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Live Monitoring of Earth Surface (LiMES): A framework for monitoring environmental changes from Earth Observations

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ABSTRACT

Global environmental changes are mostly induced by human activities (e.g., food and energy production, urbanization, mining activities). To assess and understand these changes that are occurring all around the planet, regular and continuous monitoring is an essential condition. However, due to the potentially large area spread over numerous locations that need to be followed, this usually leads to a low frequency of monitoring of environmental changes of only a few selected sites at best.

With the increasing number of freely and openly accessible big remotely-sensed Earth Observations (EO) Data repositories and the increasing capabilities of open and interoperable software solutions it is now possible to automate various EO data processing tasks to monitor environmental changes at large scale.

This paper presents the Live Monitoring of Earth Surface (LiMES) framework that helps to automate image processing tasks in transforming raw data into information and knowledge through workflows using interoperable processing service chains for monitoring environmental changes. Both benefits and limitations are demonstrated and discussed through the implementation of a prototype to facilitate the update on the status of some of the 278 UNEP Environmental Hotspots. We believe that such a framework can help to reduce the gap between massive volumes of EO data and the users such as International Organizations (IO) in order to help them better fulfil their environmental monitoring mandates by bringing raw data to a level which can be used by non-remote sensing experts for basic impacts assessments.

1. Introduction

Remote sensing techniques allow monitoring environmental changes over large areas. The resolutions (spatial, temporal and spectral) need to be carefully matched with the type of analysis pursued. Among other, the United Nations Environment Programme, the Ramsar Convention and the IUCN World Heritage have the mandate to monitor thousands of sites worldwide, covering hundreds of millions of hectares. Multiple drivers cause changes affecting these areas: climate change, urbanization, deforestation, conversion of mangroves to fish and shrimps farms, pollution. Given the size of these sites (usually between 400,000 and 2,000,000 ha), the request for long historical period, medium resolution and the costs, Landsat archive is the ideal sensor. The complexity does not depend on the individual remote sensing processing for each site, it depends upon how to deal with the monitoring of 2530 sites covering 500 million ha with an appropriate spatial resolution. Here we show how to obtain and process thousands of Landsat images to support monitoring of land cover changes.

Human activities such as extractive industry, food and energy production, transportation, tourism, urbanization, with their corresponding use of resources and pollutions, are rapidly transforming the environment. Between 47 and 59 billion tons of material are mined every year (Steinberger et al., 2010). In 2010, 13 million ha of forest were cut down, mostly for conversion to crop land (FAO, 2010). Even protected areas are not spared: 114 out of the 229 World Heritage sites are at threat from human activities (WWF, 2016). These are some examples of processes that are inducing Global Environmental Changes.

Turner differentiates two types of global environmental changes: systemic and cumulative (Turner et al., 1990). The former includes localized sources of changes leading to global effects (e.g., climate change, ozone layer hole, sea level rise, ocean acidification). The latter (cumulative) includes multiple transformations having local impacts, but which are nevertheless global because they are occurring on a worldwide

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scale, scattered over many different locations. Deforestation, loss of biodiversity, soil erosion, pollution, and urbanization are examples that fall in this category. Most of these cumulative changes have an influence on land cover. Given their global distribution, monitoring cumulative changes by tracking land cover evolution is challenging, but necessary for various policy goals (e.g., conservation, spatial planning, enforcement of existing protected areas and/or conventions, tracking progresses on Sustainable Development Goals (SDGs), raising awareness on environmental impacts).

The rapid environmental changes from multiple threats call for a regular monitoring on status and trends. However, because these large area are spread over numerous locations it leads to low update frequency, or to assessments based on literature reviews without the possibility of monitoring specific sites on a continuous basis (Dixon et al., 2016). In particular, the recent adoption of the United Nations 2030 Agenda on Sustainable Development and the definition of 17 Sustainable Development Goals (SDG) together with 169 targets and related indicators calls for more frequent updates at lower levels of aggregation. This is likely to exceed the capacity of national statistic offices, especially in developing countries (United Nations, 2012; IEAG, 2014; United Nations, 2015).

Simultaneously, the data revolution generated by new technologies (e.g., satellites, mobile devices, cloud computing, crowdsourcing, physical and chemical sensors, linked data) provides an exponentially increasing volume and variety of data, "*creating unprecedented possibilities for informing and transforming society and protecting the environment*." (IEAG, 2014). This raises the importance of data for decision-making and for accountability as key elements of the post-2015 development agenda and the implementation of the SDGs. Understanding the Earth system as a whole is crucial to supporting economic growth, inclusive development and environmental sustainability, rendering the Sustainable Development Agenda a transformative step from the Millennium Development Goals (Sachs, 2012). A data revolution that is tailored to sustainable development will require, more than in the past, the integration of new data, including geospatial information and in situ monitoring, with socio-economic and statistical data. Opportunities offered by technological progress should be further harnessed.

Comprehensive, coordinated and sustained observations of the Earth, acquired by satellites, ground, marine-based systems and airborne platforms, are essential for monitoring the state of the planet, increasing understanding of Earth processes, and enhancing predictability of Earth system behaviour. Earth Observations (EO) can be defined as the gathering of information by remote sensing or in-situ measurements about physical, chemical and biological conditions of the Earth system. In this paper, EO data are intended as remotely-sensed images acquired by satellite. EO deliver timely information, beneficial for all citizens, organizations and governments, to build accountability, help make appropriate decisions, and ultimately improve people's lives (GEO secretariat, 2004; GEO secretariat, 2011; GEO secretariat, 2015). Advances in technologies and capacities (e.g. data acquisition systems, computing, networks) help monitoring global changes that transcend political and geographic boundaries (Vitolo et al., 2015). Organizations such as the Ramsar Convention and IUCN are concerned with a large number of sites that are extensive, remote, and scattered. The difficulty for organizations such as these is the lack of capacity to keep track of the status of a large number of sites that are often large, remote, and scattered, across a wide range of environments. Consequently, EO can be considered as crucial to getting long-term global coverage and provide useful for monitoring of land cover changes over time and over vast expanses (Skidmore et al., 2015). The methodologies to analyse data are well documented and transparent, and EO can be a good complement to national statistics (e.g., cross-validation) (Sustainable Development Solutions Network et al., 2015).

With an increased number of satellite sensors, we can now obtain more data offering higher spatial, spectral and temporal resolutions. Moreover, the adoption of broad open data policies allows users to freely access low to medium-resolution imagery such as USGS Landsat, NASA MOderate resolution Imaging Spectroradiometer (MODIS), Japan Aerospace Exploration Agency (JAXA) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) or ESA Sentinels (Ryan, 2016). The Landsat archive offers free access to images and global coverage since 1972 (Roy et al., 2014). The recent launch of the ESA Sentinel satellites is providing additional free monitoring capabilities. Dealing with such a wealth of data is now technically feasible, but requires extensive automation. Indeed, the increasing resolution of remote sensing images as well as the efforts and costs required to convert EO data into meaningful information on biophysical variables have hampered a systematic analysis to monitor changes from these Big Data archives (Lewis et al., 2016). To tackle this issue, the development of large-scale analytical tools to efficiently extract relevant information for answering scientific questions as well as for supporting decision making processes represents a major challenge for the EO community. Several ongoing efforts are aiming to bring information from low to medium resolution imagery to users. The Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Schmidt et al., 2013) is a software jointly developed by NASA and the University of Maryland that is aiming to produce top-of-atmosphere reflectance from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) Level 1 data and apply atmospheric corrections to generate surface-reflectance product for Climate Data Record. The MODIS Rapid Response Project has developed a system for generating products on a variety of rapid events (e.g., active fires, floods, dust storms, volcanic eruptions) (Descloitres et al., 2002). With the Rapid Response system, MODIS data are processed within a few hours of data acquisition to provide active fire detection at 250 m resolution. Similarly, the NASA Land, Atmosphere Near real-time Capability for Earth Observing System (LANCE) generates EO products in near-real time to support research and applications in various domains such as climatology, ecology, or disaster relief (Michael et al., 2010). The Deep Space Climate Observatory (DSCOVR) is a NOAA EO and space weather satellite to monitor, with the use of the Earth Polychromatic Imaging Camera (EPIC) sensor, changes in ozone, aerosols, dust and volcanic ash, cloud height, vegetation cover and climate (Burt and Smith, 2012). EPIC takes full Earth pictures about every 2 h. These examples demonstrate how NASA's Earth Observing System (EOS) is trying to reduce data latency by rapidly generating after acquisition scientific products useful for various communities of users (Brown et al., 2014). The challenge is to turn raw data into understandable information by developing appropriate algorithms, tools and platforms needed to access, store, process and interpret data to finally make use of the large volume of data that is stored in electronics silos (Gore, 1998; Craglia et al., 2008; Craglia et al., 2012).

Even if these systems are providing useful and high quality products to expert users they remain still difficult to handle for tracking, monitoring, visualizing, understanding, and communicating environmental changes, especially for organizations that have environmental monitoring mandates (e.g., Ramsar Convention, IUCN, UNEP). These systems are designed to process one specific sensor data (e.g., Landsat, MODIS), they provide limited interactions with users (e.g., only download a specific product), and products and algorithms are not published using interoperable standards, consequently limiting the usability and integration of processed data and resources.

Recognizing these issues, the aim of this paper is to present the Live Monitoring of Earth Surface (LiMES) framework, to enable rapid access and processing of EO Big Data for monitoring cumulative changes through land cover changes. LiMES is aiming at automating various image processing tasks and helps transforming raw data into information and knowledge by translating expert knowledge into workflows using interoperable processing service chains. The framework is designed using a combination of large storage capacities, high performance computers, and interoperable standards to develop a scalable, consistent, flexible and efficient analysis system that can be used on various domains through decades of data for monitoring purposes. A proof-of concept has been implemented using Landsat medium-resolution

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imagery to ease the update on the status of some of the 278 UNEP Environmental Hotspots, created for the UNEP Atlas of Our Changing Environment (UNEP, 2005).

2. The LiMES framework for environmental monitoring from EO

Traditional methods for measuring and monitoring environmental changes are usually based on literature reviews (Dixon et al., 2016), map interpretation, compilation of ancillary data, and ground measurements. These methods are not effective to support monitoring programs because they differ widely, datasets are often inconsistent and incompatible, tasks are time-consuming and expensive, and few data are shared openly (Petrou et al., 2015). To tackle these issues, remotely sensed Earth Observations have been used for decades to provide reliable and accurate information over long periods of time and over different spatial scales. The rapid development of new sensors, data handling capabilities, image analysis techniques, and free access to large data repositories (e.g., GEOSS (http://www.geoportal.org), USGS Earth Explorer (http://earthexplorer.usgs.gov), Sentinels Scientific Data Hub (https://scihub.copernicus.eu)) is increasingly making it possible to monitor spatio-temporal changes on a continuous basis (depending on orbits and cloud cover). Continued and timely assessment of wetlands, land cover or protected areas enables timely intervention for protection and restoration so that they continue providing essential ecosystem services. The advantages of using remote sensing in spatial analysis are that satellite data are periodic observations providing useful information in various wavelength; they cover large areas making data collection less costly and less time consuming than with in-situ and analogue data; they provide a repetitive coverage allowing monitoring of dynamics (e.g., water, forest); they facilitate data acquisition at various scales and resolution; and a single remotely sensed scene can be analysed and interpreted to various purposes and applications (Klemas, 2011). In this context, the "Live" of the LiMES framework must be understood as tracking the evolution of a given site on a continuous basis allowing users to visualize changes through time using both archived data and when possible the most recent data available. Even if, the framework is not meant to be a near-real time system, once a site to monitor is defined and there is a new scene acquired and available in the selected data repository, LiMES will process it to get the most recent data for this site.

Recognizing that EO data are an important resource for land cover changes monitoring, and to take advantage of Big remotely-sensed Data repositories, it is necessary that all actions are coordinated in a coherent chain from capture to decision making and to support a wide range of stakeholders (Miller and Mork, 2013). Such a data value chain should help to create and build value through enhanced data discovery (e.g., capture, storage, organization), integration (e.g., visualization, access), and exploitation (e.g., transformation, analysis, tailored products and services). To ensure that measurements and outputs are meaningful and sustainable, interoperability standards can help documenting, sharing, searching, accessing, interpreting, and integrating EO data and ultimately strengthening the provider-user interface (Ostensen et al., 2008).

With the existing technology, it is now possible to automate EO data processing to monitor environmental changes. Major data repositories like GEOSS and Sentinels Scientific Data Hub can be searched by systems such as LiMES to access relevant data on selected sites, download them, generate different processing, calculate indices and plot them as graphs and/or maps to monitor/compare their evolution through time (Eerens et al., 2014). This allows the processing of numerous sites including back processing and regular updates. Moreover, with the help of web technologies (e.g., API, standards, scripting languages), it is possible to build applications tailored to various users needs (e.g., dashboards), to share generated data and information to a wide audience using interoperable web services, ensure the reuse of generated data and information. It can allow other users to easily develop narratives (e.g. story maps) to explain current changes, causes and consequences.

2.1. Scope and objectives

The main objective of LiMES is to automate the processing of optical satellite imagery for monitoring land cover changes of several hundreds of sites per year. The whole process of satellite images analysis is complex and requires several intermediary steps: site identification, discovery, download, conversion of raw files into images, stacking, image corrections, actual processing (e.g., computation of index, pan-sharpening), and visualization (Lewis et al., 2016) (Fig. 1). Most of these steps can be automated but the main issues are related to the site definition, the image selection and the quality check where human intervention is required. The intention is to reduce these human interventions to a minimum and to facilitate as much as possible providing guidance to users.

Ultimately, the LiMES framework is aiming at simplifying the production of information requested for monitoring and reporting needs on status, trends and assessing progress towards achieving environmental goals.

2.2. System architecture

The LiMES architecture is presented in Fig. 2 and it is composed of 7 main components:

- *Remote Sensing Data Acquisition:* is the layer of sensors and satellites specialized in collecting remote sensing data with different acquisition frequencies, different spatial resolutions, or different spectral bands.
- *Data Providers* layer is composed of different specialized organizations engaged in acquiring remote sensing data, storing it in different formats and providing this data to users under different standards. The data providers can provide the data using different protocols and under different formats, influencing the speed and the quality of data acquisition. Currently, LiMES is designed to handle various Application Programming Interfaces (APIs) to query and access data from United States Geological Survey (USGS), Google Earth Engine, Amazon Web Services, and GEOSS.
- Within the *Computing Environment* layer, we can identify different computing infrastructures such as Cloud, Clusters or even local servers. Based on a series of parameters, such as the number of sites, the algorithms complexity, the required processing, we can use one or even several such computing infrastructure, to obtain better performances.
- The *Processing Layer* offers functionalities for different image processing algorithms and additional actions such as image discovery, image conversions, pan-sharpening, index computation, image correction, and download. All implemented functionalities are written in Python scripts interacting with different geospatial processing libraries such as Geospatial Data Abstraction Library (GDAL) and Open Geometry Reformatter (OGR). This allows one to easily expand the system with new functionalities (e.g., algorithm, technique).
- The *Geoserver* component offers support for geospatial data manipulation and sharing, using standardized Open Geospatial Consortium (OGC) services, such as Web Map Service (WMS) for data visualization (Open Geospatial Consortium, 2006a, 2006b), Web Feature Service (WFS) and Web Coverage Service (WCS) for data download of respectively vector and raster data (Open Geospatial Consortium, 2006a, 2006b), and Web Processing Service (WPS) for data processing (Open Geospatial Consortium, 2007).
- The *Data Quality and Validation* layer is a component requiring some human intervention to validate the results of image processing. This step is done by experts (e.g., remote sensing and/or thematic specialists) in order to ensure that the generated results are of sufficient

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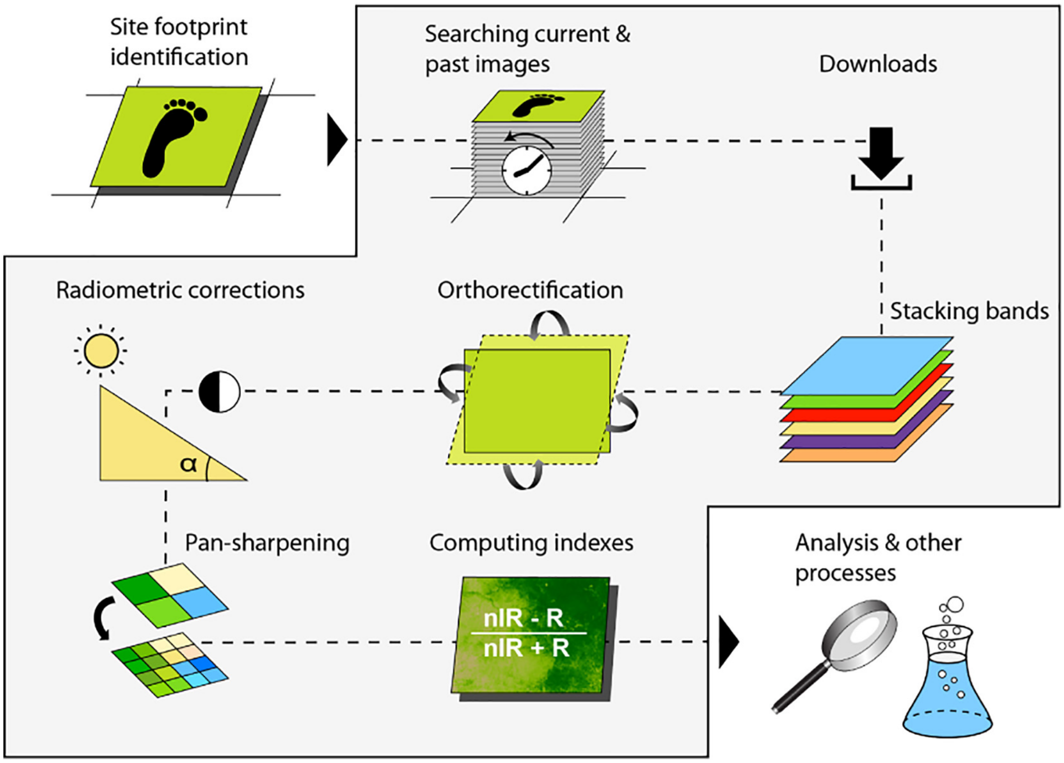

Fig. 1. Automatization in LiMES. All the tasks in the grey box can be automated.

quality for monitoring requirements. Once results are validated they are made available and accessible on the User Interface component.

- The *User Interface* offers different visualization services in an easy and interactive manner, helping the user to retrieve and visualize the data in different formats and for different purposes.

Through these different components, the LiMES framework is aiming at reducing the processing complexity as much as possible while giving the user a large degree of flexibility. All the functionalities in LiMES are offered as Python scripts and exposed as WPS processes in a dedicated Python Web Processing Service (PyWPS) instance installed on a server. PyWPS is an OGC WPS server implementation written in Python. The WPS standard describes how a client (e.g., desktop GIS application, web portal) can request geospatial processing services over a network (e.g., Internet), and how inputs and outputs are handled (Vitolo et al., 2015). PyWPS provides an environment for writing and publishing Python scripts for processing remote sensing and geospatial data using GDAL/OGR, Geographic Resources Analysis Support System – Geographic Information System (GRASS-GIS) and R software functionalities in the backend (Čepický and de Sousa, 2016).

Within this architecture, once data have been processed, results are automatically published in Geoserver and made accessible using WMS and WCS standards for data visualization and download. Automatic publication is achieved using the Representational State Transfer (REST) API provided by Geoserver for programmatically managing data without manual intervention. By making results interoperable, data sharing and integration with other desktop or web-based applications are facilitated and therefore the use of results can be expanded.

Currently, it offers the following capabilities: (1) Allows a fast and easy update of the site through an automated workflow; (2) Fully based on open source and OGC standards compliant components and technologies: Python, GRASS-GIS, GDAL, OGC Web Services (OWS), OpenLayers; (3) Automatic Processing – based on Python and PyWPS; (4) Scalability – allows the processing and monitoring of thousands of sites; (5) Can be used for various thematic, such as: Hotspots monitoring, Ramsar Convention, World Heritage Protected Areas, and at various geographical scales; (6) Flexibility – for easily adding other (satellite) data providers; (7) Full transparency – all processes as well as all used images (and their references) are available as metadata; (8) Reproducibility – the complete set of data and the history of processing applied are available to view or download so as to enable a user to reproduce the performed analyses locally or elsewhere. Additional more advanced functionalities are already planned, such as allowing parallel processing of sites – the results will be considerably improved as the number of sites increases; visual compatibility of images; mosaicking; cloud masking; sun angle corrections; management of no-data in surface statistics; display and result analysis filtered by date (e.g., Month – to monitor seasonal variations, Year – to monitor long term variations); allowing more (guided) user interaction in image selection; and result image ranking by the users.

2.3. Execution flow

The execution flow of LiMES is presented in Fig. 3, where all the main steps of the flow are clearly emphasized and delineated: discovery, download, processing, validation and display.

LiMES will perform a series of predefined satellite image processing tasks via a set of scripts:

- *Discover*: periodically and automatically locate the satellite images to process,
- *Download*: automatically download the images of interest through the fastest provider available,
- *Process*: pre-processes the satellite images (e.g., perform atmospheric corrections using the 6S algorithm; assessment of cloud, shadows and snow using FMask) (Vermote et al., 1997; Zhu et al., 2015) and applies the processes defined for each site using GDAL/OGR, GRASS-GIS and R open source software,
- *Validate*: allows the administrator of a site to publish or reject the generated products (e.g., due to a large nodata area in the area of interest),

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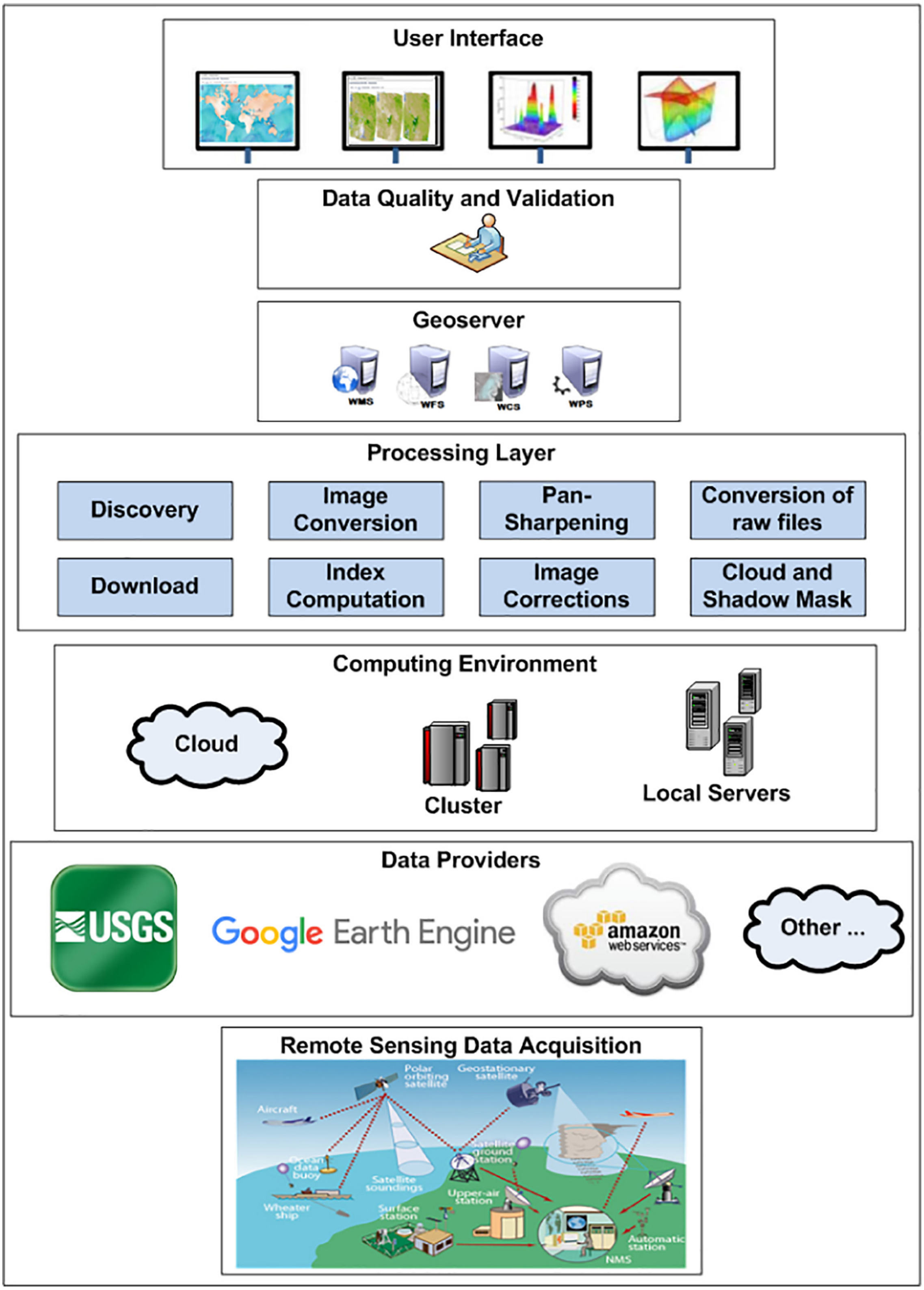

Fig. 2. LiMES general architecture.

- *Display*: allows any user around the World to visualize, examine and download generated products through a web interface.

The required manual action will be limited to identifying the sites to be analysed, and validating the result of the automated process. Once a user has defined a study area, the frequency of monitoring and the desired outputs via the LiMES framework, the required algorithms will identify the relevant satellite images, stack the different layers, perform atmospheric corrections, transform the signal into spectral reflectance, as well as apply image processing pre-defined for each site individually. For example, a site dedicated to the wetland monitoring will need

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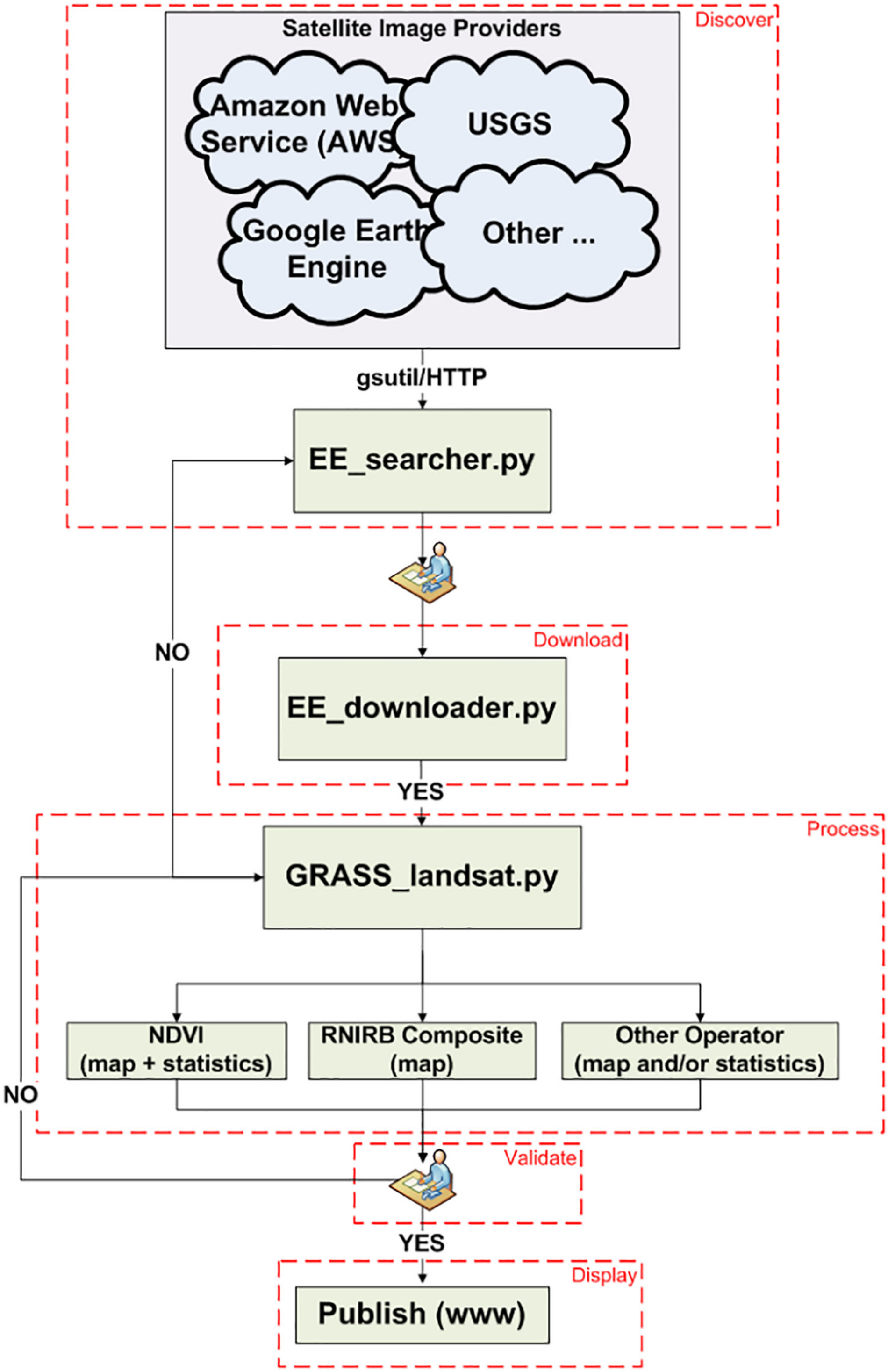

Fig. 3. Execution workflow in LiMES.

Normalized Difference Water Index (NDWI) maps, while a site dedicated to deforestation monitoring will need Normalized Difference Vegetation Index (NDVI) and/or Land Cover maps. The output is a time series of images, which can be used to assess changes within a selected site.

2.4. LiMES implementation and functionalities

In order to validate the technical feasibility, identify the potential issues and determine the potential of such framework, a proof-of-concept application has been implemented to monitor five UNEP Environmental Hotspots.

The "One Planet, Many People. Atlas of Our Changing Environment" (UNEP, 2005) tries to provide insights on the many ways that people around the world have altered the environment. It illustrates through a collection of "before/after" satellite image pairs of 279 sites around the World how natural processes and human-induced activities have modified their surroundings and continue to make observable and measurable changes to the global environment. This collection of data is available in UNEP Live (http://www.uneplive.org) and on Google Earth (under Global Awareness theme) (Fig. 4).

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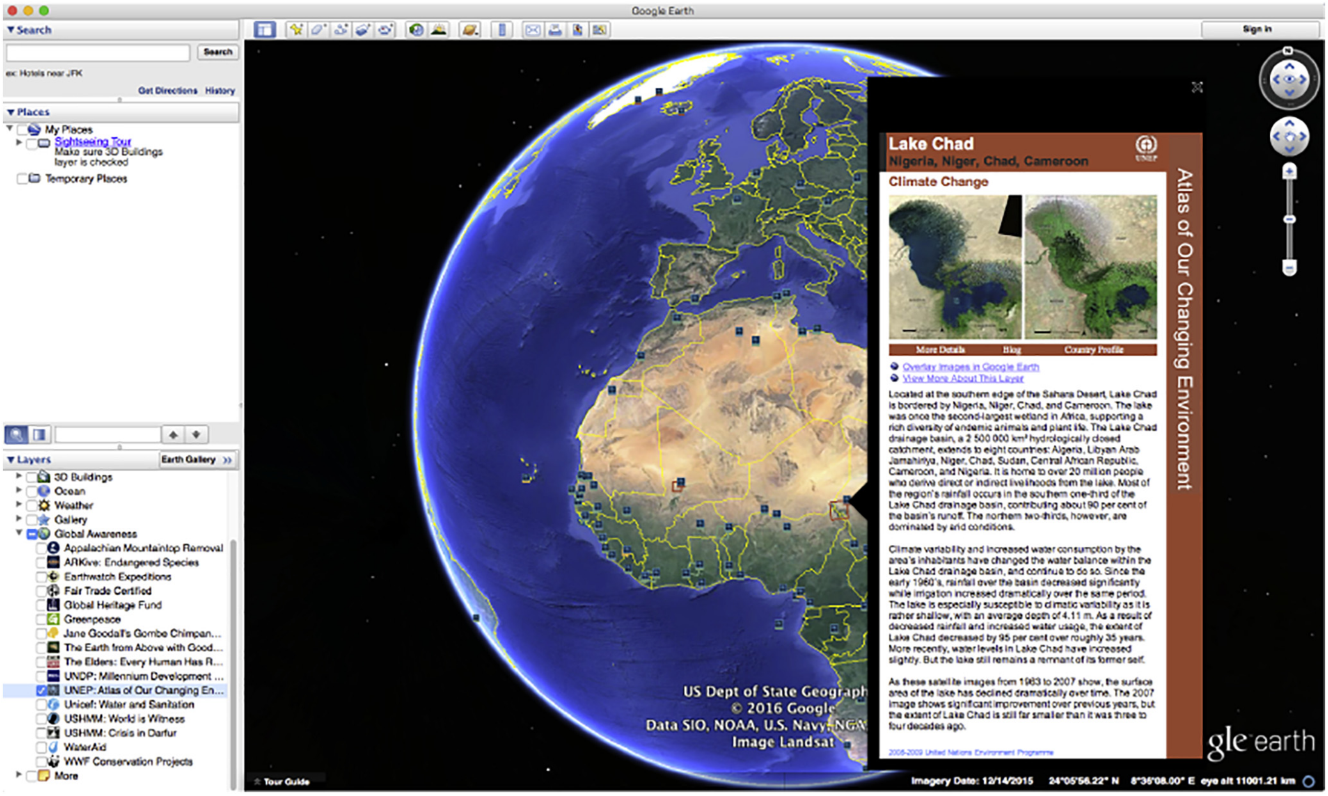

Located at the southern edge of the Sahara Desert, Lake Chad is bordered by Nigeria, Niger, Chad, and Cameroon. The lake was once the second-largest wetland in Africa, supporting a rich diversity of endemic animals and plant life. The Lake Chad drainage basin, a 2 500 000 km² hydrologically closed catchment, extends to eight countries: Algeria, Libyan Arab Jamahiriya, Niger, Chad, Sudan, Central African Republic, Cameroon, and Nigeria. It is home to over 20 million people who derive direct or indirect livelihoods from the lake. Most of the region's rainfall occurs in the southern one-third of the Lake Chad drainage basin, contributing about 90 per cent of the basin's runoff. The northern two-thirds, however, are dominated by arid conditions.

Climate variability and increased water consumption by the area's inhabitants have changed the water balance within the Lake Chad drainage basin, and continue to do so. Since the early 1960's, rainfall over the basin decreased significantly while irrigation increased dramatically over the same period. The lake is especially susceptible to climatic variability as it is rather shallow, with an average depth of 4.11 m. As a result of decreased rainfall and increased water usage, the extent of Lake Chad decreased by 95 per cent over roughly 35 years. More recently, water levels in Lake Chad have increased slightly. But the lake still remains a remnant of its former self.

As these satellite images from 1963 to 2007 show, the surface area of the lake has declined dramatically over time. The 2007 image shows significant improvement over previous years, but the extent of Lake Chad is still far smaller than it was three to four decades ago.

2006-2009 United Nations Environment Programme

Fig. 4. UNEP Atlas of Our Changing Environment in Google Earth.

The major issue for this environmental monitoring platform is that all tasks to process these data are done by individual researcher's location by location. This a repetitive and time consuming work that limits the number of sites that can be monitored. Consequently, the LiMES framework can help to automate the processing and monitoring of the defined/selected sites. This is an ideal use case to apply and test the proposed approach.

A web-based application has then been developed to offer an intuitive user interface to increase and facilitate data supply, access, processing and delivery (Fig. 5). This has been developed as a prototype and is not meant to be fully operational but rather more for demonstration purposes.

Through a set of different modules users will be able to visualize land cover changes, have access to the most recent images, track the evolution through time, and gain a deeper understanding of the dynamics of environmental change. For each site, a quick overview provides a rapid comparison between the oldest image and the most recent one. A locator map as well as a brief description of the environmental causes of land cover changes (provided by experts) are also available. Additionally, a set of tools gives the ability to explore, track and compare changes across time in various ways. The swipe option allows revealing/hiding a target layer by moving to the right/left side of mouse position on a map. The side-by-side option (Fig. 6) visualizes up to three images. The zoom is synchronized, so the users can navigate within images and the corresponding area in the other images will be displayed for an easy comparison on the status across time.

Being a demonstration application, not all the functionalities have been currently implemented. Metadata can be expanded to give more details (e.g., algorithm applied, type of product, nature of the remote sensing imagery) on the provided data; indication of scale and north arrow can be added. Other future capabilities will allow comparing earliest/latest images with a flicker function, generate animation of selected sequence of images, visualizing trends as graphs, generate a PDF report for a specific site, and provide widgets to embed desired functionalities in other websites. All of the processed data are freely available and accessible through data sharing technologies (e.g., OGC web services) allowing users to visualize, process, and download data. Finally, a visual narrative (e.g., story maps) based on extensive scientific evidence will serve as a vivid reminder that this planet is our only current home, and that sound policy decisions and positive actions by societies and individuals are needed to sustain the Earth and the well-being of its inhabitants. These stories can range from a global scope showing for example deforestation around the globe (http://limes.grid.unep.ch/dev/storymaps/forest/) to a local perspective in the case of Iraqi marshlands (http://limes.grid.unep.ch/dev/storymaps/marshlands/).

An essential component of the LiMES platform is the processing toolbox that is aiming at hiding EO data processing complexity while giving users as much flexibility as possible. This toolbox is presented to users as a step-by-step online procedure where: (1) users define an area of interest, a time frame, and select processing algorithms; then (2) an automatic sequence of search (in various data repositories), download, and image processing according to the user's selections; (3) when the processing tasks are finished, the results are stored in a database and published on the platform.

3. Use cases where LiMES framework can be applied

The current LiMES prototype has been presented to different International Organizations (e.g., IUCN, Ramsar Convention) that have environmental monitoring mandates. The scattered distribution, the size and the number of sites is posing a monitoring challenge for these organizations, leading to low frequency of updates on the status of these sites. These institutions are currently lacking tools, capabilities and metrics to monitor in a comparable way spatial and temporal changes at various scales. The LiMES framework can support them in implementing a consistent monitoring tool to follow the evolution 2240 wetlands (as of May 2016) located in 169 countries covering more than 200 million ha or to monitor the IUCN 229 World Heritage

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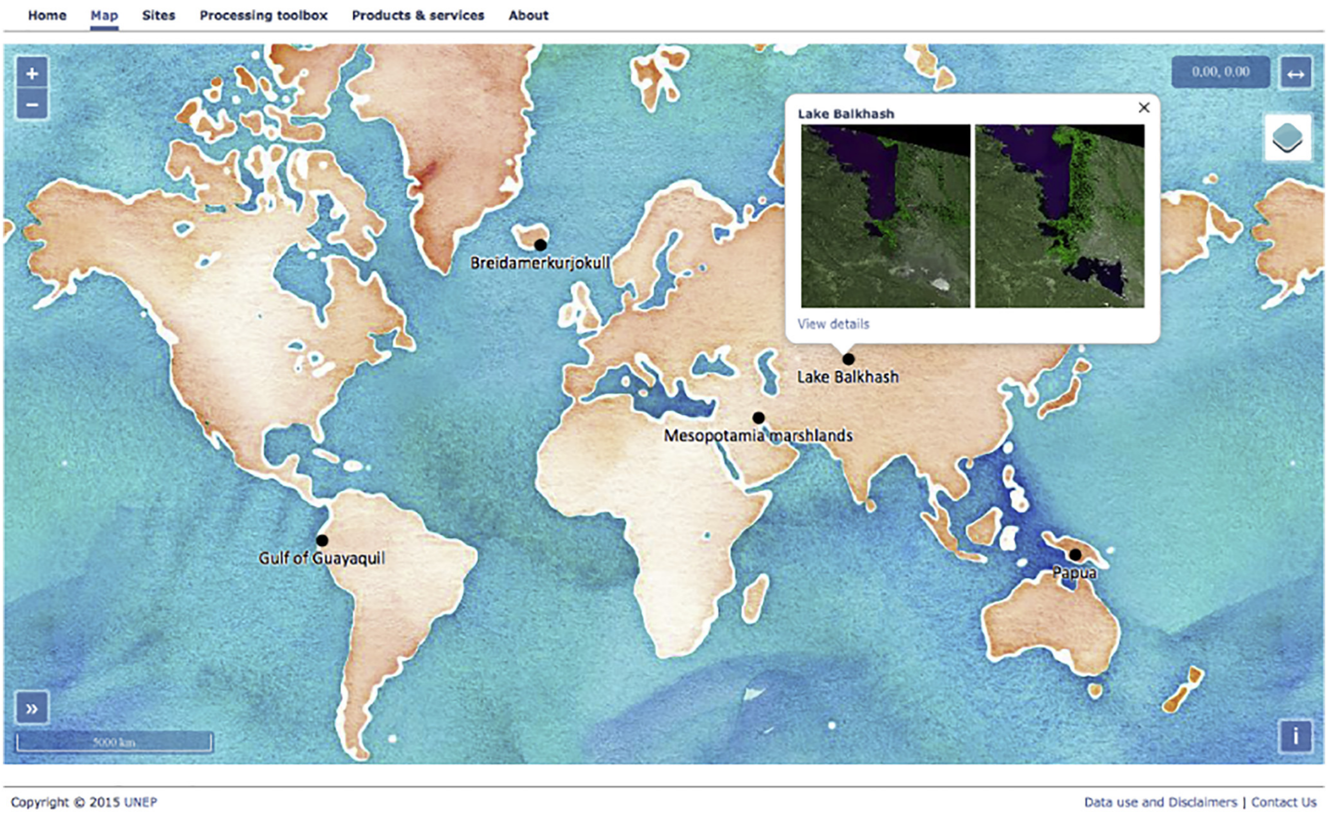

Fig. 5. The LiMES application.

Natural Sites, which are covering 280 million ha in 97 countries. Finally, it can help tracking progress towards Sustainable Development Goals on Wetlands (target 6.6) and Protected Areas (target 15.1). Hereafter, we present more in details how EO data and LiMES framework can be applied in these case studies.

3.1. Ramsar convention & wetlands

Under the Convention on Wetlands, each Contracting Party (i.e., binding agreement with one or more countries to actively support the Convention (http://ramsar.rgis.ch/cda/en/ramsar-about-parties/main/ramsar/1-36-123_4000_0__)) undertakes to designate at least one wetland site for inclusion in the List of Wetlands of International Importance (http://www.ramsar.org/document/the-list-of-wetlands-of-international-importance-the-ramsar-list). In May 2016, according to the Ramsar Sites Information Service (RSIS – https://rsis.ramsar.org) there were 2240 “Ramsar Sites” (RS) on the territories of over 169 Ramsar Contracting Parties across the world.

Designating a wetland on the Ramsar List is a complex process requiring frequent interactions between the Ramsar regional teams and the Contracting Parties. Site managers and local authorities continuously need to work towards managing, monitoring and preserving the ecological character of the Ramsar Site.

The periodic RS updating process provides an assessment of the application of the Ramsar Convention by the States Parties. It also provides


Landsat 5 - 27.03.1985

Landsat 7 - 23.11.2000

Landsat 8 - 25.01.2015

Fig. 6. The side-by-side comparison for the Gulf of Guyaquil (Ecuador) showing the impacts of fish farming between 1985 and 2015. Fishfarming areas are represented in light blue in the middle of the images. The loss of mangroves (in green) and growth of the aquaculture industry can be seen along the coast and in the altered dendritic patterns (branching like a tree) of coastal waterways. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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updated information about the sites in order to register potential changes in the state of conservation of sites.

The monitoring covers the assessment of the use of the sites, the status of its conservation (biodiversity, hydrology and biophysical environment), the assessment of the impacts from any driver of change, including deforestation, climate change, urbanization, or pollution.

For Wetlands of International Importance (‘Ramsar Sites’) designated under the Ramsar Convention, the ecological character of some 8% of the 2240 Sites (as of May 2016) were reported to have changed, is changing or is likely to change as the result of technological developments, pollution or other human interference. Moreover, the basic background data for another 58% of the Sites was significantly out of date or was missing so that it was not possible to assess if changes had taken place or not.

The tasks for monitoring include updating the Ramsar Information Sheet; providing Standing Committee meetings with documents on Ramsar Sites Status (once a year); regular exchanges with Contracting Parties and partners to update a tracking sheet on Ramsar Sites; and national reports for COPs (one each three year).

Considering the significant number of Ramsar Sites worldwide and limited opportunities to visit many sites each year, the work of the Secretariat staff in site monitoring is restricted to mainly receiving reports from the Contracting Parties or 3rd Parties regarding change (past, present or future) that has/is/will take place in the wetland. Whereas the monitoring of sites is based essentially on observations reported by the Parties, there are issues associated with differences in the quality of assessment between sites (hence low comparability) and the quality of the information reported. Some assessments may overstate the threat while other reports may understate it.

Other important limitations include the inability to assess all sites on a regular basis, the delay in receiving report of threats, late warnings and the difficulty to assess the extension of the changes in the ecological characters.

EO including time series at regular intervals can be used to provide information relating to changes in (1) the area of the wetland, (2) the vegetation cover around and in the wetland, and (3) of human activities that may affect the wetland.

One example is the Lake Balkhash located in Kazakhstan (http://limes.grid.unep.ch/sites_desc.html?id=0). The lake is a very important resource for the surrounding population. Water from the lake and its tributary rivers is used for irrigation as well as for municipal and industrial purposes, including supplying the water needed by the Balkhash Copper Melting Plant. While fishes from the lake are an important food source, artificially low water prices have encouraged excessive use and waste of lake water. The United Nations has warned that Lake Balkhash, which is the second largest lake in Central Asia after the Aral Sea, could dry up if current trends are not reversed (Thevs et al., 2017). The LiMES methodology has been used to process a series of Landsat images from 1993 to 2014 showing a shrinking of the lake in the 90s and a recovery starting from the year 2000 with water flowing again in the lake and wetlands/marshlands reappearing (Fig. 7).

The remote sensing contribution can also assist where the spatial information is incomplete or completely absent, as in the case of lack of land use data, issues of sites boundaries, lack of reliable maps of the sites and their surrounding area.

Other important contributions offered include an actual support for the quantification of the environmental status of the watershed as well as an effective monitoring plan (ecology, hydrology and socio-economic) of the sites and their watershed.

Consequently, the LiMES framework can be a valuable contribution to (1) assess conditions of Ramsar Sites and monitor trends over time; (2) identify and delineate Ramsar Sites areas over large river catchments; (3) analyse the intra- and inter-annual variations of the water surfaces, inside and around Ramsar Sites, and (4) monitor aquatic pollution and physical disturbances of water bodies within Ramsar Sites.

3.2. IUCN & protected areas

One of the roles of the International Union for Conservation of Nature (IUCN) is to ensure the preservation and conservation of the UNESCO natural world heritage sites. There are 229 sites covering over 280 million ha of land and sea, which are globally recognized as the World's most important protected areas.

By a complete review and critical analyses of the available information, IUCN adopts both a reactive and pro-active approach in order to identify threats to ecosystems early, evaluate the current state of conservation and ensure a sustainable site management. Until recently issues were exclusively identified by the examination of problems

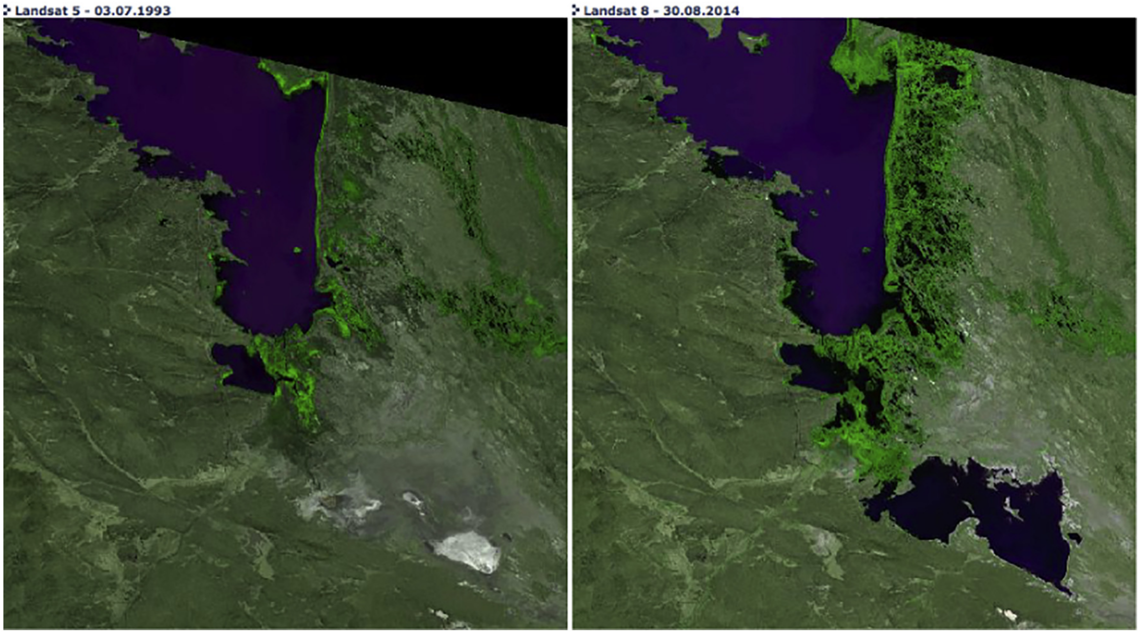

Fig. 7. The lake Balkhash that almost disappeared in 1993 (left image) and in 2014 (right) where water is flowing again (in dark blue) and wetlands/marshlands (in light green) are reappearing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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raised by media reports or relevant stakeholder. However remote sensing monitoring is under consideration on a few pilot sites.

When an issue has been identified, recommendations are addressed to the World Heritage Committee secretariat and land cover changes are monitored until they are no longer considered as a threat.

According to a recent WWF report (WWF, 2016), despite the attention paid to these sites through the UNESCO world heritage convention, nearly 50% of the sites are at risk from harmful industrial activities. Moreover, ecosystem degradation could affect millions of people living nearby, which are dependent on the services they provide for their livelihoods and well-being. The main threats are overfishing, oil and gas exploitation, illegal logging, large-scale industrial infrastructure (i.e. highways, railways…), mining concessions, poorly managed water use, etc. But often, threats result from a combination of multiple harmful activities.

The sustainable management of world heritage sites and more broadly protected areas could play a key role in the Sustainable Development Goals (SDG) by supporting local communities in the long term and globally by mitigating climate change effects.

For a given area to be monitored, being able to access a time-series of processed images according to user requirements (e.g., algorithm to apply, type of sensor) can facilitate and improve the sustainable management of the natural protected areas. The new ideal tool/application should also provide comprehensive, consistent and accurate land cover information, at different scales, over time. An improved detection mechanism of changes will allow early detection of both natural and anthropogenic disturbances.

The advantages of such an approach will be the homogenization of practices, improving comparability and the ability to monitor developments independently (without consulting States Parties and stakeholders) accelerating the monitoring process.

4. Discussion

The LiMES framework is, to our knowledge, among the first attempt to provide a globally consistent tool for spatial and temporal monitoring of environmental changes (e.g., land cover) entirely based on interoperable components. Probably the closest effort is represented by the H2020 EU-funded project called Satellite-based Wetland Observation Service (SWOS - http://swos-service.eu) continuing the efforts of GlobWetlands I and II projects. However, SWOS differs from LiMES that it is developing mostly desktop software components and it is not based on interoperable data access and processing capabilities. Moreover, it has been designed for one thematic area, namely wetlands, whereas LiMES is based on a modular design in order to adapt to different users' requirements. The proposed approach was developed as a proof-of-concept and tested over five sites analysing 10.5 GB of Landsat medium resolution images in 20 min. The successful implementation showed benefits, limitations and the need for further developments that will be further discussed in the next sections.

4.1. Benefits

The major benefit from the LiMES framework is that it enables interoperability along the entire Data Value Chain. It helps bridging the gap between large volumes of EO data and the people that want to use it to tackle key environmental challenges. It increases and facilitates data supply, access, processing and delivery. In particular, it helps transforming raw data into information and knowledge by translating expert knowledge into workflows using interoperable processing services chains.

The proposed framework helps to overcome some challenges related to different dimensions of Big Earth Observations Data: (1) it helps processing large Volumes of EO data; (2) in terms of Velocity, it is able to process a new scene for a defined location as soon as it is available in data repositories; (3) the proposed approach enables ingesting a Variety of sensors. The prototype currently accesses Landsat data and some tests have already been made to access the Sentinel(s) repository. Adding additional freely accessible repositories such as ASTER or SPOT would be easy. Other dimensions can be also tackled throughout the platform like Veracity (e.g., ground truth, citizen/participatory science), an enhancement of the Value of Big EO Data repositories, the facilitation of Visualization, and the capture of the Variability of a change occurring in a specific location.

From a technical perspective, the fact that the platform is entirely based on interoperable components enhance the reusability and modularity of the provided services allowing the development of tailored processing workflows to extract useful information answering the monitoring needs of specific scientific communities. Moreover, such an approach enhances usability, performance, and scalability. It enables efficient processing of near-real time data (e.g., near-real time monitoring) and increases transparency and comparability because all processes and data sources are documented. Finally, it can facilitate communicating results to end-users with the story maps module allowing the presentation of some relevant results in a consistent, dynamic, and thematic-oriented story.

Ultimately, the LiMES framework can strengthen the relevance of Big EO Data for issues at the science-policy interface addressing among others the challenges of quantifications, transparency, and accountability for environmental monitoring. By its modular and interoperable design, it helps providing tailored services and therefore can increase monitoring capacities of institutions like the Ramsar Convention, IUCN and UNEP. Consequently, it can help institutions to move towards the Big Data revolution, by supporting Data for Development with a viable alternative to complement traditional statistics using EO data that can deliver more frequent updates, and demonstrate that EO can support International Organizations (IO) and Multilateral Environmental Agreements by contributing to monitoring activities and indicators generation required by initiatives such as the Sustainable Development Goals (Sustainable Development Solutions Network et al., 2015).

4.2. Challenges

Even if the proposed approach can bring several promising benefits to facilitate environmental monitoring using EO data, there are also several issues that need to be tackled.

To increase the ability to access and use EO data, the most important challenge concerns the development of capacities. Capacity building encompasses three levels: (1) Human (i.e., educating and training people to access and use EO resources); (2) Institutional (i.e., foster the use of EO to enhance decision-making); (3) Infrastructure (i.e., hardware, software, and technology required to access and use EO resources) (Giuliani et al., 2013). By developing such capacities in remote sensing, people will be able to provide guidance on the interpretation of imagery presented in system such as LiMES and enhance the relevance of EO to support decision-making.

Another significant challenge relates to Big Data management, storage, and processing performances. Distributed and high performance computing are solutions that can certainly help to solve this issue (Rodila et al., 2015).

An important aspect is the communication of data quality and uncertainty as it can strongly influence decisions and policy design (Otto et al., 2015). Emerging standards such as WMS-Q, QualityML, and UncertML can be the basis for a standardized and interoperable approach for environmental monitoring (Bastin et al., 2013).

Another issue relates to the access of heterogeneous EO data repositories. Indeed, the proposed framework can integrate various sensors such as Landsat, Sentinels, ASTER, using dedicated APIs developed by data providers. However, this requires to programmatically handle in the backend several APIs that can differ significantly. One promising solution promoted by the Global Earth Observation System of Systems

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(GEOSS) is a brokering framework enabling interconnection of hundreds of heterogeneous resources published by different data providers by mediating different standards used by different scientific communities, and adapting them to interfaces commonly used by users of these resources (Nativi and Bigagli, 2009; Nativi et al., 2013; Nativi et al., 2015). This facilitates cross and multi-disciplinary discovery, access and use of disparate data and information through a consistent and harmonized interface known as the GEO Data and Access Broker (DAB). GEO DAB is an essential component of the GEOSS Common Infrastructure (GCI) that transparently connects user's requests to resources shared by providers. In order to programmatically use the DAB functionalities, a set of APIs (http://api.eurogeoss-broker.eu) is provided, greatly simplifying the development of applications that require access to a diversity of EO resources.

From an interoperability perspective, being syntactically interoperable is only the first step towards full interoperability. However, to be fully interoperable, semantic interoperability is a major issue to tackle. Being semantically interoperable enables computer systems to exchange data with unambiguous shared meaning, enabling machine logic, inferencing, knowledge discovery and data federation between information systems (Hitzler and Janowicz, 2013; Kazmierski et al., 2014; Mihon et al., 2015; Nativi et al., 2015).

Finally, other issues range from how to generate appropriate algorithms to process large number of images that suit a wide range of ecosystems taking into account seasonality, handling mosaicking and cropping, or using correctly the information that has been generated (e.g., maps useful for general trends should not be used individually, or out of context).

4.3. Perspectives

The proposed methodology was developed as a proof-of-concept and the implementation was successful. The greatest prospect is to apply the LiMES framework at large scale with international institutions or programmes to increase knowledge on Wetlands (e.g., Ramsar), Protected Areas (e.g., IUCN), Cultural Heritage Sites (e.g., UNESCO), Environmental Hotspots (e.g., UNEP), Deforestation (e.g., UN-REDD) or Humanitarian/Disaster rapid mapping (e.g., UNOSAT) and leverage the monitoring capabilities of Big EO Data repositories. This will require in particular adding new data repositories (e.g., SPOT, Sentinel 3); generate dedicated algorithms and tailored interoperable processing workflows; and consolidate the processing toolbox to enable users delineate new sites to be processed with several options depending of the type of the ecosystems.

From our point of view, the LiMES framework can be also extended to operate as an Early Warning Monitoring System. Indeed, the following functionalities are already available or can be easily implemented: (1) Full automation, (2) full exploitation of available information (large amount of free available satellite images underexploited), (3) high number of analyses should allow auto-calibration (without considering outliers), (4) tool for preprocessing images, (5) continuous monitoring should enhance a better tracking of the human activities for a sustainable management of this natural resources, (6) wide distribution of information through web applications should contribute to encourage ecosystem services valuation (e.g., InVEST models can be published as WPS) and their preservation.

Finally, the LiMES platform could be a useful tool for citizen science. Indeed, through a Massive Online Open Course (MOOC) hundreds of people could be trained and provided with the appropriate instructions to operate the LiMES tool for producing an assessment on the status of the 2240 Ramsar Wetlands, the 229 IUCN World Heritage or the 278 UNEP Environment Hotspots. Using participatory science, the MOOC participants could be able to upload their assessments into the platform. After peer-reviewing processes, the results could be ranked from high to low priorities, in order to help IUCN, Ramsar and UNEP in assessing the status of their sites.

5. Conclusions

The Live Monitoring of Earth Surface (LiMES) framework provides a globally consistent tool for spatial and temporal monitoring of cumulative land cover changes which can be used by non-remote sensing experts for basic impacts assessments of sites. It helps reducing the gap between massive volumes of EO data and the people that want to use it. The information generated through LiMES can deliver valuable insights to track, visualize, analyse, understand, and communicate environmental changes. It enables rapid access and analysis of EO Big Data repositories and demonstrates the benefits of using interoperable processing services chains for remote sensing applications. The combination of large storage capacities with high performance computers together with interoperable solutions has enabled a scalable, consistent and efficient analysis environment that can be applied on various thematic through decades of data. Such an approach can significantly increase the Data Value Chain and can facilitate extracting information and knowledge from Big EO Data. This method shows that it is operationally feasible and can leverage the information potential of EO Data to monitor environmental changes in any place of the World.

By collaborating with institutions that have environmental monitoring mandates, the LiMES framework can support them in getting ready for Data for Development and the Big Data revolution; demonstrate the use of EO for supporting International Organizations (IO)/Multilateral Environmental Agreements (MEA) in implementation of the 2030 Agenda on Sustainable Development, help to increase the monitoring capacity of institutions; and finally enhance the relevance of EO for issues at the science-policy interfaces by addressing (among others) the challenges of quantification (via estimates of changes in the areas of different cover types), transparency, and accountability for environmental monitoring.

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References

Bastin, L., Cornford, D., Jones, R., Heuvelink, G.B.M., Pebesma, E., Stasch, C., Nativi, S., Mazzetti, P., Williams, M., 2013. Managing uncertainty in integrated environmental modelling: the UncertWeb framework. Environ. Model. Softw. 39, 116–134.

Brown, M.E., Carroll, M.L., Escobar, V.M., 2014. User needs and assessing the impact of low latency NASA Earth observation data availability on societal benefit. Space Policy 30 (3, Part A), 135–137.

Burt, J., Smith, B., 2012. Deep space climate observatory: the DSCOVR mission. 2012 IEEE Aerospace Conference.

Čepický, J., de Sousa, L.M., 2016. New implementation of OGC Web Processing Service in Python programming language. PyWPS-4 and issues we are facing with processing of large raster data using OGC WPS. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLI-B7, pp. 927–930.

Craglia, M., Goodchild, M.F., Annoni, A., Camara, G., Gould, M., Kuhn, W., Mark, D., Masser, I., Maguire, D., Liang, S., Parsons, E., 2008. Next-Generation Digital Earth: a position paper from the Vespucci Initiative for the Advancement of Geographic Information Science. Int. J. Spat. Data Inf. Res. 3, 22.

Craglia, M., de Bie, K., Jackson, D., Pesaresi, M., Remetey, F., Remetey-Fülöpp, G., Wang, C., Annoni, A., Bian, L., Campbell, F., Ehlers, M., van Genderen, J., Goodchild, M., Guo, H., Lewis, A., Simpson, R., Skidmore, A., Woodgate, P., 2012. Digital Earth 2020: towards the vision for the next decade. Int. J. Digital Earth 5 (1), 4–21.

Descloitres, J., Sohlberg, R., Owens, J., Giglio, L., Justice, C., Carroll, M., Seaton, J., Crisologo, M., Finco, M., Lannom, K., Bobbe, T., 2002. The MODIS rapid response project. IGARSS: IEEE International Geoscience and Remote Sensing Symposium, Toronto, Canada, pp. 1191–1192.

Dixon, M.J.R., Loh, J., Davidson, N.C., Beltrame, C., Freeman, R., Walpole, M., 2016. Tracking global change in ecosystem area: the Wetland Extent Trends index. Biol. Conserv. 193, 27–35.

Eerens, H., Haesen, D., Rembold, F., Urbano, F., Tote, C., Bydekerke, L., 2014. Image time series processing for agriculture monitoring. Environ. Model. Softw. 53, 154–162.

Please cite this article as: Giuliani, G., et al., Live Monitoring of Earth Surface (LiMES): A framework for monitoring environmental changes from Earth Observations, Remote Sensing of Environment (2017), http://dx.doi.org/10.1016/j.rse.2017.05.040

FAO, 2010. Global Forest Resources Assessment 2010. FAO, United Nations. Food and Agriculture Organization of the United Nations, Rome, p. 378.

GEO Secretariat, 2004. From Observation to Action - Achieving Comprehensive, Coordinated, and Sustained Earth Observations for the Benefit of Humankind: Framework for a 10-year Implementation Plan. p. 7 (Geneva, Switzerland).

GEO Secretariat, 2011. How GEOSS Supports Decision Making in Nine Societal Benefit Areas (SBAs). p. 2 (Geneva, Switzerland).

GEO Secretariat, 2015. The Contributions of Earth Observations in Achieving the Post-2015 Development Agenda. p. 3 (Geneva, Switzerland).

Giuliani, G., Ray, N., Lehmann, A., 2013. Building regional capacities for GEOSS and INSPIRE: a journey in the Black Sea catchment. Int. J. Adv. Comput. Sci. Appl. 19–27 (EnviroGRIDS Special Issue on "Building a Regional Observation System in the Black Sea Catchment").

Gore, A., 1998. The Digital Earth: understanding our planet in the 21st Century. Aust. Surveyor 43 (2), 89–91.

Hitzler, P., Janowicz, K., 2013. Linked data, big data, and the 4th paradigm. Semantic Web 4 (3), 233–235.

IEAG, 2014. A World That Counts: Mobilising the Data Revolution for Sustainable Development. United Nations, New York, p. 32.

Kazmierski, M., Desconnets, J.-C., Guerrero, B., Briand, D., 2014. GEOSUD SDI: accessing Earth Observation data collections with semantic-based services. AGILE'2014 International Conference on Geographic Information Science. Springer:, Castellon, Spain.

Klemas, V., 2011. Remote sensing of sea surface salinity: an overview with case studies. J. Coast. Res. 27 (5), 830–838.

Lewis, A., Lymburner, L., Purss, M.B.J., Brooke, B., Evans, B., Ip, A., Dekker, A.G., Irons, J.R., Minchin, S., Mueller, N., Oliver, S., Roberts, D., Ryan, B., Thankappana, M., Woodcock, R., Wyborn, L., 2016. Rapid, high-resolution detection of environmental change over continental scales from satellite data - the Earth Observation Data Cube. Int. J. Digital Earth 9 (1), 106–111.

Michael, K., Murphy, K., Lowe, D., Masuoka, E., Vollmer, B., Tilmes, C., Teague, M., Ye, G., Maiden, M., Goodman, H.M., Justice, C., 2010. Implementation of the Land, Atmosphere Near Real-time Capability for EOS (LANCE). 2010 IEEE International Geoscience and Remote Sensing Symposium.

Mihon, D., Bacu, V., Colceriu, V., Gorgan, D., 2015. Modeling of Earth Observation use cases through KEOPS system. 2015 IEEE International Conference on Intelligent Computer Communication and Processing (ICCP).

Miller, H.G., Mork, P., 2013. From data to decisions: a value chain for big data. IT Prof. 15 (1), 57–59.

Nativi, S., Bigagli, L., 2009. Discovery, mediation, and access services for earth observation data. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sen. 2 (4), 233–240.

Nativi, S., Craglia, M., Pearlman, J., 2013. Earth science infrastructures interoperability: the brokering approach. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 6 (3), 1118–1129.

Nativi, S., Mazzetti, P., Santoro, M., Papeschi, F., Craglia, M., Ochiai, O., 2015. Big Data challenges in building the Global Earth Observation System of Systems. Environ. Model. Softw. 68 (0), 1–26.

Open Geospatial Consortium, 2006a. OpenGIS Web Map Server Implementation Specification. p. 85.

Open Geospatial Consortium, 2006b. Web Coverage Service (WCS) Implementation Specification. p. 143.

Open Geospatial Consortium, 2007. OpenGIS Web Processing Service. p. 87.

Ostensen, O., O'Brien, D., Cooper, A., 2008. Measurements to know and understand our world. ISO Focus (February), 35–37.

Otto, F.E.L., Frame, D.J., Otto, A., Allen, M.R., 2015. Embracing uncertainty in climate change policy. Nat. Clim. Chang. 5 (10), 917.

Petrou, Z.I., Manakos, I., Stathaki, T., 2015. Remote sensing for biodiversity monitoring: a review of methods for biodiversity indicator extraction and assessment of progress towards international targets. Biodivers. Conserv. 24 (10), 2333–2363.

Rodila, D., Ray, N., Gorgan, D., 2015. Conceptual model for environmental science applications on parallel and distributed infrastructures. Environ. Syst. Res. 4 (1), 1–16.

Roy, D.P., Wulder, M.A., Loveland, T.R., Woodcock, C.E., Allen, R.G., Anderson, M.C., Helder, D., Irons, J.R., Johnson, D.M., Kennedy, R., Scambos, T., Schaaf, C.B., Schott, J.R., Sheng, Y., Vermote, E.F., Belward, A.S., Bindschadler, R., Cohen, W.B., Gao, F., Hipple, J.D., Hostert, P., Huntington, J., Justice, C.O., Kilic, A., Kovalskyy, V., Lee, Z.P., Lymbumer, L., Masek, J.G., McCorkel, J., Shuai, Y., Trezza, R., Vogelmann, J., Wynne, R.H., Zhu, Z., 2014. Landsat-8: science and product vision for terrestrial global change research. Remote Sens. Environ. 145, 154–172.

Ryan, B., 2016. The benefits from open data are immense. Geospat. World 72–73.

Sachs, J.D., 2012. From millennium development goals to sustainable development goals. Lancet 379 (9832), 2206–2211.

Schmidt, G., Jenkerson, C., Masek, J., Vermote, E., Gao, F., 2013. Landsat ecosystem disturbance adaptive processing system (LEDAPS) algorithm description. U.S. Geological Survey Open-File Report 2013-1057. U.S. Geological Survey, Reston, VA, p. 27 U.S. Geological Survey: Reston, VA.

Skidmore, A., Pettorelli, N., Coops, N.C., Geller, G., Hansen, M., Lucas, R., Mücher, C.A., O'Connell, B., Paganini, M., Pereira, H.M., Schaepman, M., Turner, E.W., Wang, T., Wegmann, M., 2015. Environmental science: agree on biodiversity metrics to track from space. Nature 523 (7561), 403–405.

Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of materials use: a socioeconomic and geophysical analysis. Ecol. Econ. 69 (5), 1148–1158.

Sustainable Development Solutions Network, Paris 21, UNIDO, UNICEF, OpenData Watch, Simon Fraser University, Center for International Earth Science Information Network, World Bank, 2015. Data for Development: A Needs Assessment for SDG Monitoring and Statistical Capacity Development. p. 82 (New York, USA).

Thevs, N., Nurtazin, S., Beckmann, V., Salmyrzauli, R., Khalil, A., 2017. Water consumption of agriculture and natural ecosystems along the Ili River in China and Kazakhstan. Water 9 (3), 207–222.

Turner, B.L., Kasperson, R.E., Meyer, W.B., Dow, K.M., Golding, D., Kasperson, J.X., Mitchell, R.C., Ratick, S.J., 1990. Two types of global environmental change. Glob. Environ. Chang. 1 (1), 14–22.

UNEP, 2005. One Planet Many People, Atlas of Our Changing Environment. U. N. E. Programme. United Nations Environment Programme, Nairobi, p. 322.

United Nations, 2012. The Future We Want. A/RES/66/288. U. Nations, New York, p. 53.

United Nations, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. A/RES/70/1. U. Nations, New York, p. 35 (A/RES/70/1).

Vermote, E.F., Tanré, D., Deuzé, J.L., Herman, M., Morcette, J.-J., 1997. Second simulation of the satellite signal in the solar spectrum, 6S: an overview. IEEE Trans. Geosci. Remote Sens. 35 (3), 675–686.

Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C.J.A., Buytaert, W., 2015. Web technologies for environmental Big Data. Environ. Model. Softw. 63, 185–198.

WWF, 2016. Protecting People Through Nature: Natural World Heritage Sites as Drivers of Sustainable Development. Dalberg Global Development Advisors, Switzerland, p. 76.

Zhu, Z., Wang, S., Woddcock, C.E., 2015. Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. Remote Sens. Environ. 159, 269–277.

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