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Definition of candidate Essential Variables for the monitoring of mineral resource exploitation

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ABSTRACT

The practice of raw material extraction has a high impact on the environment and represents a potential threat to the health and thriving of local communities. The concept of Extractive Essential Variables (EEVs) are explored in order to propose variables that can be used to quantify the environmental footprint of mineral extraction. Considering the interdependence of mining activities with social, economic and environmental issues, the variables target the development of monitoring tools for the implementation of the Sustainable Development Goals (SDGs). The identification of EEVs is based on the use of Earth Observation products in the field of mineral resources exploitation. A list of variables is proposed based on three classes of Essential Variables (EVs): installation and exploration phase, mineral extraction, and ore processing. These variables take into account the impacts of mining on the hydrology, land, water resources and the atmosphere of the area subjected to mineral exploitation. One of the variables is implemented as an operational workflow addressing SDG15, “life on land”. The workflow is intended to assess the area of forest ecosystem lost due to the presence of a mining site. Geospatial data on the extent of mining concessions and forest cover are combined using ArcGISTM. The workflow is successively translated into a Unix script to automatize the process of data treatment. The script is developed using the Geospatial Data Abstraction Library (GDAL). The use of a Virtual Laboratory Platform (VLab), a web-service-based access platform, increases the accessibility of data and resources and the re-use of the script. This work is a first attempt to propose a framework of EEVs, derived data workflows, while the underlying methodology, partially based on scientific publications and on personal reasoning, still needs to be tested and, improved based on expertise in the sector.

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1. Introduction

The extraction of minerals from natural deposits has been a constant in the history of humankind and one of the pillars supporting the economic and technological development from which we benefit today (Ray et al. 2016). Nevertheless, mineral extraction comes with a cost often neglected due to the major benefits generated by this industry. In the form of raw materials or processed ores, minerals are present in every aspect of daily life and the continuous demand for them fuels the quest for new territories to exploit at the expense of natural ecosystems, often generating land-use conflicts with existing soil occupation (Lacroix et al. 2019; Atibu et al. 2018). The extraction and processing of minerals are connected with sustainability issues related to the use of natural resources, especially when aiming to guarantee the integrity of such resources for the benefit of future generations (IIED 2002). Therefore, the need to include sustainable practices in the extractive field is

a prerequisite for the viability of this industry (Lindahl 2014; Drielsma et al. 2016).

The degree and extent of environmental impacts are dependent on the size, type and location of the deposit, which contribute to determining the extraction and processing methods employed to access the mineral (Azapagic 2004; Awuah-Offei and Adekpedjou 2011; Ferreira and Garcia Praça Leite 2015). Additionally, the level of technological development, the social and economic context of the region, as well as the guiding principles of the extractive company in terms of sustainability, can all play a role in determining the degree of disturbance in the surrounding region. The impacts of mining activities are responsible for a deterioration of ecosystem quality, and potential decreases in productivity and integrity. The negative impacts affecting terrestrial ecosystems include: clear-cutting of vegetation (Macdonald et al. 2015), removal of soil with consequent disturbances of local flora and fauna (Van Wilgenburg et al. 2013), increased rate of erosion,

sedimentation and landslide, changes in the hydrology of the area, and risk of contamination of groundwater and superficial water resources (Akiwumi and Butler 2008; Karmakar and Das 2012; Frelich 2014; Vela-Almeida and Wyseure 2016). These and other concerns have prompted the development of strategies to efficiently address sustainability issues linked to mineral extraction in line with the United Nations Sustainable Development Goals (SDGs) and related policy frameworks. Currently few are the measures in place to reduce the footprint of extractive activities on natural systems (Azapagic 2004; Ferreira and Garcia Praça Leite 2015). The creation of a common framework aiming to assess the performance of extractive companies, is hindered by the heterogeneity of the extractive methods applied and by weak regulations over the extractive practices in terms of due diligence and compliance (Stevens et al. 2013).

To put the sustainability issues related to mineral extraction in the context of policy frameworks, the development of a standardized method for performance assessment and monitoring is required. Such activities are deeply entangled with the social, environmental and economic dimensions of sustainable development, and to fully understand the issues deriving from mineral extraction is to address the governance aspects aiming to fulfill the SDG targets (Costanza, Fioramonti, and Kubiszewski 2016). It is thus important to promote more transparent practices and facilitate access to data in relation to extractive activities. Earth Observation (EO) products have proven to be the effective resources in providing timely and accessible environmental tools and data to monitor the status of and changes in natural environments (Santo and Sanchez 2002; Bartholomé and Belward 2005; Padmanaban, Bhowmik, and Cabral 2017). The combination of remote sensing and in situ measurements, can provide information on physical, chemical and biological conditions as well as allow the characterization of a system in its entirety (Giuliani et al. 2017). The use of EO products and in particular satellite images, can facilitate the acquisition of valid data for the monitoring of extensive areas affected by a mining site and allow a better understanding of the changes affecting the different components of an ecosystem (e.g. hydrology, biodiversity). Furthermore, the temporal aspect associated with satellite images can allow for the observation of the mining site's evolution over time and the assessment of its impacts on the landscape. The adoption of EO data in the field of environmental monitoring has been used to support the concept of Essential Variables (EVs), which has been applied in the monitoring of climate, oceans and biodiversity.

According to the ConnectinGEO project, EVs represent “a set of variables that determine the system's state and developments, and allow us to define

metrics that measure the trajectory of the system” (ConnectinGEO 2016a). The concept of EVs was developed in support of the necessity for accurate and continuous information on the atmosphere, land, and oceans to monitor the Earth's climate, and understand past, current and future climate variability (Bojinski et al. 2014; Brummitt et al. 2017; Turak et al. 2016). Understanding the dynamics of ecosystems is important to efficiently manage them, and to assess where the changes are occurring, at what rate and how they will evolve in the future. Despite the concept of EV being extensively explored in the climate, ocean and biodiversity domain (Pereira et al. 2013; Reyers et al. 2017), the implementation of EVs in the extractive field has not yet been investigated.

This work is centered on the development of a framework for Extractive Essential Variables (EEVs) which potentially allows for a comprehensive assessment of the influence of mineral extraction on the surrounding landscape and related ecosystems. Different scenarios of disturbances from mining activities will be considered, and instruments for their monitoring will be proposed. Geographic Information Systems (GIS) and spatial datasets will represent a support to the implementation of extractive indicators and translated into operational workflows. The outputs deriving from these workflows could generate cartographic products, timely dashboards and supporting material for decision makers and stakeholders to facilitate the understanding of environment-related issues connected to mineral extraction. Environmental indicators for the extractive industry could represent the final output of a process aiming at unifying field-based observations and the political will for sustainable and conscious use of natural resources for environmental welfare.

2. Development methodology of Extractive Essential Variables

2.1. The concept of Essential Variables

In accordance with the definition of EVs provided by ConnectinGEO (see above), the concept of EVs put the focus on the key elements of a system in order to identify essential dimensions of natural system changes and to incorporate monitoring efforts into an efficient natural system management framework (Reyers et al. 2017). EVs represent the element translating primary observations (e.g. raw data, Earth Observation products) into useful information needed at various scales of decision-making (Pereira et al. 2013). They have assumed the role of monitoring tools in the context of policy implementation and compliance (Geijzendorffer et al. 2015; Blonda et al. 2016). By defining a set of minimum social,

environmental and economic measurements, it is possible to derive multiple indicators used to measure the progress made towards the implementation of the SDG targets (Stafford-Smith et al. 2017; Convention on Biological Diversity 2013).

Originally conceived to better monitor the trends and changes occurring at the level of global climate, the concept of EVs has been extended to other research groups focused on characterizing the Earth's system and its components (e.g. atmosphere, hydrosphere, biosphere, land). This allows to obtain a complete image on the state of important environmental variables and to capture critical dimensions of the Earth system (Reyers et al. 2017). Progress has been made in ocean monitoring to develop Essential Ocean Variables (EOVs) for understanding the ocean and its dynamics (Constable et al. 2016). Essential Biodiversity Variables (EBVs) were developed by the Group on Earth Observations Biodiversity Observation Network (GEO BON) to produce variables for assessing the trends and rates of change in global biodiversity. Analogously to EOVs and EBVs, other communities are now working towards the development of EVs in areas such as Water, Agriculture, Ecosystems, Energy, Health, Disasters, and Weather (GEO 2014; ConnectinGEO 2016a; Anderson et al. 2017).

Despite the general acceptance of EVs, the lack of homogeneous and continuous data on natural systems represents an ongoing limitation towards their further development. Considering the differences existing between countries in terms of technological and monitoring efforts, it is important to define achievable sets of measurements for environmental monitoring, to guarantee a shared and unified monitoring system in the different environmental fields (Stafford-Smith et al. 2017). The suggested criteria for the development of EVs are as follows (Bojinski et al. 2014):

- **Relevance.** The variable is critical for characterizing the climate system and its changes;
- **Feasibility.** Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods;
- **Cost effectiveness.** Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

2.2. EEVs as an instrument to monitor the impacts of mineral extraction

Despite the potential of mining activities to alter the surrounding environment and to influence the socio-economic realities of the region, the concept of EEVs is still in its early stages. There are numerous studies

targeting the impacts of extraction on the fauna and flora and the disruption of land and aquatic ecosystems (Santo and Sanchez 2002; Van Wilgenburg et al. 2013; Frelich 2014; Macdonald et al. 2015; Padmanaban, Bhowmik, and Cabral 2017; Castro Pena et al. 2017). And there are the indicators aiming to assess the impacts of the mineral industry (Azapagic 2004; Marnika, Christodoulou, and Xenidis 2015). Nonetheless, the lack of common practices in the monitoring system, and in the type, quality, and availability of data, facilitate uncoordinated monitoring and the proliferation of different indicators, hindering coherence and efficiency (Reyers et al. 2017). By introducing the concept of EEVs, we aim to facilitate the harmonization of existing monitoring instruments in the extractive industry and guide the development of a comprehensive global observation system in support of decision-making.

Although extraction and processing of minerals are tightly linked to the local socio-economic context, for this study, the focus is placed on the development of indicators that assess the impact of mineral extraction on natural environments. This decision was taken firstly due to the limited expertise of the research group on social and economic issues, and secondly due to the complexity in finding reliable data on which indices addressing these subjects may be based. Companies are hesitant to provide information about environmental and economic risks their business may represent for the region of interest (Yoo and Nam 2015). An example is represented by the mine closure obligations which include the provisions for decommissioning and rehabilitation. Despite the companies' obligation to provide reports relative to the decommissioning of the site, management can decide to withhold disclosure of information to protect their reputation (Ferguson and Walker 2011). This and other loopholes in the due diligence requirements that are placed on companies by the country-specific legislation for mineral exploitation can jeopardize the availability of valuable information on the social and economic impacts of mining at a regional level (Sturdy and Cronje 2017). In addition, the diversified practices and the way each company provides information relative to its activities may obstruct the creation of relevant and large-scale applicable indicators for the social and economic impacts of mineral extraction.

The approach chosen for the development of environmental indicators is inclusive of the relationships and interactions existing between different subsystems of the Earth. Considering the crossed domain nature of these fields, the EVs developed for one system (EOVs and EBVs) can be used for the development of EEVs. The EEVs were proposed based on their relevance, feasibility, and cost-effectiveness. They are relevant for helping to answer questions like "What is changing? Why is it changing? What

are the consequences?”. They are sensitive to change for being able to repeatedly measure the state of the system over time, and scalable considering that EO products and geospatial datasets can be applied at the local, regional and global scale (depending on the availability of national cadaster data). They are feasible in the sense that they allow for measurement independently from the technological development of the particular country, and inclusive of the cost – which should not be precluding.

2.3. EEVs framework

When considering the different stages implemented in the extractive process, the most negative in terms of impacts on the natural ecosystems are the exploration phase and installation of the mining site, the extraction of the mineral, and the ore processing (Azapagic 2004; Awuah-Offei and Adekpedjou 2011; Durucan, Korre, and Munoz-Melendez 2006). The processes related to the installation of the mining site are associated with the construction of roads and mining facilities which are responsible for the clear-cutting of vegetation. This reflects on direct consequences on natural habitats and their integrity. The loss and degradation of natural habitat can enhance or promote the decline in species abundance and richness, ultimately leading to the extinction of species at the local level (Ginocchio and Baker 2004; Faucon et al. 2010; Kociolek et al. 2010; Castro Pena et al. 2017). Through the development of instruments helping to translate these stressors into quantitative or qualitative metrics, it will be possible to better assess the impact of mineral extraction on the biodiversity of impacted areas. In the same way, it is possible to determine the impact of mineral extraction in terms of loss of ecosystem services and

productivity, by targeting aspects like the chemical balance of water and its availability, alterations in the chemical composition of the soil and changes in the hydrology and dynamics of the landscape.

Out of the four steps involved in the extractive process – the exploration phase, installation of the mining facilities, mineral extraction and processing, and closure and remediation of the site – only three of them were considered appropriate for the selective process of environmental indicators. This is because the closure and remediation phases are subsequent to the alteration of natural systems and thus not suitable to represent the nature of changes affecting the area. The choice of the proposed EEVs is arbitrary, and does not represent an exhaustive list able to cover all the aspects of the interaction between mineral extraction and natural environment. They were selected considering some of the most important subjects of concern highlighted in scientific publications dealing with conservation of natural ecosystems in the context of mineral extraction.

Considering all of the above, the proposed EEVs in this work were distributed into three classes or categories: installation and exploration phase, mineral extraction, and ore processing (as shown in Table 1). The reasoning behind the selective process was driven by three questions: “Why is it changing?”, “How is it changing?”, and “What are the consequences?”. Through these questions, it was possible to break up the phases involved in the extraction process and understand at what level they interact with the surrounding natural environment. As a consequence, we were able to select aspects of an ecosystem susceptible to changes and determine possible indicators for the assessment of these impacts.

The first class of EEVs considers some of the impacts deriving from the explorative phase and

Table 1. Office word 2016/PC.

Group of EEVs	EEV category (function of the ecosystem which is affected)		EEV
1. Variables related to the installation of the mining site	Land	1.1 Ecosystem structure 1.2 Sensitive species 1.3 Avian species 1.4 Terrestrial species 1.5 Forest 1.6 Land use and agriculture 1.7 Species habitat	1.1 Degree of fragmentation 1.2 Extinction risk index 1.3 Population abundance 1.4 Population abundance 1.5 Surface of forest lost 1.6 Surface of crop lost 1.7 Surface of natural habitat lost
2. Variables related to the extraction method	Water resources/ Hydrology	2.1 Mining related water use 2.2 Groundwater 2.3 Lakes and superficial water	2.1 Data on water extraction per year 2.2 Groundwater volume changes 2.3 Changes in water surface, lake extent
	Atmosphere	2.4 Atmospheric composition	2.4 Content of greenhouses gas and/or pollutants
3. Variables related to the ore processing technique	Land Water resources	3.1 Soil chemical pollution 3.2 Groundwater	3.1 Changes in soil chemical composition 3.2 Groundwater chemical pollution

the settlement of the mining site. Both of these processes are responsible for changes in the ecosystem structure directly affecting natural habitats. This category will contain indicators relative to habitat fragmentation, changes in abundance of avian, terrestrial and endemic species. The second class of EEVs revolves around the mineral extraction process. The extraction method varies according to the nature of the mineral deposit, and the mineral to be extracted can lead to different impacts on the ecosystems (Frelich 2014; Ferreira and Garcia Praça Leite 2015). By identifying EVs within this category, it will be possible to develop indicators to monitor changes in the hydrology of the area and the chemical composition of the atmosphere. The third class of EEVs will target the ore processing methods and some of the deriving impacts such as water and soil pollution.

2.4. Proposed EEVs categories

2.4.1. Group 1: variables related to the exploration and installation of the mining site

This group of variables targets various aspects of the exploration phase and the installation of the mining site that are liable to alter the ecosystem structure. It targets land use conflicts deriving from the installation of the mining facilities, such as the loss of forested areas, species habitats and agricultural dedicated areas.

(1) Ecosystem structure category. It determines the degree of fragmentation of the ecosystem following the installation of a mining site. A large proportion of the world's mineral and energy resources are found in forested regions, which are consequently subject to severe disturbance by surface mining. This can lead to alterations in the ecosystem structure, function, and services (McGarigal, Cushman, and Regan 2005; Layman et al. 2007).

(2) Sensitive species category. It expresses the percentage of the surface area of habitat loss over the total area inhabited by a particular species as a consequence of the occupation by mining facilities. As the availability of accessible mineral deposits decreases, the exploration of remote areas holding minerals of interest increases. This can represent a threat to the conservation of isolated species. In particular extractive practices, requiring blasting can irreversibly damage unique ecosystems and biodiversity. Metallophyte plants represent an example of threatened species because they thrive on mineral deposits (Ginocchio and Baker 2004; Saad et al. 2011). The indicator is calculated from the mining activity area and the area covered by the habitat of a species and it can be expressed as

$$\text{surface of habitat lost(\%)} = \frac{\text{mining activity area}}{\text{total surface of the habitat}} \times 100\% \quad (1)$$

(3) Avian species category. The loss or alteration of avian population habitats can lead to a decrease in the population abundance. Disturbances on habitat results in nesting site loss, increased noise, and habitat fragmentation (Kociolek et al. 2010; Van Wilgenburg et al. 2013). The indicator is a measure of the changes in the abundance of a given avian species as a consequence of the start of mining activities.

(4) Terrestrial species category. It expresses the changes in the abundance of terrestrial species over the time following the start of extractive activities. Mining has a direct impact on local habitat degradation through the removal of vegetation and soil. This can impact the mobility of terrestrial species, facilitate the introduction of alien species, and other negative stresses that affect the growth of populations. This can be reflected in a decrease in the population abundance (Kociolek et al. 2010; Bernhardt and Palmer 2011; Frelich 2014; Castro Pena et al. 2017).

(5) Forest category. It expresses the percentage of forest lost following the installation of the mining site. Vegetation will be gradually and incrementally removed to accommodate mining. Impacts associated with vegetation removal could include an increase in soil erosion and differences between pre-mining and post-mining vegetative communities. The suggested indicator could be expressed as

$$\text{surface of forest lost(\%)} = \frac{\text{mining activity area}}{\text{total surface of the forested area}} \times 100\% \quad (2)$$

(6) Land use agriculture category. Extractive activities are often in conflict with existing land use, creating conflicts of interest between different soil occupations. Despite the temporal economic benefits associated with the mine, the economic loss for local communities depending on agriculture for their livelihoods can be large. For regions where agricultural production represents the main economic activity, an increase in land degradation can affect the communities' ability to sustain themselves. The indicator is calculated from the mined surface and the area covered by crops and represents the percentage (%) of crop surface lost following the installation of the mine (Waldner et al. 2017). The indicator could be expressed as

$$\text{surface of crop lost(\%)} = \frac{\text{mining activity area}}{\text{total surface of the crop}} \times 100\% \quad (3)$$

(7) Species habitat category. Direct impacts of surface mining on wildlife may be substantial. They include injuries or mortality caused by mine-related

traffic; direct loss of less mobile wildlife species; restrictions on wildlife movement created by fences, roads, spoil piles and pits; displacement from existing habitat in areas of active mining including abandonment of nesting and breeding habitats for birds; and increased noise, dust and human presence (Frelich 2014). This indicator expresses the percentage (%) of the habitat lost following the installation of the extractive site.

$$\text{habitat lost(\%)} = \frac{\text{mining activity area}}{\text{total surface of aspecies habitat}} \times 100\% \quad (3)$$

2.4.2. Group 2. variables related to the extraction method

The variables proposed in this group consider some of the impacts deriving from different extraction methods. In particular, they address effects on the hydrology of the landscape where the mine is located in terms of changes in the volume of groundwater and superficial water, and river diversion.

(1) Mining-related water use category. Quantifying the annual consumption of water related to mining activities is important because water extraction and water diversion for the operations carried out by the mine can influence the amount of water available for other uses. The amount of water used by the mine, and the impacts it will have on the overall hydrology depend on the type of mine and the extraction method. Data on water extraction and water use will provide information on the availability of fresh water in the basin.

(2) Groundwater category. Mining-related activities are responsible for influencing the groundwater volume (Zhao, Ren, and Ningbo 2017). In the case of open-pit mines, measures are taken to prevent water from accumulating in the pit. In the case of a pit overlapping an aquifer, the water is pumped out to prevent flooding from groundwater. This practice is responsible for fluctuations of the water table and this can reduce the amount of water available to the base-flow of surface watercourses.

(3) Lakes and superficial water category. Mineral activities are responsible for alterations of the hydrology of the region and consequently, the surface water will be affected.

(4) Atmospheric composition category. The dispersion of dust, pollutants and greenhouse gases in the air within the mining facilities results from activities such as blasting, excavation, loading and hauling of overburden and coal, and wind erosion of disturbed land, all of which produce fugitive dust (Hendryx 2009). Nitrogen oxides are the principal fugitive gaseous emissions produced during surface coal mining operations (Oluwoye et al. 2017).

2.4.3. Group 3. variables related to the ore processing

The variables proposed for this group relate to aspects of the ore processing phase that vary according to the nature of the mineral deposit being exploited. Some of the issues taken into consideration are the contamination of water resources and soil by the metals' leachability, and dust and pollutant dispersion from blasting.

(1) Soil chemical pollution category. The potential dispersion of pollutants and chemical substances in the soil is a consequence of the leachability of waste rock disposal sites (Asami 1988). In calculating this indicator, parameters such as waste rock leachability and the coefficient of permeability of the soil should be taken into consideration.

(2) Underground water pollution category. Groundwater pollution can occur directly or indirectly as a consequence of surface mining. Direct pollution can occur from the diversion of contaminated drainage from the mine or acid mine drainage. This pollution will pose a danger to the entire basin.

(3) Superficial water pollution category. Mineral processing is related to the risk of acid drainage. Acid generation takes place in the pH range when iron sulfide minerals are exposed to and react with oxygen and water. If leaking occurs in a water body or is transported by runoff it can pose a threat to aquatic life and make water unfit for human consumption (Naicker, Cukrowska, and McCarthy 2003; Eisler and Wiemeyer 2004).

3. EEVs in practice and links with SDGs

Due to the variety and complexity of environmental systems, numerous indicators were developed in order to translate environmental data into useful information for measuring progress towards SDGs (Kurtz, Jackson, and Fisher 2001; Kim 2013). To slow down this proliferation logic, the concept of EVs stand out as theoretical knowledge defining a framework within which environmental, economic and social sustainability issues can be coordinated (Reyers et al. 2017). This approach prioritizes the development of indicators considering only the most valuable elements for summarizing the critical aspects of an ecosystem.

Starting from primary observations (e.g. in situ data collection, raw data, remote sensing systems), it is possible to identify the critical components in the extractive supply chain and define EVs. Following is a figure showing how the three categories of the proposed EEVs – exploration and installation phase, mineral extraction and ore processing – can be related to the SDGs and the Aichi Biodiversity targets to monitor their compliance (Figure 1).

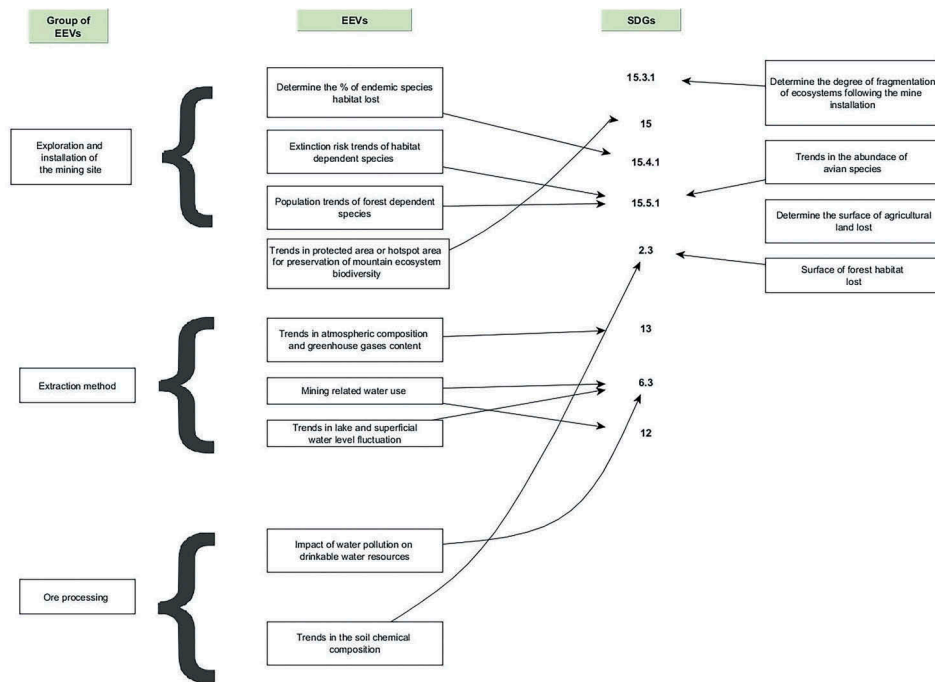


Figure 1. yEd graph editor™/PC.

As shown in the Figure 1, the proposed EEVs can contribute monitoring the trends in distribution, abundance and extinction rate of species (SDG target 15); trend and coverage of biodiversity hotspots for endemic species and/or habitat dependent species (SDG target 15.4.1 and 15.5.1); trends in the changes of soil occupation following the installation of the mining site (SDG target 2); changes in the chemical composition of water and water use (SDG target 6 and 12), soil and atmosphere (SDG target 2 and 13). The approach chosen to test the feasibility and relevance of these variables in assessing the environmental issues linked to mineral extraction, is the development of operational workflows based on geospatial data. Each of the workflows can use a combination of primary observation data as input for the computation of relevant variables. In this study, a workflow estimating the impact of mineral extraction on forest cover will be illustrated.

3.1. Workflow implementation

The Virtual Laboratory (VLab), initially developed in ECOPOTENTIAL project (<http://www.ecopotential-project.eu/>) and improved in the GEOessential project (<http://www.geoessential.eu/>), is a virtual, open, cloud-based platform enabling information access and knowledge generation. The VLab was conceived as a resource sharing system, with a specific focus on solving interoperability issues to facilitate open knowledge scenarios. Using the VLab platform, users can access and execute workflows to enable the production of quantified variables and indicators,

and knowledge generation towards SDG monitoring. The platform provides representation of, and information about each workflow. The user can select input datasets and run previously defined workflows to generate an output dataset. End users (decision-makers, managers, etc.) are able to visualize data and run models through apps and a portal. Since VLab is interoperable with the Global Earth Observation System of Systems (GEOSS), it allows users to access datasets but also to publish the products directly into GEOSS (Figure 2).

A workflow example, successfully implemented in VLab in this work, aims at operationalizing the calculation of the variable to monitor the influence of mine installation on forest areas in the Democratic Republic of Congo (DRC). The workflow allows estimation of the surface area of forest covered by mining sites. It was developed starting from the assumption that mining sites and forests cannot coexist on the same site; the presence of the mine will correspond to the loss of an area of the forest. This indicator is not part of the SDG framework, but similarities can be found with the indicator 15.3.1 “proportion of land that is degraded over the total land area” proposed for the SDG15 and available on the UN SDG metadata repository.

The workflow is implemented based on geospatial data of the forest cover and the surface occupied by mining concessions. The output of the workflow is derived from a spatial overlap between digital polygons of the DRC mining cadaster and a TIFF file representing the forest cover (Figure 3). The value of the variable obtained, given in km², is computed as

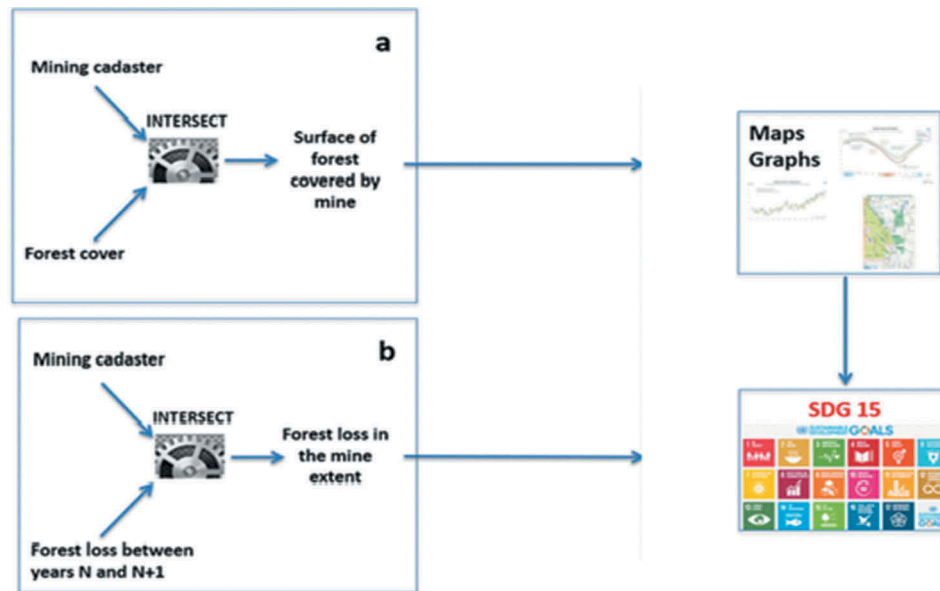


Figure 2. PowerPoint/PC.

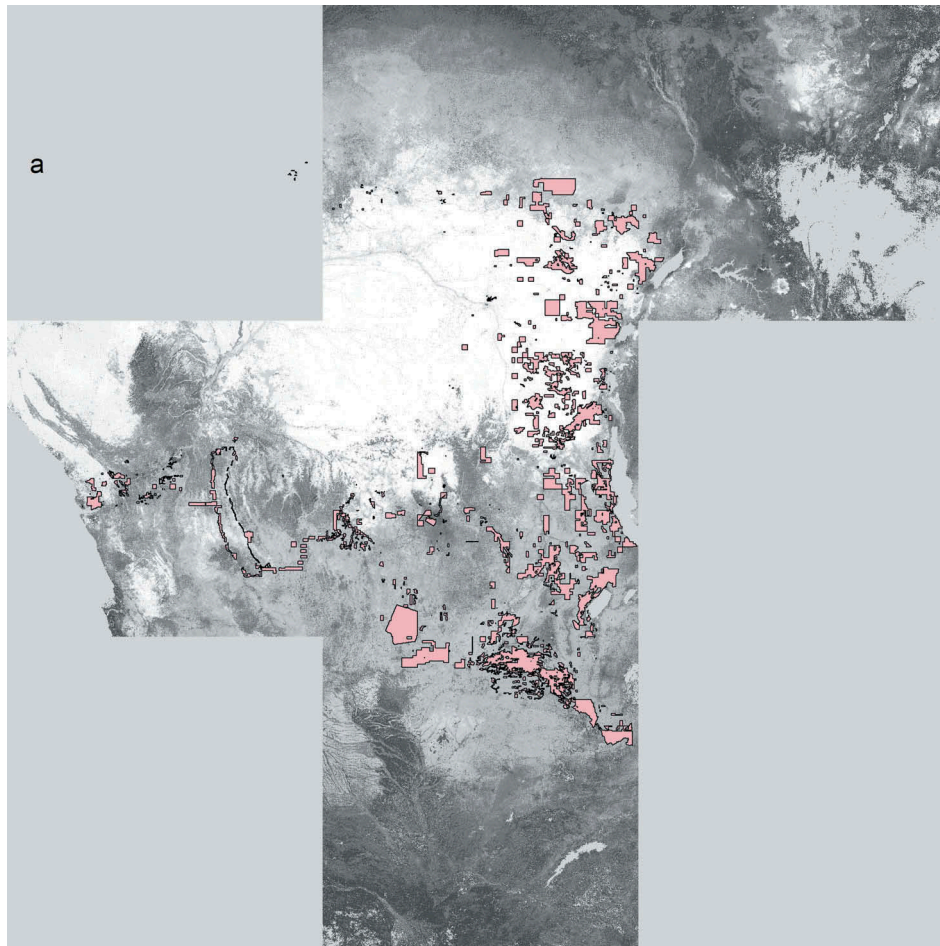


Figure 3. ArcGIS™/PC.

the ratio of the surface occupied by mining concessions and the total surface of the forest cover. Both trees cover and mining concessions are for the year of 2015.

The data for the forest cover is obtained from the website Global Forest Change from University of

Maryland, Department of Geographical Sciences (Hansen et al. 2013). The tree cover is defined as canopy closure for all vegetation taller than 5m in height. The values of forest cover for each pixel of the image are encoded as a percentage per output grid cell whose values range between 0 and 100. The size

of the pixel is 25m×25 m. The data for mining concessions are provided by the DRC mining cadaster, provided by the Ministry of Mines in DRC (<http://portals.flexicadastre.com/drc/en>). Each concession is represented as a polygon.

The workflow, initially tested on ArcMap 10.3.1, consists of a series of geoprocessing tools linked together to carry out a complete data treatment from raw data to the outputs. A Bash (Unix shell and command language) script was successively conceived to automate the process of data treatment using open source libraries such as the Geospatial Data Abstraction Library (GDAL) and avoid installing complex data treatment libraries. The script loops through all available forest cover tiles and outputs a text file reporting the total area of forest cover for each tile. A second text file is generated reporting the sum for all tiles on the DRC geographical extent.

The scripts developed to compute the indicator were first tested locally on a virtual machine, using docker technology and geodata/gdal:2.1.3 as virtual image. The docker GDAL image was chosen because it already has installed all the necessary libraries and plugins needed to execute the scripts. Once the tests were successfully performed locally, the scripts were uploaded in GitHub and executed in VLab.¹ The script is composed of:

- **A central part.** The extent and resolution of the TIFF image are obtained with the command `gdalinfo`. Successively a raster is created from the vector containing the information for the mining concessions with the command `gdal_rasterize`. The value attributed to this raster is 0 for the absence of polygons and 1 for the presence of polygons. At the end of this step, a raster with the same extent and resolution of the TIFF image of the forest is obtained. The command `gdal_calc.py` allows combining the new concessions raster with the raster of forest cover by multiplying the number of pixels of the two rasters. In an analogous approach to the “extract by mask” used in ArcGISTM, a new raster is created containing the area of the forest overlapping the concessions (Figure 4). The extent of the surface occupied by the mines is finally calculated in the newly created raster. This value is obtained by calculating the mean value of pixels present in the raster, multiplying it by the total number of pixels of the raster, and by the size of each pixel (25m×25m), and dividing by 10^{-6} to obtain the surface of the forest in SqKm.
- **A “for loop”.** The selected TIFF files are inserted into a “for loop” which allow execution of the central part of the script for each image in the input variable.
- **The outputs of the script.** A variable containing the results of every “for loop” is created, named as `detailed_rast_sum.txt`.

The total of area of forest loss over the total extent of the considered area, is obtained by summing up the outputs of every single loop in the variable `rast_sum`.



Figure 4. ArcGISTM/PC.

txt. The result obtained for the provided dataset is 143,617 km². The accuracy of the results of the workflow was tested by comparing the outputs obtained from ArcGISTM with the outputs of the script.

4. Discussion and future perspectives

The concept of EVs was originally designed to address and monitor the changes happening in natural systems. However, when talking about mineral extraction we are rather referring to an outside system bearing the potential of altering the natural system in which it is located. Thus, it is legitimate to think that the use of EVs for the extractive industry may be source of discordance considering that we are not directly dealing with natural systems. Nevertheless, it is possible to create a link between the concept of EVs and mineral extraction. By identifying the different steps involved in the supply chain, it is possible to target the impacts of each extractive activity on the surrounding ecosystem whether in the exploration, the extractive or ore processing phase.

The use of EVs in the extractive field requires both a detailed knowledge of the area in which the mine is located and a deep knowledge of the processes operating at each step of the supply chain. If mineral deposits differ in the way they can be extracted, it is important to define EVs tailored to the adequate extractive supply chain (e.g. open pit mine vs. underground mine, artisanal mining vs. industrial mining). The proposed workflow executes a complete data treatment from raw data to outputs. Articulating and automatizing the data treatment into a script, created an easily accessible instrument and provided information about the impact of mineral extraction on the land occupied by forests. The use of GIS

represented a valuable resource for the development of the workflow, allowing us to test, through trial and error, its consistency at each step of the script. The available geoprocessing tools allowed to combine sets of data for mining concessions and forest cover to determine the best approach to assess the impact of mineral extraction on the forest. Furthermore, the association of the results obtained through the script and the use of ArcGISTM allowed the visualization of the results on a map showing the extent of the forest area affected by mining activities.

The approach of operational workflows gives flexibility to the indicators it supports. The workflow assesses the impact of mineral extraction on forest and can have different applications depending on the input data. The outputs and thus the information derived from the indicator are related to the type of mine that is present in the area. For example, an open pit mine will have a major impact in terms of forest loss compared with an underground mine. Other factors that can influence the outcome of mineral activities on the forest include the mineral extracted by different extractive methods, and the processing of the ore. At the same time, it is possible to introduce a temporal aspect in the assessment of forest loss by calculating the surface of forest loss before and after the mine was operational. By comparing the results of two different years, it is possible to obtain the surface lost, derive the pace of deforestation as a consequence of the mine, and obtain useful information for the purpose of environmental monitoring in relation to mineral extraction.

Noteworthy were the difficulties encountered in the development of the workflow at the level of data availability. The lack of standardized data on mining activities across different countries and the limited access to up-to-date information on the extent of the mines represented one of the biggest challenges when implementing the proposed workflows. Despite most nations providing a cadaster of the mines present in their territory, the data are not available for download. The mineral industry is trying to be more transparent in its activities and performances but the lack of data on mineral activities still represents a major problem obstructing the deployment of efficient monitoring tools and indicators.

The workflow proposed in this work must be considered as a first attempt to create good indicators able to serve the purpose of monitoring tools for the compliance of the SDGs in the context of mineral extraction. The workflows were proposed based on the literature review conducted to understand the problems and the impact that mineral extraction has on the environment. The methodology proposed, partially based on scientific publications and on personal reasoning, needs to be tested, improved and discussed with experts in the sector. The extractive

variables proposed in this study should be translated into operational workflows to verify their benefits in providing information on the nexus connecting mining activities and environmental sustainability.

Although the focus of this paper is on defining EEVs (EEVs) for environmental monitoring, the socio-economic aspect of mineral extraction should also be addressed by working towards the development of Socio-Economic Essential Variables for the extractive field. The lack of indices to assess the social and economic aspects of mineral activities will undermine the ability of EVs to effectively track the progress towards SDG targets. A comprehensive implementation of SDGs requires the inclusion of crosscutting instruments like the footprint indicator helping to address the three pillars of sustainable development. The welfare of economies and societies should not be considered as a separate issue from the ecological aspects of mineral extraction, and the creation of indicators, linking environmental, economic and social aspects, should be considered.

The definition of EEVs will seize fundamental system aspects and help to define a coordinated framework for the implementation of SDGs in the field of mineral extraction. To achieve this objective, improvement should be considered in the use and accessibility of Earth Observation (EO) as a source of data for Earth's system monitoring. EO products and the related infrastructures should put additional focus on 1) the availability and accessibility of EO resources to help improve the understanding of Earth processes and their predictions; 2) providing a platform to help connect partners of different scientific communities and promoting a collaborative approach of the co-creation of tools and indicators for better exploitation of the data available; 3) promoting an open system platform approach for data access, integration, and use and the sharing of knowledge-based products in the field of mineral extraction.

5. Conclusions

The objective of this study was to test the applicability of the concept of EVs in the extractive field. It was possible to develop and execute a workflow targeting the impact of mineral extraction on the forest falling within the perimeter of the area assigned to mineral extraction. The workflow first tested on ArcGISTM was successfully implemented into a script to have an easy-to-access tool that provides an estimation of the surface of forest lost because of mining activities.

The use of EO data remotely acquired by satellite proved to be a useful source of information for monitoring vast areas and provided timely data on the state of natural systems. The use of satellite images containing the information on mining concessions and forest extent, allowed us to combine those data

and obtain visual support showing the impact of extraction on the landscape. The combination of complementary data types, raw data and satellite images allow the creation of transversal indicators to assess the progress against SDG targets and other frameworks. Furthermore, the use of EVs to create a monitoring framework, holds the potential to promote standardization of data to ensure its quality and comparison with an analogous sets of data representative of other regions. The issue of data quality and accessibility also needs to be addressed in the perspective of creating a common monitoring system for mineral extraction. This needs to take into consideration the different technology plan and infrastructure advancement around the world and thus promote feasible data treatment and collection methods.

Mineral extraction represents a fundamental source of raw materials for the development of the economy and its practice is inscribed into a long-established production system. Although alternatives to the extraction of new minerals can be envisioned for the future in order to decrease the pressure on natural ecosystems, the exploration and exploitation of new mineral deposits are still the privileged approaches. For this reason, the mineral industry needs to take all necessary measures to prevent or reduce to the minimum the loss of net environmental continuity and ecosystem integrity. The use of EVs as sustainable development indicators will help to translate the sustainability issues linked to mineral extraction into concrete measure of environmental performances, which will ultimately lead to the compliance with SDGs and other political frameworks looking towards a more attentive approach to natural resource exploitation.

Note

1. <http://confluence.geodab.eu/display/VLAB/Publish+a+model+from+a+Git+repository>.

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