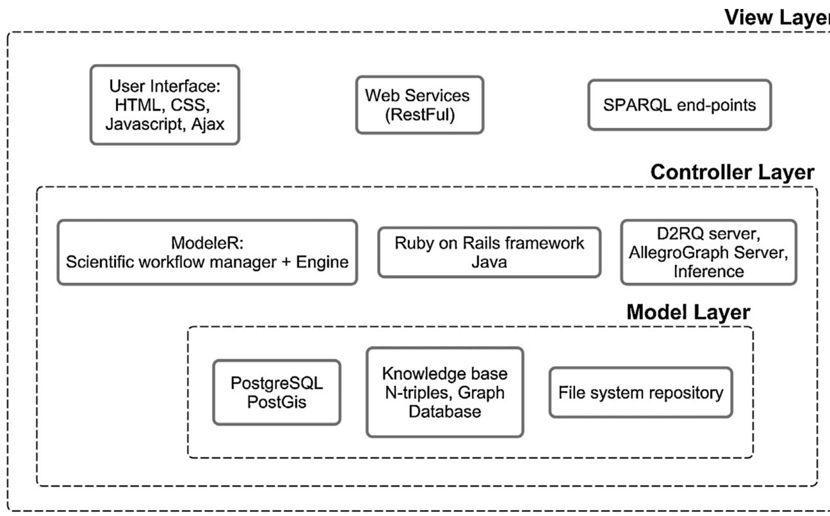


Fig. 3. System architecture.

ontology, we used Time Ontology in OWL (Web Ontology Language) (Hobbs and Pan, 2004) and Basic Geo (WGS84 lat/long) Vocabulary (Brickley, 2003) external ontologies. The OWL-Time ontology promoted by W3C (World Wide Web Consortium) (W3C, 2013), provides a vocabulary for expressing instants and intervals, together with information concerning durations and date/time information (Hobbs and Pan, 2006). The Basic Geo is an RDF (Resource Description Framework) vocabulary for representing latitude, longitude, altitude information as well as other information related to spatial-located items.

Thus, the ontology takes into account three different parts (Fig. 5):

1. Representing spatial information. The main concept is the *Pixel*, which represents a pixel from a MODIS image. Some pixels that share similar functions (i.e. be covered by the same habitat) may belong to a *Patch*. Finally, some patches sharing the same dynamics may belong to a *Group*. The properties called *PixelBelongsToPatch* and *PatchBelongsToGroup* help to define the relationships between the previously defined concepts. *PixelIsNearTo* is another useful property that adds the functionality of proximity to any pixel. The distance threshold used was 500 m between pixels (500 m is the spatial resolution of MODIS snow products). This property is symmetric because when a pixel A is near B, B is also near A.
2. Indicators. This part contains a concept (*IndicatorValues*) that represents the different values that take an indicator (see "Data sets and derived information" section) at a given time point (through the concept called *time: Year* and the property *HasYear*) and in a given place (through the concept *Pixel* and the property

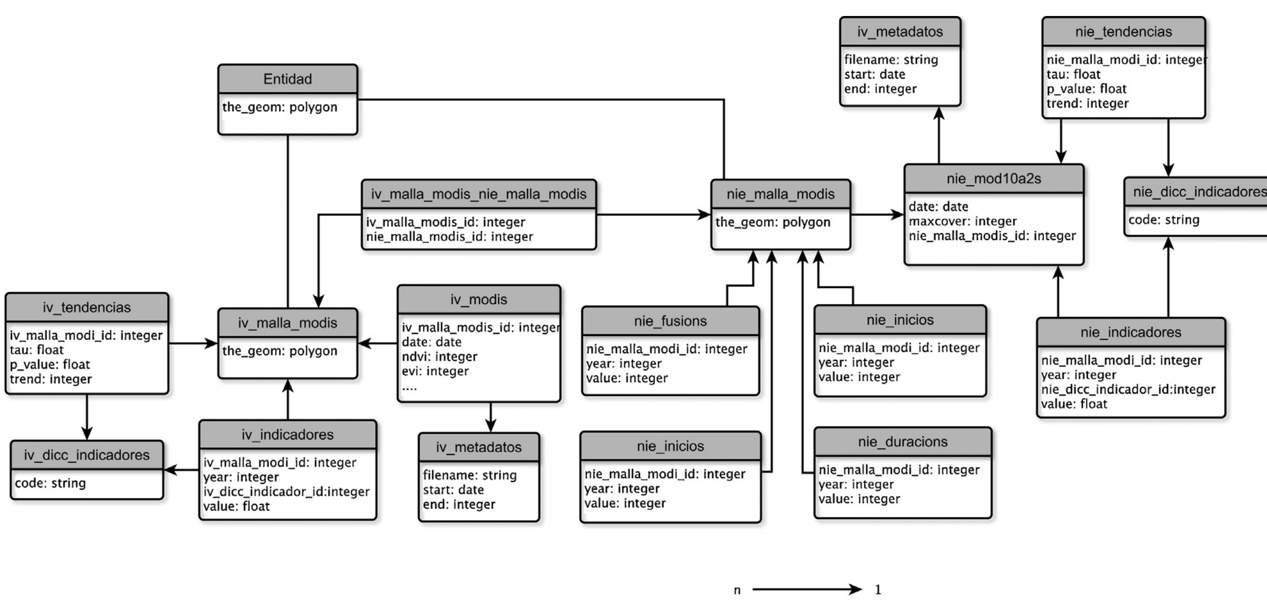


Fig. 4. Database schema. For each MODIS product the relational model stores three types of information: (i) spatial distribution of the pixels (*nie_malla_modis* and *iv_malla_modis tables*); (ii) values of NDVI and NDSI from original HDF files (*nie_mod10a2s* and *iv_modis* tables); and (iii) the metadata associated with each original image (*nie_metadatos_modis* and *iv_metadatos* tables). The database also contains an auxiliary table to manage spatial entities (i.e. *Q. pyrenaica* patches). Finally, there was a set of tables containing the aggregated information and indicators obtained after processing the raw data (see "Data sets and derived information" section) (tables *iv_tendencias*, *iv_indices*, *nie_inicios*, *nie_fusions*, *nie_tendencias*).

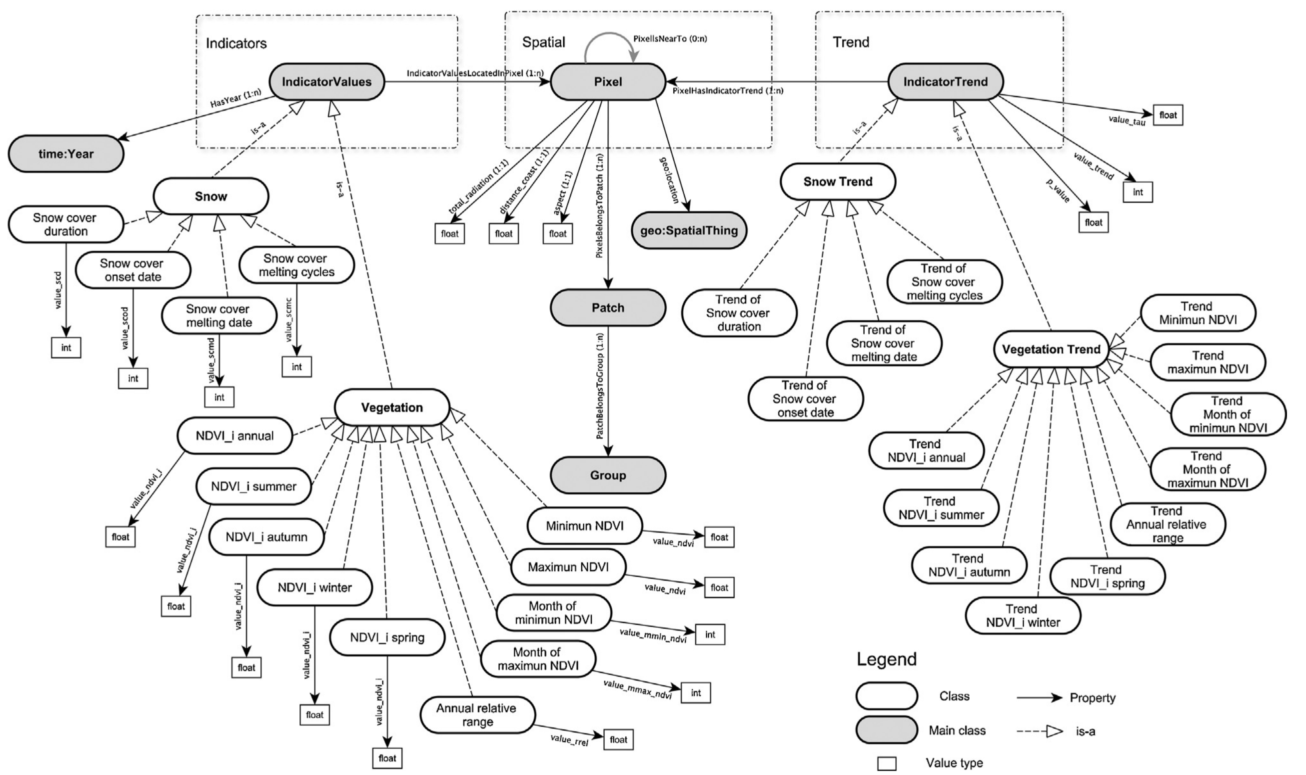


Fig. 5. Detailed representation of the ontology created. Three main parts are considered: spatial information, indicators, and temporal trends of the indicators.

IndicatorValuesLocateInPixel). We have also included a concept to describe all the indicators (*Snow-cover duration*, *Snow-cover onset date*, *NDVI_i annual*, *Maximum NDVI*, etc.). These concepts are grouped according to their thematic area (*Snow* and *Vegetation*). Each indicator has a property called *value* that is measured using a given specific unit.

3. The temporal trends are described in a concept called *IndicatorTrend*. This concept shows the temporal trend of a single point for the whole time series (it is linked to *Pixel* via *PixelHasIndicatorTrends*). We have also created a concept for each temporal trend calculated for the previously described indicators (*Trend of Snow cover duration*, *Trend NDVI_i annual*, etc.). These concepts are also grouped according to their thematic area (*Snow Trend*, *Vegetation Trend*). All these concepts have the following properties:

(a) *value_tau* and *p_value*: These properties contain the statistic (*value_tau*) and the significance (*p_value*) reached by the Mann–Kendall trend analysis.
(b) *value_trend*: Categorical property ranges from −1 (significant negative trend) to 1 (significant positive trend). It is calculated according to the values of *value_tau* and *p_value*.

This schema was implemented using OWL DL (Description logic) that allows an enhanced expression level and does not limit the values for cardinality (Smith et al., 2004). The structure of the ontology created can be downloaded following this link: http://iecolab.es/indicators.rdf.

Knowledge base, SPARQL endpoint and inference

The next step after creating the ontology is to map the records in the database that contain the data to the ontology. Firstly, we used D2RQ (Bizer et al., 2004) to map the relational database to OWL ontology. This software allows instance data to be retrieved from relational databases on-the-fly during the execution of SPARQL queries. Nevertheless, this procedure is time consuming and demands powerful computational capabilities. Thus, we dumped the mapping created with D2RQ into an intermediate N-triples file to avoid this drawback (Sarkar et al., 2011). This file was created with the data existing in the database and has all the triplets contained in the knowledge base.

To store the knowledge base, our tests with the open-source Apache Fuseki and Jena (http://jena.apache.org/) frameworks yielded unsuccessful results as soon as the data volume started to grow. Because we need an efficient implementation that can be scaled to large, enterprise-class data (Wilkinson et al., 2003), we also conducted some tests with AllegroGraph (http://www.franz.com/agraph/allegrograph/) and Virtuoso (http://virtuoso.openlinksw.com/), choosing the former option because of its capabilities and user-friendly management environment. This software is a triplestore that uses a graph database and it has the ability to encode values directly into its triples.

To enhance the results of the queries, a reasoning task can be also triggered within the generation of the system output process. AllegroGraph provides a built-in inference engine that derives implicit information from the knowledge base. Thus, users can easily turn it on by toggling that option in the query builder interface to enrich their queries. The inference engine is useful to find relations on different types of indicators and other implicit properties such as *PixelIsNearTo*. For example, *Savia* can answer questions concerning implicit knowledge of pixels with a positive trend on seasonal mean of NDVI near others with a negative trend in snow-cover melting dates.

Study case

For the improvement of the conservation status of habitats, it is necessary to implement management plans according to the Annex 6 of the Habitats Directive. Our system provides knowledge useful to design those management plans. We have used *Q. pyrenaica* forests in Sierra Nevada (Spain) to explore the importance of snow duration in the functioning of *Q. pyrenaica* forests. We have chosen this habitat as a case study for two reasons: (a) its interesting ecological dynamics (deciduous forest in a Mediterranean mountain) and (b) the need to manage these forests in a global-change context.

We have structured the case study according to three questions that will provide two types of results. Some of them will help in the understanding of the ecological functioning of the target habitat. And others will demonstrate how ontologies are useful tools to make remote sensing information more accessible for non-expert users.

Which pixels show a trend towards higher productivity in summer?

Q. pyrenaica forests show a well-defined growth season centred in summer (Alcaraz-Segura et al., 2006; Dionisio et al., 2012). Some works have pointed out changes in habitat functioning: increase in annual vegetation greenness in Sierra Nevada (Alcaraz-Segura et al., 2008, 2010) and seasonal functional changes in *Q. pyrenaica* woodlands (Martínez and Gilabert, 2009), during the last decade.

This question aims to explore whether our target habitat is undergoing changes in summer productivity, specifically which *Q. pyrenaica* forests of Sierra Nevada have shown a positive trend of the value of summer productivity (summer NDVI).

Which pixels show a trend towards an earlier snowmelt?

Several studies have pointed out a trend towards higher temperatures and lower precipitation for the Mediterranean area (García-Ruiz et al., 2011; Giorgi and Lionello, 2008). Significant declines in snow-cover extent and duration has been reported in some European mountains (Marty, 2008; Moreno-Rodríguez, 2005; Nikolova et al., 2013; Scherrer et al., 2004). Climate projections forecast an increase of +4.8 °C at the end of the 21st century (Benito et al., 2011) for Sierra Nevada and it is expected that snowmelt will occur earlier in the year and will be more rapid (García-Ruiz et al., 2011).

The second question that we raised concerns the observed changes in snowpack in Sierra Nevada. We are interested specifically in which pixels show a trend towards earlier snowmelt during spring-summer. This question is crucial, given that *Q. pyrenaica* forests need water in summer for growth.

Which Q. pyrenaica patches show a trend towards a more productive summer and earlier snowmelt?

This question explores the relationships and co-occurrence between biological production and snow-cover features.

Snow-related variables can explain the distribution of plant communities in the landscape (Jones et al., 2001). This causal relationship is more important at high elevation (Bonet and Cayuela, 2009) in Sierra Nevada. But snow cover also explains part of the ecosystem functioning. Trujillo et al. (2012) observed that vegetation greenness increases with snow accumulation. This relationship varies with elevation, reaching a maximum between 2000 and 2600 m.

Some works have pointed out the influence of snow on greenness in Pyrenean oak forests (Alcaraz-Segura et al., 2009; Dionisio et al., 2012), but to date we have found no studies that analyse the coupling between snow cover and forest greening. Water availability is a key issue on the distribution of *Q. pyrenaica* (del Río et al., 2007; Gavilán et al., 2007). This combination of plant growth and water scarcity makes summer a critical season for the functioning of this habitat.

The third question assesses the capacity of our ontology to show relationships similar to those described above. We have explored the co-occurrence of significant trends in biological production and snow-cover melting date in *Q. pyrenaica* forests. In other words, we have analysed which *Q. pyrenaica* forests show a trend towards higher productivity and earlier melting date in summer.

Results

We translated the above questions from natural language into ontology. For the first and second questions ("Which pixels show a trend towards higher productivity in summer?" and "Which pixels show a trend towards an earlier snowmelt?" sections) we used two concepts (*Pixel, IndicatorTrend*) and some properties describing these concepts (*value_trend, value_tau, PixelHasIndicatorTrends, Trend NDVI_i summer, Trend of Snow cover melting date*) included in the ontology. Specifically:

- "select all *Pixel* where *IndicatorTrend* is positive for summer NDVI-I indicator" for first question (Fig. 6a)
- "select all *Pixel* where *IndicatorTrend* is negative for snow-cover melting date" for second question (Fig. 6b)

We used SPARQL language to query the knowledge base.

Regarding the first question, we found that 75% of pixels had a positive significant trend for summer NDVI (Fig. 6a). For these, more than 80% showed a strong or very strong positive trend. In general, *Q. pyrenaica* patches located on the north face of Sierra Nevada showed a higher amount of significant pixels than the southern ones did (see map in Fig. 6a).

The second question showed that almost 70% of the pixels covered by *Q. pyrenaica* forests had a strong or very strong negative and significant trend towards an earlier melting date (Fig. 6b). Similar to NDVI, the northern patches showed a higher amount of significant pixels than the southern ones.

The third question is more difficult to translate to the ontology because it takes into account two datasets and more concepts than the previous questions. We have included a concept called *Patch*, being a subset of pixels that share some ecological features (they belong to the same *Q. pyrenaica* population). This question also includes other concepts already mentioned (*Pixel, IndicatorTrend*) and properties describing those concepts (*value_trend, value_tau, PixelHasIndicatorTrends*). We also calculated the percentage of pixels per *Patch* that showed trends towards more productive summers and earlier snowmelt. These elements were used to translate the original question to another one that was more suitable for the ontology: select all Pixels where the *IndicatorTrend* is positive for the summer NDVI-I indicator (*Trend NDVI_i summer*) and negative for snow-cover melting date (*Trend of Snow-cover melting date*). We used SPARQL language to query the knowledge base. The results can be displayed both in a map and table format (Fig. 7).

Savia provides two types of answers for this question: (a) A table (Fig. 7) shows the different *Q. pyrenaica* patches ranked according to the percentage of pixels having the described trends in summer productivity and snow-cover melting date. (b) A binary map showing the pixels (grouped by *Patch*) that satisfy both conditions (Fig. 7). All the patches that share the same behaviour are considered as *Groups*.

Discussion and conclusions

The system that we have created adds a semantic component to EO imagery using ontologies to describe this information. *Savia*

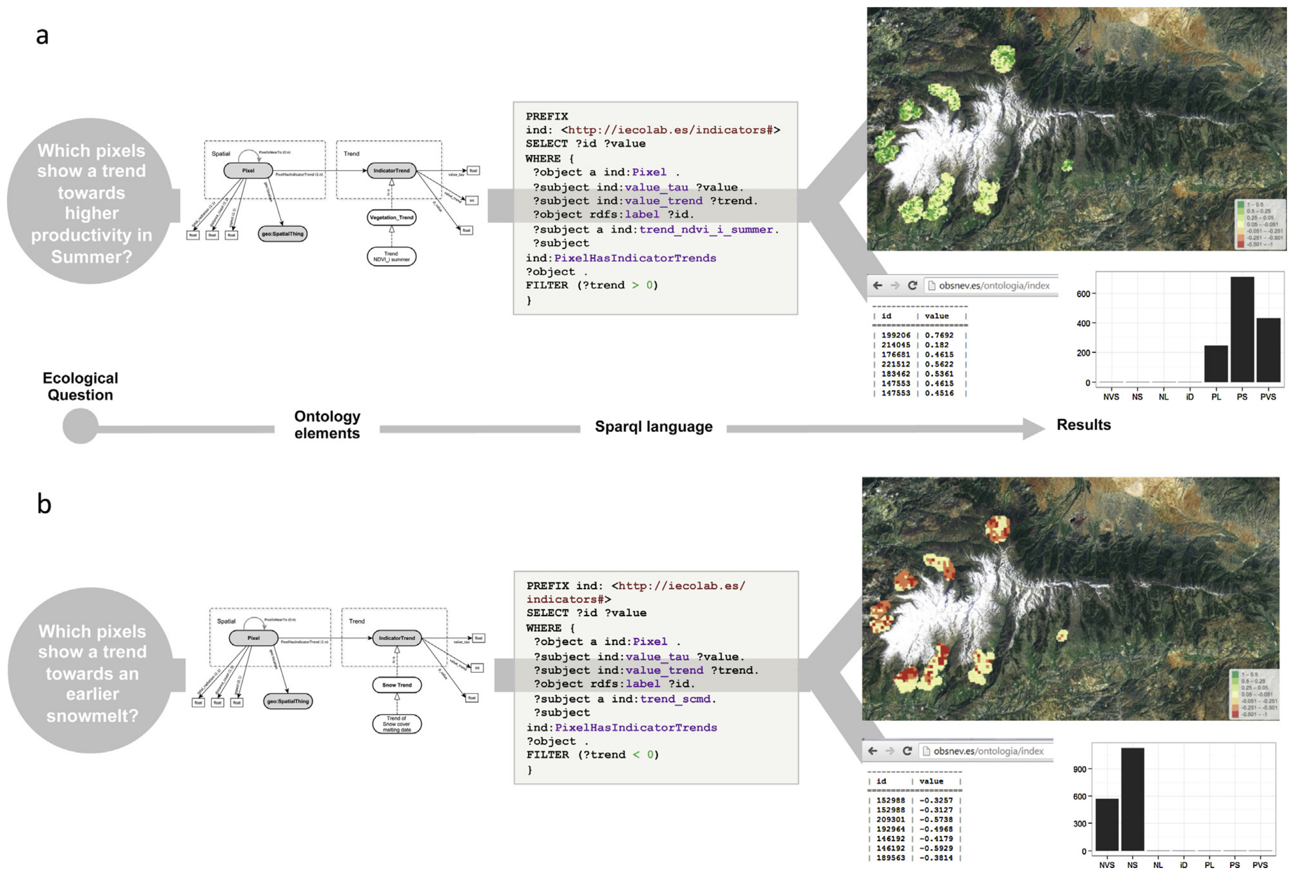


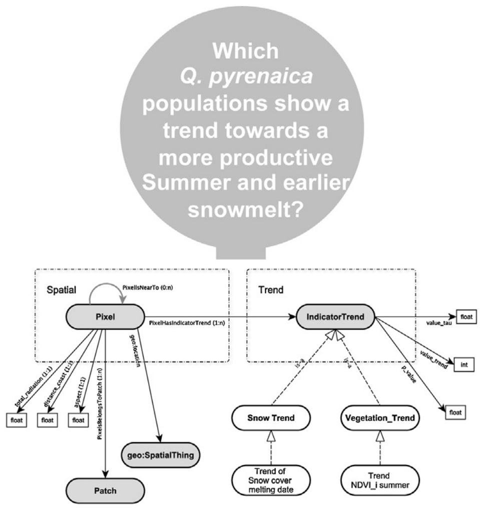
Fig. 6. Scheme showing how the ontology solves questions regarding habitat functioning (a) and the behaviour of an abiotic factor (b). For each ecological question, different ontology elements are used to answer it. Then SPARQL language is used to query the knowledge base. Finally, results can be shown in different formats: map, csv or histogram. See first and second questions of the study case. All pixels are displayed on the resulting map, but for those that have a significant positive trend the tau value is retrieved. In the map, we show seven different colours corresponding to this classification of tau values: [1, 0.5], [0.5, 0.25], [0.25, 0.05], [0.05, −0.051], [−0.051, −0.251], [−0.251, −0.501], [−0.501, −1].

is an operational system that is available for any user via the web (http://obsnev.es/ontologia/index).

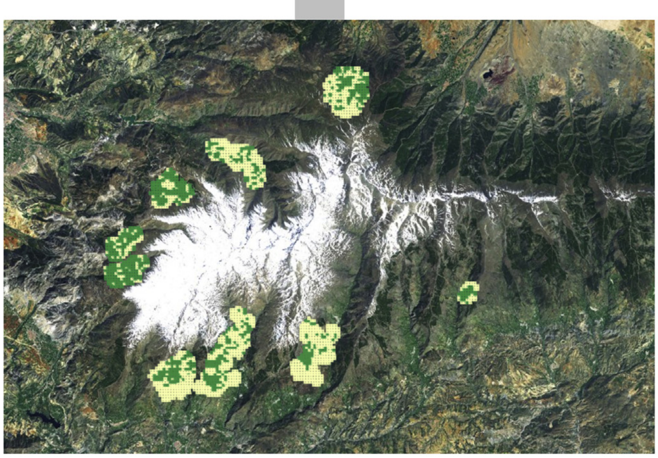
Our system implements a query builder user interface that allows users to build questions using SPARQL. It also includes a set of predefined questions to show its capabilities. Furthermore, users can select different output file formats to display results (csv, text or map). All the analytical procedures needed to run this system have been documented using a model repository called ModeleR (Bonet et al., 2014; Pérez-Pérez et al., 2012). The ontology created reuses and extends public ontologies like OWL-Time and Basic Geo (WGS84 lat/long) Vocabulary. The database containing MODIS images was translated into facts within a knowledge base. This requires a mapping between the database and the concepts contained in the ontology. The dynamical queries to knowledge base, using the mapping tool, were one of the most relevant bottlenecks that we have found during the implementation of the system, and we finally used enterprise-ready software to optimize queries to the knowledge base. We also used an inference engine to solve complex queries that require using advanced properties in the ontology (transitivity and symmetry, mainly).

We tested the ontological system in a case study focusing on *Q. pyrenaica* habitat in Sierra Nevada. We identified significant trends in summer NDVI for 75% of pixels covered by the target habitat. These pixels were located mainly in northern-faced patches (aspect was calculated using DEM). These results could be explained by a different pattern of summer productivity among the *Q. pyrenaica* patches. We have also described similar trends in snow patterns: 70% of pixels show a significant and negative trend towards an earlier melting date. Most of those pixels are also located in northerly facing patches. This result could have several hydrological and ecological implications: (a) water from the melted snow is available for vegetation earlier each year, which could help deciduous trees to overcome the summer drought, (b) the ground is free of snow during a longer period each year, which could provide extra area to treeline communities for altitudinal shifts.

The ontology has also helped to unveil the co-occurrence of significant trends both in snow cover (abiotic factor) and ecosystem functioning (NDVI). Thus, western patches display a high percentage of pixels showing this co-occurrence. The ecological implications of this co-occurrence can be explained by arguing that the earlier snowmelt provides water to *Q. pyrenaica* trees when they are in the middle of their growing season. This earlier amount of water supply encourages trees to be more productive in summer. On the other hand, the southern patches also show this co-occurrence in the opposite way: the lack of significant trends in summer productivity for southern patches could be explained by the lack of pixels with trends towards earlier snowmelt in these areas. Although these results are still preliminary, we have established a link between the status of an abiotic factor and the functioning of ecosystems. Some forest activities can be scheduled according to the trends observed. It could be useful, for example, to reinforce the western patches by planting *Q. pyrenaica* trees. These new trees could take advantage of the productive summers in order to create denser forests. These ecological results are similar to others found in different habitats (Trujillo et al., 2012).




```
PREFIX
ind: <http://iecolab.es/indicators#>
SELECT distinct ?id ?value
WHERE {
?ndvi ind:value_trend ?value.
?pixel rdfs:label ?id.
?ndvi a ind:trend_ndvi_i_summer.
?ndvi ind:value_trend ?trend_ndvi.
?snow a ind:trend_scmd.
?snow ind:value_trend ?trend_snow.
?ndvi ind:PixelHasIndicatorTrends ?pixel.
?pixel a ind:Pixel.
?pixel ind:PixelIsNearTo ?cercanos.
?snow ind:PixelHasIndicatorTrends ?cercanos.
FILTER (?trend_ndvi > 0 && ?trend_snow < 0)
}
```



```
PREFIX ind: <http://iecolab.es/indicators#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT ?patch (SUM(?pixel_ndvi_snow)/SUM(?pixel_ndvi)
               AS ?rank) {
     {SELECT ?patch (COUNT(DISTINCT ?pixel)
      as ?pixel_ndvi)   (0 as ?pixel_ndvi_snow)
      WHERE {
      ?ndvi a ind:trend_ndvi_i_summer.
      ?ndvi ind:value_trend ?trend_ndvi.
      ?ndvi ind:PixelHasIndicatorTrends ?pixel.
      ?pixel a ind:Pixel.
      ?pixel ind:PixelBelongsToPatch ?patch.
      FILTER (?trend_ndvi > 0)}
      GROUP BY ?patch }
UNION
     {SELECT ?patch (COUNT(DISTINCT ?pixel)
      as ?pixel_ndvi_snow) (0 as ?pixel_ndvi)
      WHERE {
      ?ndvi a ind:trend_ndvi_i_summer.
      ?ndvi ind:value_trend ?trend_ndvi.
      ?snow a ind:trend_scod.
      ?snow ind:value_trend ?trend_snow.
      ?ndvi ind:PixelHasIndicatorTrends ?pixel.
      ?pixel a ind:Pixel.
      ?pixel ind:PixelIsNearTo ?cercanos .
      ?snow ind:PixelHasIndicatorTrends ?cercanos .
      ?pixel ind:PixelBelongsToPatch ?patch .
      FILTER (?trend_ndvi > 0 && ?trend_snow < 0)}
      GROUP BY ?patch }
}
GROUP BY ?patch
ORDER BY DESC(?rank)
```

patch	rank
Patch_5	0.79285714285714285714
Patch_4	0.67521367521367521367
Patch_3	0.67080745341614906832
Patch_9	0.5
Patch_1	0.40234375
Patch_6	0.33771929824561403508
Patch_7	0.31754874651810584958
Patch_2	0.29017857142857142857
Patch_8	0.18861209964412811387

Fig. 7. Scheme showing the process of answering a complex query by the ontology. The question takes into account trends in habitat functioning as well as trends in snow-cover melting date. We first show the concepts used by the ontology to answer the query, then the SPARQL code and finally the results found. The left branch provides a map showing those pixels with trends towards more productive summers and earlier snowmelt date. The right branch offers a table ranking the Pyrenean oak patches according to the percentage of pixels that satisfies both conditions.

The results (both ecological and methodological) demonstrate that the information in the MODIS time series is useful to assess the functioning of a terrestrial Natura 2000 habitat. We have described the temporal behaviour of *Q. pyrenaica* forests in Sierra Nevada, distinguishing among patches located in areas with different environmental conditions. We have also shown temporal trends in several functioning indicators. The trends discovered would help managers to assess the conservation status of this habitat. They can also build management plans using the knowledge provided by our ontology (i.e. to decide where to locate plantations taking into account the productivity trends). We have also described the behaviour of a key abiotic factor: snow cover; and we calculated trends for several snow-cover related indicators (snow duration, snow-cover melting date, etc.). Those could help managers to identify places where snow-cover trends could change in the coming years. Finally, we have detected relationships between trends in habitat productivity and snow-cover melting date for the target habitat. All this knowledge is offered to users (mainly managers and scientists) through a web portal, the use of which does not require expertise in remote sensing. Thus, we believe that this work is a worthwhile example of a web-based expert system created using an interdisciplinary approach.

Acknowledgments

This research was conducted in the collaborative framework of the "Sierra Nevada Global Change Observatory" Project from the Environment Department of Andalusian Regional Government and the Sierra Nevada National Park. This projects aims to compile the information necessary to identify the impacts of global change in Sierra Nevada. Funding was provided by the project MIGRAME (RNM 6734) from the Excellence Research Group Programme of the Andalusian Government and from the Fundación Biodiversidad (30B1681503, Spanish government Programme to monitor the impacts of global change in National Parks). We thank the collaboration of Jesus de Marco and members of IFCA (Instituto de Física de Cantabria) for technical support in the use of EGI infrastructure. This work has been conducted in the context of LifeWatch Spain JRU (Joint Research Unit). A. J. Pérez-Luque acknowledges the MICINN for the PTA 2011-6322-I contract.

References

Alcaraz-Segura, D., Cabello, J., Paruelo, J., 2009. Baseline characterization of major Iberian vegetation types based on the NDVI dynamics. Plant Ecol. 202, 13–29, http://dx.doi.org/10.1007/s11258-008-9555-2.

Alcaraz-Segura, D., Cabello, J., Paruelo, J.M., Delibes, M., 2008. Trends in the surface vegetation dynamics of the national parks of Spain as observed by satellite sensors. Appl. Veg. Sci. 11, 431–440, http://dx.doi.org/10.3170/2008-7-18522.

Alcaraz-Segura, D., Liras, E., Tabik, S., Paruelo, J., Cabello, J., 2010. Evaluating the consistency of the 1982–1999 NDVI trends in the Iberian Peninsula across four time-series derived from the AVHRR sensor: LTDR, GIMMS, FASIR, and PAL-II. Sensors 10, 1291–1314, http://dx.doi.org/10.3390/s100201291.

Alcaraz-Segura, D., Paruelo, J., Cabello, J., 2006. Identification of current ecosystem functional types in the Iberian Peninsula. Glob. Ecol. Biogeogr. 15, 200–212, http://dx.doi.org/10.1111/j.1466-822X.2006.00215.x.

Antoniou, G., van Harmelen, F., 2004. A Semantic Web Primer. The MIT Press, Cambridge.

Arvor, D., Duriex, L., Andrés, S., Laporte, M.A., 2013. Advances in geographic object-based image analysis with ontologies: a review of main contributions and limitations from a remote sensing perspective. ISPRS J. Photogram. 82, 125–137, http://dx.doi.org/10.1016/j.isprsjprs.2013.05.003.

Bard, J.B.L., Rhee, S.Y., 2004. Ontologies in biology: design, applications and future challenges. Nat. Rev. Genet. 5, 213–222, http://dx.doi.org/10.1038/nrg1295.

Benito, B., (Thesis) 2009. Ecoinformática apicada a la conservación: simulación de efectos del cambio global en la distribución de la flora de Andalucía. University of Granada.

Benito, B., Lorite, J., Peñas, J., 2011. Simulating potential effects of climatic warming on altitudinal patterns of key species in mediterranean-alpine ecosystems. Clim. Change 108, 1–13, http://dx.doi.org/10.1007/s10584-010-0015-3.

Bizer, C., Seaborne, A., Berlin, F.U., Labs, H., 2004. D2RQ-treating non-RDF databases as virtual RDF graphs. In: Proceedings of the 3rd International Semantic Web Conference (ISWC2004).

Blanca, G., Cueto, M., Martínez-Lirola, M.J., Molero-Mesa, J., 1998. Threatened vascular flora of Sierra Nevada (Southern Spain). Biol. Conserv. 85, 269–285, http://dx.doi.org/10.1016/S0006-3207(97)00169-9.

Blanca, G., Mendoza, R., 2000. Libro rojo de la flora silvestre amenazada de Andalucía: especies vulnerables. Junta de Andalucía. Consejería de Medio Ambiente, Sevilla.

Bonet, F.J., Aspizua, R., Zamora, R., Sánchez, F.J., Cano-Manuel, F.J., Henares, I., 2011. Sierra Nevada observatory for monitoring global change: towards the adaptive management of natural resources. In: MaB, A.M.A. (Ed.), Biosphere Reserves in the Mountains of the World. Excellence in the Clouds? Austrian Academy of Sciences Press, pp. 48–52.

Bonet, F.J., Cayuela, L., 2009. Seguimiento de la cubierta de nieve en Sierra Nevada: tendencias en la última década y posibles implicaciones ecológicas de las mismas. In: IX Congreso Nacional de La Asociación Española de Ecología Terrestre: La Dimensión Ecológica Del Desarrollo Sostenible: Ecología, Del Conocimiento a La Aplicación. Asociación Española de Ecología Terrestre, Úbeda.

Bonet, F.J., Pérez-Pérez, R., Benito, B.M., de Albuquerque, F.S., Zamora, R., 2014. Documenting, storing, and executing models in ecology: a conceptual framework and real implementation in a global change monitoring program. Environ. Model. Softw. 52, 192–199, http://dx.doi.org/10.1016/j.envsoft.2013.10.027.

Brickley, D., 2003. Basic Geo (WGS84 lat/long) Vocabulary, http://www.w3.org/2003/01/geo/ (accessed November 2013).

Cabello, J., Fernández, N., Alcaraz-Segura, D., Oyonarte, C., Piñeiro, G., Altesor, A., Delibes, M., Paruelo, J., 2012. The ecosystem functioning dimension in conservation: insights from remote sensing. Biodivers. Conserv. 21, 3287–3305, http://dx.doi.org/10.1007/s10531-012-0370-7.

Camacho-Olmedo, M.T., Jiménez-Olivencia, Y., García-Martínez, P., Mentor, J., Paniza, A., 2002. La alta alpujarra granadina en la segunda mitad del siglo XX a través de la cartografía evolutiva de su paisaje: dinámica vegetal y repoblación forestal. Cuad. Geogr. 32, 25–42 http://www.ugr.es/ cuadgeo/docs/articulos/032/032-002.pdf

CBD (Secretariat of the Convention on Biological Diversity), 2005. Handbook of the Convention on Biological Diversity, Biological Conservation.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M.D., 2007. Shifting plant phenology in response to global change. Trends Ecol. Evol. 22, 357–365, http://dx.doi.org/10.1016/j.tree.2007.04.003.

del Río, S., Herrero, L., Penas, Á., 2007. Bioclimatic analysis of the *Quercus pyrenaica* forests in Spain. Phytocoenologia 37, 541–560, http://dx.doi.org/10.1127/0340-269X/2007/0037-0541.

Dionisio, M., Alcaraz-Segura, D., Cabello, J., 2012. In: Young, S. (Ed.), Satellite-based monitoring of ecosystem functioning in protected areas: recent trends in the oak forests (*Quercus pyrenaica* Willd.) of Sierra Nevada (Spain). International Perspectives on Global Environmental Change, pp. 355–374.

EIONET, 2013. Online Report on Article 17 of the Habitats Directive: Conservation Status of Habitats and Species of Community Interest (2001–2006). European Environment Agency, http://bd.eionet.europa.eu/article17/index_html/habitatsummary (accessed December 2013).

Evans, D., 2012. Building the European Union's Natura 2000 network. Nat. Conserv. 1, 11–26, http://dx.doi.org/10.3897/natureconservation.1.1808.

Fallahi, G.R., Frank, A.U., Mesgari, M.S., Rajabifard, A., 2008. An ontological structure for semantic interoperability of GIS and environmental modeling. Int. J. Appl. Earth Obs. Geoinf. 10, 342–357, http://dx.doi.org/10.1016/j.jag.2008.01.001.

Förster, M., Frick, A., Walentowski, H., Kleinschmit, B., 2008. Approaches to utilising QuickBird data for the monitoring of NATURA 2000 habitats. Community Ecol. 9, 155–168, http://dx.doi.org/10.1556/ComEc.9.2008.2.4.

Franco, J., 1990. *Quercus* L. In: Castroviejo, A., Laínz, M., López-González, G., Montserrat, P., Muñoz-Garmendia, F., Paiva, J., Villar, L. (Eds.), Flora Iberica, vol. II. Real Jardín Botánico CSIC, Madrid, pp. 15–36.

García, I., Jiménez, P., 2009. 9230 Robledales de *Quercus pyrenaica* y robledales de *Quercus robur* y *Quercus pyrenaica* del Noroeste ibérico. In: Ministerio de Medio Ambiente, y Medio Rural y Marino (Ed.), Bases Ecológicas Preliminares Para La Conservación de Los Tipos de Hábitat de Interés Comunitario En España. Ministerio de Medio Ambiente, y Medio Rural y Marino, Madrid.

García-Ruiz, J.M., López-Moreno, J.I., Vicente-Serrano, S.M., Lasanta–Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth-Sci. Rev. 105, 121–139, http://dx.doi.org/10.1016/j.earscirev.2011.01.006.

Gavilán, R., Sánchez Mata, D., Vilches, B., Entrocassi, G., 2007. Modeling current distribution of Spanish *Quercus pyrenaica* forests using climatic parameters. Phytocoenologia 37, 561–581, http://dx.doi.org/10.1127/0340-269X/2007/0037-0561.

Giorgi, F., Lionello, P., 2008. Climate change projections for the mediterranean region. Glob. Planet. Change 63, 90–104, http://dx.doi.org/10.1016/j.gloplacha.2007.09.005.

Gruber, T., 1993. A translation approach to portable ontology specifications. Knowl. Acquis. 5 (2), 199–220, http://dx.doi.org/10.1006/knac.1993.1008.

Hall, D., Riggs, G., Salomonson, V.V., DiGirolamo, N., Bayr, K., 2002. MODIS snow-cover products. Remote Sens. Environ. 83, 181–194, http://dx.doi.org/10.1016/S0034-4257(02)00095-0.

Hashimoto, S., Tadono, T., Onosato, M., Hori, M., Moriyama, T., 2011. A framework of ontology-based knowledge information processing for change detection in remote sensing data. IEEE Int. Geosci. Remote Sens. Symp., 3927–3930.

Hayes-Roth, F., Waterman, D.A., Lenat, D.B., 1983. Building Expert Systems. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.

Hoare, D., Frost, P., 2004. Phenological description of natural vegetation in southern Africa using remotely-sensed vegetation data. Appl. Veg. Sci. 7 (1), 19–28, http://dx.doi.org/10.1111/j.1654-109X.2004.tb00591.x.

Hobbs, J.R., Pan, F., 2004. An ontology of time for the semantic web. ACM Trans. Asian Lang. Inf. Process. 3, 66–85, http://dx.doi.org/10.1145/1017068.1017073.
Hobbs, J.R., Pan, F., 2006. Time Ontology in OWL, http://www.w3.org/TR/owl-time/ (accessed November 2013).
Huete, A., Didan, K., Miura, T., Rodriguez, E., Gao, X., Ferreira, L., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213, http://dx.doi.org/10.1016/S0034-4257(02)00096-2.
Hyde, P., Dubayah, R., Walker, W., Blair, J.B., Hofton, M., Hunsaker, C., 2006. Mapping forest structure for wildlife habitat analysis using multi-sensor (LiDAR, SAR/InSAR, ETM+ Quickbird) synergy. Remote Sens. Environ. 102, 63–73, http://dx.doi.org/10.1016/j.rse.2006.01.021.
Jones, H., Pomeroy, J., Walker, D., Hoham, R. (Eds.), 2001. Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems. Cambridge, United Kingdom.
Jones, M.B., Schildhauer, M.P., Reichman, O.J., Bowers, S., 2006. The new bioinformatics: integrating ecological data from the gene to the biosphere. Annu. Rev. Ecol. Evol. Syst. 37, 519–544, http://dx.doi.org/10.1146/annurev.ecolsys.37.091305.110031.
Justice, C., Townshend, J.R., Vermote, E., Masuoka, E., Wolfe, R., Saleous, N., Roy, D., Morisette, J., 2002. An overview of MODIS land data processing and product status. Remote Sens. Environ. 83, 3–15, http://dx.doi.org/10.1016/S0034-4257(02)00084-6.
Kalluri, S., Gilruth, P., Bergman, R., 2003. The potential of remote sensing data for decision makers at the state, local and tribal level: experiences from NASA's Synergy program. Environ. Sci. Policy 6, 487–500, http://dx.doi.org/10.1016/j.envsci.2003.08.002.
Kendall, M., 1975. Rank Correlation Methods. London.
Larin Fonseca, R., Garea Llano, E., 2011. Automatic representation of geographical data from a semantic point of view through a new ontology and classification techniques. Trans. GIS 15, 61–85, http://dx.doi.org/10.1111/j. 1467-9671.2010.01242.x/.
Lindenmayer, D.B., Likens, G.E., 2010. The science and application of ecological monitoring. Biol. Conserv. 143, 1317–1328, http://dx.doi.org/10.1016/j.biocon.2010.02.013.
Lloyd, D., 1990. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. Int. J. Remote Sens. 11, 2269–2279, http://dx.doi.org/10.1080/01431169008955174.
Louette, G., Adriaens, D., Adriaens, P., Anselin, A., Devos, K., Sannen, K., Van Landuyt, W., Paelinckx, D., Hoffmann, M., 2011. Bridging the gap between the Natura 2000 regional conservation status and local conservation objectives. J. Nat. Conserv. 19, 224–235, http://dx.doi.org/10.1016/j.jnc.2011.02.001.
Madin, J., Bowers, S., Schildhauer, M., Krivov, S., Pennington, D., Villa, F., 2007. An ontology for describing and synthesizing ecological observation data. Ecol. Inform. 2, 279–296, http://dx.doi.org/10.1016/j.ecoinf.2007.05.004.
Madin, J.S., Bowers, S., Schildhauer, M.P., Jones, M.B., 2008. Advancing ecological research with ontologies. Trends Ecol. Evol. 23, 159–168, http://dx.doi.org/10.1016/j.tree.2007.11.007.
Mann, H., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.
Martínez, B., Gilabert, M.A., 2009. Vegetation dynamics from NDVI time series analysis using the wavelet transform. Remote Sens. Environ. 113, 1823–1842, http://dx.doi.org/10.1016/j.rse.2009.04.016.
Marty, C., 2008. Regime shift of snow days in Switzerland. Geophys. Res. Lett. 35, L12501, http://dx.doi.org/10.1029/2008G.
McLeod, A., 2011. Kendall: Kendall Rank Correlation and Mann–Kendall Trend Test. R Package Version 2.2, http://CRAN.R-project.org/package=Kendall (accessed July 2013).
Melendo, M., Valle, F., 1996. Estudio comparativo de los melojares nevadenses. In: Chacón, J., Rosúa, J.L. (Eds.), 1ª Conferencia Internacional Sierra Nevada, Conservación y Desarrollo Sostenible, vol. 2. , pp. 463–479.
Moreno-Rodríguez, J. (Ed.), 2005. Evaluación preliminar de los impactos en España por efecto del cambio climático. Ministerio de Medio Ambiente, Madrid.
Nikolova, N., Faško, P., Lapin, M., Švec, M., 2013. Changes in snowfall/precipitation-day ratio in Slovakia and their linkages with air temperature and precipitation. Contrib. Geophys. Geod. 43, 141–145, http://dx.doi.org/10.2478/congeo-2013-0009.
Oliva-Santos, R., Maciá-Pérez, F., Garea-Llano, E., 2014. Ontology-based topological representation of remote-sensing images. Int. J. Remote Sens. 35, 16–28, http://dx.doi.org/10.1080/01431161.2013.858847.
Paruelo, J., Lauenroth, W., 1995. Regional patterns of normalized difference vegetation index in North American shrublands and grasslands. Ecology 76, 1888–1898, http://dx.doi.org/10.2307/1940721.
Paruelo, J.M., Epstein, H.E., Lauenroth, W.K., Burke, I.C., 1997. ANPP estimates from NDVI for the central grassland region of the United States. Ecology 78, 953–958, http://dx.doi.org/10.2307/2266073.
Pereira, H.M., Cooper, H.D., 2006. Towards the global monitoring of biodiversity change. Trends Ecol. Evol. 21, 123–129, http://dx.doi.org/10.1016/j.tree.2005.10.015.
Pérez-Pérez, R., Benito, B.M., Bonet, F.J., 2012. ModeleR: an enviromental model repository as knowledge base for experts. Expert Syst. Appl. 39, 8396–8411, http://dx.doi.org/10.1016/j.eswa.2012.01.180.
Piñeiro, G., Oesterheld, M., Paruelo, J., 2006. Seasonal variation in aboveground production and radiation-use efficiency of temperate rangelands estimated through remote sensing. Ecosystems 9, 357–373, http://dx.doi.org/10.1007/s10021-005-0013-x.
Potter, C., Brooks, V., 1998. Global analysis of empirical relations between annual climate and seasonality of NDVI. Int. J. Remote Sens. 19, 2921–2948, http://dx.doi.org/10.1080/014311698214352.
R Core Team, 2013. R: A Language and Environment for Statistical Computing, http://www.r-project.org/ (accessed July 2013).
Renear, A.H., Palmer, C.L., 2009. Strategic reading, ontologies, and the future of scientific publishing. Science 325, 828–832, http://dx.doi.org/10.1126/science.1157784.
Rittger, K., Painter, T.H., Dozier, J., 2013. Assessment of methods for mapping snow cover from MODIS. Adv. Water Resour. 51, 367–380, http://dx.doi.org/10.1016/j.advwatres.2012.03.002.
Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., Hashimoto, H., 2004. A continuous satellite-derived measure of global terrestrial primary production. Bioscience 54, 547–560, http://dx.doi.org/10.1641/0006-3568(2004)054%5B0547:ACSMOG%5D2.0.CO;2.
Salomonson, V., Appel, I., 2006. Development of the Aqua MODIS NDSI fractional snow cover algorithm and validation results. IEEE Trans. Geosci. Remote Sens. 44, 1747–1756, http://dx.doi.org/10.1109/TGRS.2006.876029.
Sarkar, A., Marjit, U., Biswas, U., 2011. Linked data generation for the university data from legacy database. Int. J. Web Semant. Technol. 2, 21–31, http://dx.doi.org/10.5121/ijwest.2011.2302.
Scherrer, S.C., Appenzeller, C., Laternser, M., 2004. Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. Geophys. Res. Lett. 31, L13215, http://dx.doi.org/10.1029/2004GL020255.
Sellers, P.J., Berry, J.A., Collatz, G.J., Field, C.B., Hall, F.G., 1992. Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. Remote Sens. Environ. 42, 187–216, http://dx.doi.org/10.1016/0034-4257(92)90102-P.
Sellers, P.J., Randall, D.A., Collatz, G.J., Berry, J.A., Field, C.B., Dazlich, D.A., Zhang, C., Collelo, G.D., Bounoua, L., 1996. A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: model formulation. J. Clim. 9, 676–705, http://dx.doi.org/10.1175/1520-0442(1996)009<0676:ARLSPF>2.0.CO;2.
Silva, M.P.S., Camara, G., Souza, R.C.M., Valeriano, D.M., Escada, M.I.S.,2005. Mining patterns of change in remote sensing image databases. In: Proceedings of the Fifth IEEE International Conference on Data Mining (ICDM'05). IEEE. Computer Society, http://dx.doi.org/10.1109/ICDM.2005.98.
Smith, M.K., Welty, C., McGuinness, D.L., 2004. OWL Web Ontology Language, http://www.w3.org/TR/owl-guide/ (accessed November 2013).
Trujillo, E., Molotch, N.P., Goulden, M.L., Kelly, A.E., Bales, R.C., 2012. Elevation-dependent influence of snow accumulation on forest greening. Nat. Geosci. 5, 705–709, http://dx.doi.org/10.1038/ngeo1571.
Tucker, C.J., Townshend, J.R.G., Goff, T.E., 1985. African land-cover classification using satellite data. Science 227, 369–375, http://dx.doi.org/10.1126/science.227.4685.369.
Turner, D.P., Ritts, W.D., Cohen, W.B., Gower, S.T., Running, S.W., Zhao, M., Costa, M.H., Kirschbaum, A.A., Ham, J.M., Saleska, S.R., Ahl, D.E., 2006. Evaluation of MODIS, NPP and GPP products across multiple biomes. Remote Sens. Environ. 102, 282–292, http://dx.doi.org/10.1016/j.rse.2006.02.017.
Vanden Borre, J., Paelinckx, D., Mücher, C.A., Kooistra, L., Haest, B., De Blust, G., Schmidt, A.M., 2011. Integrating remote sensing in Natura 2000 habitat monitoring: prospects on the way forward. J. Nat. Conserv. 19, 116–125, http://dx.doi.org/10.1016/j.jnc.2010.07.003.
W3C, 2013. Large Triple Stores, http://www.w3.org/wiki/LargeTripleStores (accessed November 2013).
Wang, X., Xie, H., 2009. New methods for studying the spatiotemporal variation of snow cover based on combination products of MODIS Terra and Aqua. J. Hydrol. 371, 192–200, http://dx.doi.org/10.1016/j.jhydrol.2009.03.028.
Wang, L., Sousa, W.P., Gong, P., Biging, G.S., 2004. Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. Remote Sens. Environ. 91, 432–440, http://dx.doi.org/10.1016/j.rse.2004.04.005.
Wiegand, N., García, C., 2007. A task-based ontology approach to automate geospatial data retrieval. Trans. GIS 11, 355–376, http://dx.doi.org/10.1111/j.1467-9671.2007.01050.x.
Wilkinson, K., Sayers, C., Kuno, H.A., Reynolds, D., 2003. Efficient RDF storage and retrieval in Jena2. Proceedings of First International Workshop on Semantic Web and Databases 3, 131–150.
Williams, R.J., Martinez, N.D., Golbeck, J., 2006. Ontologies for ecoinformatics. Web Semant. Sci. Serv. Agents World Wide Web 4, 237–242, http://dx.doi.org/10.1016/j.websem.2006.06.002.
Xue, Y., Chen, Z., Xu, H., Ai, J., Jiang, S., Li, Y., Wang, Y., Guang, J., Mei, L., Jiao, X., He, X., Hou, T., 2011. A high throughput geocomputing system for remote sensing quantitative retrieval and a case study. Int. J. Appl. Earth Obs. Geoinf. 13, 902–911, http://dx.doi.org/10.1016/j.jag.2011.06.006.