The BIO_SOS European initiative for habitat monitoring

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Abstract. The main objective of the Biodiversity Multi-Source Monitoring System: From Space To Species (BIO_SOS) is the development of a knowledge-based pre-operational ecological modeling system suitable for effective and timely multi-annual monitoring of NATURA 2000 sites and their surrounding areas particularly exposed to different and combined type of pressures. The proposed system, named Earth Observation Data for Habitat Monitoring (EODHaM), is compliant with on-going GEOSS, GMES and INSPIRE initiatives. Based on the expert knowledge of botanists, ecologists and local site managers, the BIO_SOS is developing a deductive-learning (i.e., knowledge-based) classification system that is able to integrate remotely sensed data from satellite sensors and on-site data. Land cover/use (LC/LU) and habitat classes are described by the experts in terms of their temporal characteristics and spatial relationships, geometric and morphological attributes and this information is used in the classification. Once land cover classes and habitats are described through a semantic language, any site can theoretically be mapped and subsequently monitored over time. Areas in three Mediterranean and two Western Europe Countries are under investigation. To extrapolate from European test cases, extending the application domain of the methods, additional areas are being considered in two tropical countries (i.e., Brazil and India). In those areas, the Natura 2000 system does not exist, but the availability of advanced monitoring systems is particularly important for biodiversity conservation. Achievements, open issues, and challenges are highlighted and are expected to trigger the discussion.

Keywords. biodiversity, remote sensing, land cover, habitat mapping, biodiversity indicators, GMES service, Copernicus framework, ecological pressure evaluation, ecosystem modeling.

1. Introduction

NATURA 2000 sites, a network of biodiversity protected areas established with the European Union Habitats Directive (Council Directive 92/43/EEC, 21 May 1992), are severely threatened by a series of human activities, ranging from logging, poaching and agricultural intensification to mining, contamination, spillage of wastes and infrastructure development. These factors may affect both the protected sites and their surrounding landscape and eventually lead to habitat loss, degradation and fragmentation. Designation of an area as protected is often not sufficient to describe its status and timely studies targeting at the assessment of habitat condition are necessary [1-3].

Biodiversity monitoring and preservation have been recognized as tasks of principal importance for mankind during the recent 10th and 11th Conferences of the Parties (COP) to the Convention on Biological Diversity(CBD) [4,5]. A new strategic plan for halting biodiversity loss, globally, by 2020 was defined, expressed by the Aichi Targets, where species and habitat monitoring were identified among the priorities. Similar conclusions were extracted for biodiversity preservation within the European Union boundaries [6,7]. However, species and habitat monitoring may be challenging, since relevant data are often unavailable, collected in different ways, or insufficient in their spatial coverage, as reported by the European Topic Centre on Biodiversity[8]. Therefore, the development of a uniform observation system that will be easily used by all Member States for reporting obligations and defining management strategies is very important. The Biodiversity Multi-Source Monitoring System: From Space To Species (BIO_SOS) seventh Framework Programme (FP7) project aims at providing timely and automatic mapping of land surfaces and habitats and their changes over time based on remote sensing data.

The main objective of BIO_SOS is the development of a pre-operational multi-modular ecological modeling system suitable for multi-annual monitoring of NATURA 2000 sites and their surroundings. Addressing explicitly expressed regional and national user needs and being compliant with international initiatives, such as Copernicus (former GMES – Global Monitoring for Environment and Security), GEOSS (Global Earth Observation System of Systems) and INSPIRE (Infrastructure for Spatial Information in the European Community), BIO_SOS attempts to provide: i) long-term baseline data (e.g., thematic maps at 1:5000 scale or finer) of land cover types and habitats, ii) new automatic, standardized, rapid and cost-effective monitoring techniques using remote sensing data, reducing costs related to in-field campaigns, iii) methods for assessing the significance of measured land cover and habitat changes and evaluating trends, iv) modeling techniques for evaluating the combined impact that different drivers and human-induced pressures (e.g. agriculture expansion, urbanization, logging, road construction) may have on biodiversity over time and v) scientific support to evaluate the extension of the buffer area around Natura 2000 sites, where different policies should be applied.

BIO_SOS working objectives include the development of pre-operational high (HR) and very high resolution (VHR) Earth Observation (EO) data processing and understanding techniques to provide as output land cover/use (LC/LU) and LC change (LCC) maps, as well as an ecological modeling framework at both habitat and landscape level to combine EO and in-situ data for site monitoring. Thus, BIO_SOS will act as an improvement and extension of GMES/Copernicus downstream services, bringing together the ecological and remote sensing research communities.

2. BIO_SOS system description

The rule-based (deductive learning) biodiversity monitoring system proposed by BIO_SOS, named Earth Observation Data for Habitat Monitoring (EODHaM), comprises various components, drawn in Figure 1. The system is organized in three main stages, as far as the data analysis towards the final products is considered.

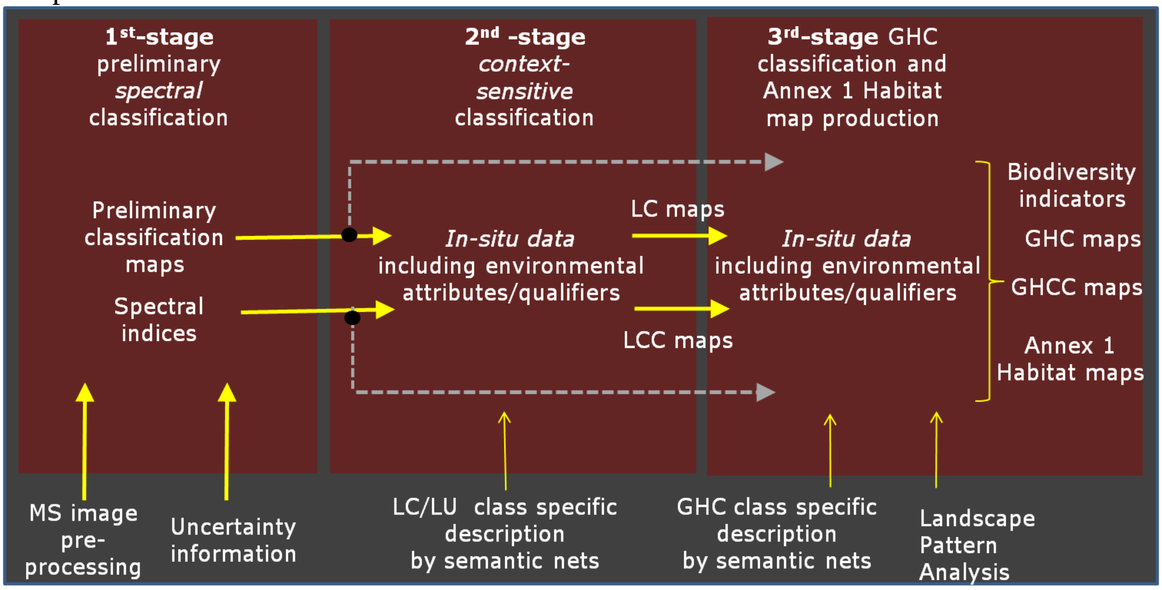

Figure 1. The main components of the EODHaM system.

In order to provide an inclusive framework, able to provide state-of-the-art biodiversity status and trends evaluation in different Natura 2000 protected sites, a series of sites of different characteristics and induced pressures are selected as case studies. In particular, 9 Mediterranean sites, 4 in Italy, 3 in Greece and 2 in Portugal, as well as 2 central and northern European sites, in Wales, United Kingdom, and the Netherlands, were selected. These sites are a diverse set of protected areas including wetlands, forests, grasslands, agricultural areas, heathlands and bogs. Site characteristics range from mountainous rough to flat coastal morphologies, from rangeland to human-dominated landscapes and land uses. The wide array of different environmental characteristics of the selected sites has been selected to ensure system robustness. Besides the selected Natura 2000 sites, two tropical sites in Brazil and India were additionally selected to increase system applicability in diverse landscapes at a global level.

2.1. EODHaM 1st stage

The first stage of the proposed EODHaM system includes a preliminary LC/LU mapping of the studied areas based solely on spectral properties extracted from the available remote sensing imagery. After comparative analysis considering different land cover taxonomies [9], the Land Cover Classification System taxonomy [10] has been selected for LC/LU mapping in BIO_SOS, providing the most informative and straightforward link to habitat categories. The LCCS taxonomy organizes land cover types in 8 main categories, depending on whether the landscape patch under consideration is vegetated or not, terrestrial or aquatic and cultivated or managed by human intervention or (semi-)natural. Additional qualifiers are added to the principal LCCS categories to describe environmental attributes and characteristics, such as vegetation life form, leaf type, canopy characteristics, soil type, etc. The 1st stage of EODHaM system provides a preliminary LCCS mapping as far as the vegetated, terrestrial or aquatic nature of the landscape is regarded (four major LCCS categories; i.e. vegetated terrestrial, vegetated aquatic, non-vegetated terrestrial, non-vegetated aquatic), while more detailed mapping is performed during the 2nd stage.

After the necessary pre-processing (e.g. geo-registration, topographic correction and ortho-rectification, atmospheric correction) of the available satellite imagery, a series of features are extracted based on the spectral properties of the imagery, with these including for example, buildings, trees, hedgerows and roads (Figure 2). Apart from being used for the preliminary classification of the landscape, the features are calculated for use in further classification steps.

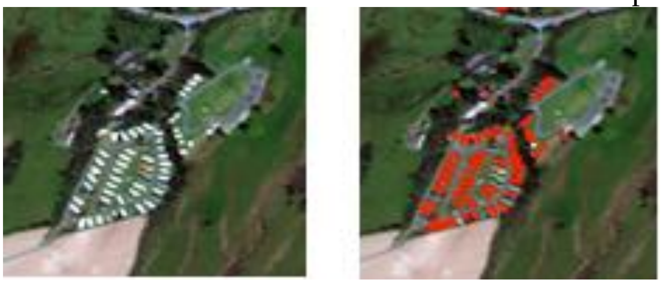

Figure 2. Delineation of caravans in a Worldview-2 image, CorsFochno site, Wales. On the left: the original image. On the right: Caravans are marked in red.

An object-oriented approach, implemented as open source software, is followed for the extraction of the studied characteristics of the landscape throughout the entire EODHaM system process. Each study site is split into patches, or objects, and both LC/LU and habitat mapping, as well as ecological modeling and trend evaluation, are performed in a patch basis. Therefore, the first step of the process deals with the extraction of objects (in addition to features), by defining segments in the remote sensing imagery depicting patches in the landscape. Segmentation of the available imagery is performed based on its spectral properties. Additional data layers (e.g. cadastral maps, roads, urban areas) may be embodied in the segmentation process, if they are available. Two segmentation layers are created. The first layer favors the creation of large segments, or objects, identifying the borders of the main landscape patches, such as agricultural field units, forest plantations, olive groves, tourist parks, industrial areas, etc. The second layer is created through the use of algorithms for the delineation of particular elements in the imagery. Thus, the layer includes smaller objects, including the previously extracted features (such as tree crowns, buildings, etc.).

Following segmentation, a series of features are calculated and assigned to the objects recognized during the first stage of the segmentation. A number of features are calculated based on the reflectance values of the pixels belonging to each segment (e.g., average or maximum reflectances in specific wavelengths, or image bands, or particular spectral indices, such as the Water Band Index (WBI) [11], the Normalized Difference Vegetation Index (NDVI) [12] and the Plant Senescence Reflectance Index (PSRI) [13]). Furthermore, additional features are extracted from information derived from the second stage of the segmentation (i.e., the percentage of the area of an object covered by trees) or from ancillary data (e.g., average vegetation canopy height within an object where a Canopy Height Model (CHM) is available). The calculated features are used either during the preliminary classification of the 1st stage of EODHaM or during the following steps.

2.2. EODHaM 2nd stage

The second stage of EODHaM refers to the extraction of detailed LCCS maps. Preliminary inputs for the mapping are VHR satellite images, having a spatial resolution of around 2m. Ancillary data, in the form of CHM, derived from Light Detection And Ranging (LiDAR) data, cadastral layers, urban infrastructure or water element boundaries, etc, may be used to enhance the LCCS mapping if available.

LCCS classes are defined in a hierarchical manner, where various qualifiers describing the properties of the object under study are included to form the class name. Such qualifiers may refer to vegetation properties, such as life form, cover, height, leaf type, phenology or stratification, or other characteristics, such as soil type and condition, lithology, water state, depth and turbidity. The amount of the qualifiers able to be extracted is related to the availability of multi-temporal images of the site and ancillary data. The more data available, the more qualifiers are specified and the more detailed and descriptive the final LCCS classes will be.

In addition to the spectral characteristics used in the 1st stage of EODHaM, topological relations among neighboring objects and temporal relations depicting the changes in an object over time, are also included as part of the 2nd stage. Therefore, the rules provided by domain experts, based on which the LCCS classification is performed may, for example, require an examination as to whether an object is adjacent to an urban area, cultivated land, open water, or comparison of its NDVI or WBI values during the period prior to the spring flush of vegetation, the peak flush and the senescent period.

2.3. EODHaM 3rd stage

Produced LCCS maps from the 2nd stage of the EODHaM system are used as input to derive habitat maps in the 3rd stage of the approach. Among the different habitat taxonomies proposed, BIO_SOS has adopted the Annex I and the General Habitat Categories (GHC) taxonomies [14, 15, 16]. The Annex I taxonomy has been established by the Habitats Directive to provide an inclusive description of habitats within the European continent and is of central importance for international reporting and Natura 2000 site management. The GHC is a recently proposed and developed habitat taxonomy, providing an exhaustive typology of habitat types that can be found in any terrestrial landscape around the globe[14]. Contrary to the Annex I taxonomy, where non-European and urban habitats are not considered, the GHC taxonomy includes habitats found in diverse landscapes, ranging from natural ecosystems to urban areas, and from sparsely vegetated areas to multi-layered tropical forests [15]. GHC categories hold a close relation to Annex I habitat classes [16]. Therefore, they can be used as basis for the extraction of Annex I maps. In total, the mapping performed in the 3rd stage of EODHaM includes the extraction of GHC and Annex I maps based on LCCS maps, as well as the translation of GHC into Annex I maps. The latter approach is favored by the large similarities between the LCCS and GHC taxonomies (i.e., they both consider life forms, canopy height and leaf type, thus making GHC a promising proxy for the extraction of Annex I through LCCS maps). Figure 3 provides an example of the LCCS to GHC mapping process performed during the 3rd stage of the EODHaM system for the protected site of Le Cesine, Apulia region, south-eastern Italy.

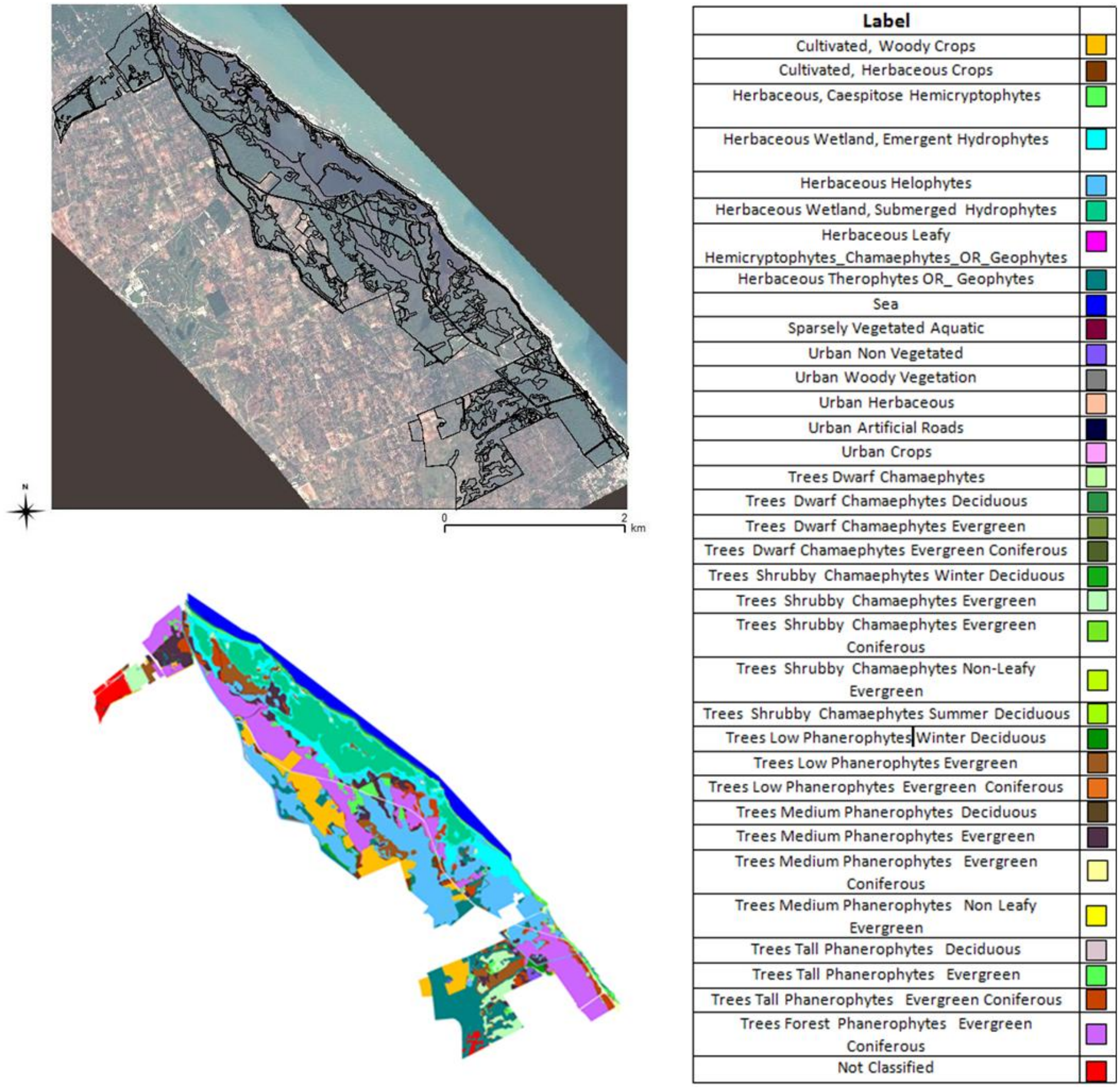

Figure 3.GHC map of Le Cesine site, Italy. On top: A Worldview-2 image of Le Cesine in true color, where object borders created after segmentation are highlighted. On the bottom: The extracted GHC map of the site.

In order to express relationships between LCCS–GHC, LCCS–Annex I and GHC–Annex Iclasses in an explicit and formal manner, the use of ontologies and semantic networks is embodied in BIO_SOS [17]. The adopted approach involves top-domain ontologies, such as OBOE (Extensible Observation Ontology) and SWEET (Semantic Web for Earth and Environmental Terminology), and domain ontologies defined specifically for the needs of the EODHaM system, involving among other land cover, image, and spatio-temporal relations. Developed ontologies represent in a modeled and structured way the expert rules used to produce both i) LCCS maps from the initial remote sensing data, and ii) habitat maps from the extracted land cover maps.

In various cases, uncertainty may be introduced to the final habitat mapping results, either because of incomplete information provided to the EODHaM system, which does not allow the discrimination among similar habitat classes, or because of uncertainty expressed by the experts through the provided rules. To handle such causes of uncertainty, the Dempster-Shafer theory is incorporated in the EODHaM system process [18,19], providing a framework that allows the use of multiple classes in cases, where complete discrimination of the single ones is not possible and assigning a belief interval to each potential single or multiple class, describing the possibility of the class to be true based on both provided and missing evidence. Furthermore, in order to counteract for inaccurate rule thresholds provided by the experts and increase the robustness and transferability of the rule-based system to similar landscapes, fuzzy logic is incorporated to the Dempster-Shafer framework. Finally, surrogate measures to vegetation height estimation through texture analysis of the VHR imagery have been tested and proposed [20], to provide alternatives in case of unavailability of LiDAR and CHM information.

2.4. EODHaM final products

The aim of BIO_SOS project, through the developed EODHaM system, is to create a robust approach for assessing biodiversity status in various landscapes and monitor its trends and potential threats. To evaluate the condition of the studied areas, appropriate biodiversity indicators have been selected to be calculated, complying with the frameworks of indicators proposed by CBD [21] and the Streamlining European Biodiversity Indicators partnership [22]. In particular, the main indicators selected to be calculated in BIO_SOS, under the SEBI framework, are i) habitats of European interest, ii) abundance and distribution of selected species and iii) fragmentation of natural and semi-natural areas. The calculation of the first and third indicators is heavily based on the habitat maps derived from the 3rd stage of the EODHaM system. The second indicator is facilitated through a series of field campaigns and niche ecological modeling tasks performed throughout the duration of BIO_SOS. Possible links between the second and the third indicator are being explored by means of both habitat and landscape modeling with the aim of assessing the usefulness of EO features as proxies for biodiversity surrogates (e.g. measures of species assemblages).

As a readily available downstream service to regional authorities and site managers, BIO_SOS is also focusing on the development of a modeling framework for pressure analysis and threat assessment in different protected areas based on the outcomes of the 3rd stage of the EODHaM system, with the aim to evaluate their impacts on habitats. Within BIO_SOS a framework was delineated that enables the integration of different approaches for the selection a set of site- and scale-specific indices and synthetic descriptors for a comprehensive quantitative assessment of variations habitat spatial patterns and hence human impact on the landscape, which can be used as a baseline for monitoring[23]. In order to assess the impacts and pressures, the framework developed by the Conservation Measurement Partnership of the International Union for Conservation of Nature and Natural Resources (IUCN/CMP)[25] is selected as the most comprehensive and widely used at the local level, because of many factors, including its hierarchical multi-level organization, flexibility, and emphasis on spatial mapping and monitoring.

For mapping of existing or potential threats, an approach is proposed that builds on this framework, but adapts it so that remote sensing data are used to monitor impacts of pressure - on landscapes, land cover/habitat types, communities and species - which can then be used to infer pressure type, frequency and intensity at different spatial resolution and then at different scales (global to local). In case a severe threat or impact is detected requiring immediate mitigation actions by policy makers and site managers, a warning signal is produced. Impacts in BIO_SOS are described from local pressures that result in land cover/habitat conversion, land cover/habitat modification, disruption of ecological regimes, changes in spatial connectivity, and disruption of community structure. The framework is conceptually robust, geographically invariant and spatially-explicit, connecting to the growing data sets from remote sources.

3. Concluding remarks

The imperative need for biodiversity preservation has been identified by several organizations worldwide. Effective and timely monitoring of biodiversity status and trends is a principal concern for many regional and national authorities and policy makers. The BIO_SOS FP7 project proposes a multi-modular system for time- and cost-efficient biodiversity monitoring and ecological modeling using remote sensing data. The proposed system, EODHaM, provides habitat maps of the sites under study following an object-oriented rule-based (deductive learning) approach.

The habitat maps are used as principal sources for quantifying biodiversity impacts and pressures. EODHaM is organized in three stages. The first stage employs spectral properties of the available remote sensing imagery to provide preliminary land cover maps, while the second stage provides more refined results considering topological and temporal relations among the elements of the site. During the third stage of EODHaM, habitat maps are produced from the land cover maps, expressed in the Annex I and General Habitat Categories taxonomies. The whole EODHaM system is implemented as open source software.

In parallel to habitat mapping, ecological modeling and species distribution analyses are performed for the pilot sites. The outcomes of the EODHaM system are used for the extraction of habitat change maps and the estimation of well defined and widely adopted biodiversity indicators. In addition, identification and assessment of pressures and impacts is performed in a near real time manner and a warning signal is extracted to pinpoint wherever mitigation actions may be required.

Overall, BIO_SOS products are built on the needs and expertise of the end users and site management community and comply with widely adopted initiatives, such as GMES/Copernicus, GEOSS and INSPIRE. BIO_SOS will provide a valuable tool for biodiversity status and dynamics assessment to authorities and policy makers, in high resolution, and a near real time and cost-effective manner.

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- The paper is dedicated to the great scientist and friend to BIO_SOS colleagues, Professor Maria Petrou, lost to cancer in October 2012.

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