Certificat complementaire en gèomatique

Determination of essential variables for the monitoring of mineral resources exploitation

Ambrosone Mariapaola

Under the supervision of Dr. Pierre Lacroix

Dr. Gregory Giuliani

July 2018

Abstract.

The extraction of mineral resources is essential to most of the economic activities sustaining the global economy. But the practice of raw material extraction comes with a high price in terms of impacts on the environment and potential threats for the health and thriving of local communities. Despite this, very little is done to establish a common framework promoting more sustainable and responsible practices in the field of mineral extraction. In this project the concept of Extractive Essential Variables (EEVs) will be explored in the attempt to propose possible candidates able to quantify the impacts mineral extraction has on the environment: new sustainable development indicators for extractive activities are proposed. Considering the high dependency mineral extraction has on social, economic and environmental issues, the use of essential variables (EVs) as a monitoring tool for the implementation and compliance of the Sustainable Development Goals (SDGs) will be explored. The identification of EEVs is based on the use of Earth Observation products in the field of mineral resources exploitation.

Different workflows are designed and one of them is implemented to address the SDG15, "life on land" and other policy frameworks such as the Aichi Biodiversity targets. The workflow is intended to assess the surface 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 ArcMap, which proved to be fundamental in delineating the data treatment and the development of the indicator. 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), allowed sharing the model and its components on a web service-based access platform, conceived to increase the accessibility of data and resources and the re-use of the script.

Workflows represent the starting point for the development of essential variable indicators in the extractive field. The literature review, associated to this work, allowed to understand the processes related to mineral extraction and to better target the components of the ecosystem more sensitive to disturbances. A list of indicators is proposed based on three classes of essential variables: mine footprint, extraction method and nature of the mineral deposit. These indicators are inclusive of the impacts of mining on the hydrology, the land, the water resources and the atmosphere of the affected area. Workflows for some of these indicators are proposed for future implementation.

Table of contents:

List of tables:

List of figures:

1. Introduction

The extraction of minerals from natural deposits has been a constant in the history of human kind and one of the pillar supporting the economic and technological development we are benefitting today. But mineral extraction comes with a cost which is mostly neglected due to the major benefits generated by this industry.

In the form of raw material or processed ores, minerals are in every aspect of the daily life and the continuous demand fuels the quest for new lands to exploit, often generating land use conflicts with the existing soil occupation. Extraction and processing of minerals are associated with sustainability issues related to the use of natural resources in a way that will ensure their integrity to the benefit of future generations (*Breaking new ground.* The report of the Mining, Minerals and Sustainable Development Project, 2002). Due to the destructive nature of mining activities, aquatic and land ecosystems are directly impacted, hence the need to include sustainable practices in the extractive field represents a prerequisite for the viability of this industry (Lindahl, 2014).

These and other concerns have prompted the development of strategies to efficiently address the sustainability issues linked to mineral extraction and target the objectives of the Sustainable Development Goals (SDGs) and other policy frameworks. In this regard, one of the approaches considered is the concept of Essential Variables, largely used for climate monitoring and biodiversity. This work is center on developing indicators or Extractive Essential Variables (EEVs), which will assess the influence of mineral extraction on the area adjacent to the mine, the surrounding landscape and the ecosystems. The combination of Earth Observation products alongside additional ancillary data types, will allow the development of adequate instruments to quantify the impacts of extractive activities. GIS application tools and spatial dataset will be used as instruments for the implementation of extractive indicators and translated in the form of operational workflows. The outputs deriving from these workflows will generate cartographic products, timely dashboards and supporting material for decision makers and stakeholders to ease the understanding of environment-related problematics linked to mineral extraction.

1.1 Extraction and processing of minerals

Previous to the exploitation of mineral deposits is the exploratory phase which aims to detect the most profitable area for the development of the mining site. For the most part, these deposits are located in remote areas necessitating the construction of infrastructures and other facilities (roads, railways, access routes). Successively three phases can be identified in the process of mineral exploitation: extraction, mineral processing and waste handling. The first step is the extraction of the ore from the rock. In the case of open pit mines, the deposit is found near the surface and easily accessible by mechanical removal of rocks or through drilling and blasting to break the rocks. The size of the pit is linked to the availability of the mineral in the deposit and its accessibility. In general, when the amount of overburden extracted is superior to the amount of ore processed, the mine is no longer rentable (Prior et al., 2011). The ore extracted is successively processed through the use of chemical compounds.

Mining is a permanent commitment to the land and the production of waste is amongst the damaging outcomes of mineral extraction. The type and amount of waste generated are dependent from the geological characteristics of the ore deposit, the type of mine (underground or open pit) and the type of mineral being extracted (Durucan et al., 2006). The principal type of waste produced are:

-   Tailings - what remains after the process of extraction of the mineral from the ore/rocks. It is mostly grounded rock mixed with different type of chemicals according to the process of extraction used.

- Overdburden - the soil and rock that need to be removed to access the mineral. It differs from tailing for being the layer of rocks covering the ore which is not processed but simply removed to access the mineral;
- Waste rock – rocks that don't contain any mineral of interest;

According to the type and use of the mineral resources extracted, the mineral industry can be divided into four subcategories:

- Energy mineral;
- Metallic minerals;
- Construction minerals;
- Industrial minerals.

The principal techniques of extraction for metallic minerals such as iron, copper and zinc are both open pits and underground mines while construction minerals, like calcium carbonate, are extracted mainly through quarrying. Depending on the technique used, mineral extraction can have different outcomes in terms of its footprint on the surrounding landscape (Azapagic, 2004; Awuah-Offei et al., 2011).

1.2 Environmental impacts of mineral extraction

Mining activities are responsible for a series of environmental impacts which can vary according to the size of the mine and the nature of the deposit, its location, the techniques and processes used to access the minerals (Ferreira et al., 2015). These impacts ultimately influence the area surrounding the extraction site by changing, in an irreversible way, the original state of these ecosystems.

The ecological footprint of mines goes well beyond their perimeter and according to the distance from the mining site it is possible to determine a primary and secondary area of impact. The primary area represents the area directly impacted by the presence of the mine, processing facilities, roads, energy transmission network. The secondary area concerns the zone near the mining site and it can be impacted at the level of its ecosystem and landscape integrity. The magnitude of the impacts on these areas decrease with increasing distance from the mining site (Frelich, 2014).

Some of the negatives impacts associated with mineral extraction are:

- **decrease of the value and utility of land for agricultural and forestry purposes**. Vegetation will be gradually and incrementally removed to accommodate mines (Macdonald et al., 2015). Consequences of vegetation removal include increased soil erosion and differences between pre- and post-mining vegetative communities;

- **disturbance to the flora and fauna of the area with consequent deterioration of the ecosystem integrity.** Direct impact of surface mining would occur on wildlife. 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; increased noise, dust and human presence (Frelich, 2014). Loss of habitat can additionally lead to changes in species composition, as forested areas are converted to grassland after reclamation (Van Wilgenburg et al., 2013);

- **increased rate of erosion, sedimentation and landslide, representing a threat for the water resources and the integrity of the landscape**. In open pit mines priority is given to the control of water entering the pit. A system of canalization is put in place to drain the pit from atmospheric precipitations. Additional

measures are considered if the pit overlaps an aquifer to prevent flooding from groundwater. Pumping for removal of excess ground water in the mining pit can have consequences on the water table. This reduces the amount of water available to the baseflow of surface water courses that can ultimately affect water supplies for agricultural and human consumption (Karmakar et al., 2012);

- **risk of release of pollutants in the groundwater or superficial water.** Mineral processing is related to the risk of acid drainage. Acid generation takes place in the pH range when iron sulphide minerals are exposed to and react with oxygen and water. Exposing these materials and breaking them up can facilitate this process. Mining exposes sulphide rich materials in the walls of open pits, mine tunnels, waste rock. If leaking in water body or transported by run off, it poses a threat to aquatic life and makes water unfit for human consumption (Vela-Almeida et al., 2016);

- **degradation of the quality of life of local communities to the benefit of short term welfare**. Activities such as blasting, excavation, loading and hauling of overburden and coal, and wind erosion of disturbed land, produce fugitive dust. Nitrogen oxides are the principal fugitive gaseous emissions produced during surface coal mining operations (Hendryx, 2009).

- **alteration of the watershed and hydrology of the basin.** Local destruction of stream segments through burial beneath valley fills or converted to waste treatment systems in the form of ponds have an impact on the integrity and functioning of the basin. Furthermore, the removal of vegetation and the compaction of soil alters the pattern of the water flowing through the watershed, changing the composition of water and altering the chemistry of the downstream receiver streams (Akiwumi et al., 2008).

2. The concept of essential variables: a tool to characterize and predict the earth's systems development

The first definition of essential variable was provided by the Global Climate Observing System (GCOS) in the 1990s in the context of climate monitoring. It defines Essential Climate Variables as:

"physical, chemical or biological variables or a group of linked variables that critically contribute to the characterization of Earth's climate" (GCOS 2010).

The concept of essential variable derived from the need to have accurate and continuous information on the atmosphere, land, and oceans to monitor the Earth's climate, and ultimately understand past, current and future climate variabilities (Bojinski et al. 2014; Brummitt et al., 2017). Later on, the concept of EVs, was expanded to other domains, such as ocean and biodiversity, to assume a broader definition more inclusive of other Earth's systems:

"minimal set of variables that determine the system's state and developments, are crucial for predicting system developments, and allow us to define metrics that measure the trajectory of the system." (Blonda et al., 2016)

In a context of changing environment, the use of essential variables is necessary to target the components of environmental systems on which variabilities can be observed and studied (Turak et al., 2016). The importance of understanding the dynamics of ecosystems allow to efficiently manage them and assess where the changes are occurring, at what rate and how they will evolve in the future. The criteria followed for the development of essential variables are:

- **Relevance**. The variable is able to characterize the system and be of use in assessing its changes;

- **Feasibility.** Observing and deriving the variable is feasible on a global scale in terms of technical requirements. It's possible to collect the information linked to the variable by using proven and reliable scientific methods;
- **Cost effectiveness**. Generate and archive data on the variable is affordable (Bojinski et al., 2014).

2.1 The application of essential variables as instrument for the SDGs compliance

During the time the concept of essential variables and its applications evolved to assume the role of monitoring tools in the context of policy implementation and compliance (Geijzendorffer et al., 2015). In particular the idea of EVs was reshaped to be of use to policy framework targeting sustainability issues in the context of natural resources exploitation. By defining the key components of ecosystems, EVs will restrain the targets to focus on, by identifying instruments for an efficient monitoring system and facilitate the fulfillment of development goals (Reyers et al., 2017).

For this project the policy instruments that will be considered for the development of EVs in the domain of mineral extraction are the Sustainable Development Goals (SDGs), a collection of 17 global goals targeting social, economic and environmental development issues and the Aichi biodiversity targets (fig. 1).

	Public awareness		Sustainable fisheries		Protected areas		Nagoya ABS Protocol
1		6		11		16	
	Value of biodiversity understood		Sustainable agriculture		Species		NBSAP revision
2		7		12		17	
	Removal of perverse incentives		Pollution		Genetic diversity		Traditional environmental
3		8		13		18	
	Sustainable production / consumption		Invasive alien species		Ecosystem services		Knowledge transfer
4		9		14		19	
	Loss of natural habitats		Climate change / ocean acidification		Ecosystem-based carbon sequestration		Resource mobilisation
5		10		15		20	

Figure 1. A diagram listing the 17 Sustainable Development Goals (SDGs) and the Aichi biodiversity target. Image source https://www.un.org/sustainabledevelopment/sustainable-development-goals/; Sumaila et al., 2017.

When determining possible candidates for EVs, with a view to create instruments for the implementation of SDGs, it is important to keep in mind the spirit of such policy measures: to consider natural systems and socio-economic activities as part of one unique system. SDGs represent the will of the international community to support and coordinate a shift towards more sustainable activities and harmonize the coexistence of human welfare and healthy natural systems. At this regard mineral extraction represents the perfect example of interconnection between the socio economic short terms benefits and the negative impacts on the surrounding ecosystems.

2.2 Towards the implementation of Essential variables in the extractive field: a current state of knowledge

Despite the potential of extractive activities to alter the surrounding environment in terms of natural ecosystems and socio-economic realities, a list of formal Extractive Essential Variables is not yet being determined. As already mentioned, extraction and processing of minerals are tightly linked to the socio-economic reality of the area, thus representing a sector that should prioritize the compliance to sustainable practices (Drielsma et al., 2016).

Of the three sustainability pillars, - social, environment, economic, the environmental one is the most advanced in term of research. Numerous are the studies conducted to assess the impact of mineral extraction on the environment, they mostly target the fauna and flora and the disruption of land and aquatic ecosystems. Nonetheless there is a lack of cohesion between the scientific research and its use for the implementation of political frameworks for sustainability.

The literature review conducted as part of this work, shows a shift in thinking of the mineral industry, willing to abide by the definition and requirements of sustainable development as stated by the Brundtland commission. In the paper published by Azapagic, 2004, the author introduces the idea of corporate sustainability, a concept encouraging mineral industry to tailor extractive practices oriented towards a more sustainable production. Presented in different guises, the concept of essential variable emerges from this

paper: the author's approach is to distinguish the different phases of the extractive supply chain and identify sustainability issues related to each of these processes. Based on the definition of Essential Variable, - a set of variables is identified to contribute to the characterization of the system -, the analysis of the extractive process from "cradle to grave" will allow to identify the key aspects of mineral extraction that represent a threat to the integrity of the environment. Derived from this approach is a list of key sustainability issues for each of the three pillars of sustainable development:

Economic issues	Environmental issues	Social issues
– Contribution to GDP and wealth creation – Costs, sales and profits – Distribution of revenues and wealth – Investments (capital, employees, communities, pollution prevention and mine closure) – Shareholder value – Value added	– Biodiversity loss – Emissions to air – Energy use – Global warming and other environmental impacts – Land use, management and rehabilitation – Nuisance – Product toxicity – Resource use and availability – Solid waste – Water use, effluents and leachates (including acid mine drainage)	– Bribery and corruption – Creation of employment – Employee education and skills development – Equal opportunities and non-discrimination – Health and safety – Human rights and business ethics – Labour/management relationship – Relationship with local communities – Stakeholder involvement – Wealth distribution

Figure 2. Summary of the key sustainability issues for the mining and the minerals sector (Azapagic, 2004).

Another relevant paper for the development of indicators for mineral extraction is presented by Marnika et al., 2015. The study provides a list of indicators based on raw data to calculate qualitative and quantitative characteristics of the impact of mining activities in protected areas. The author provides a framework analyzing the different role mineral extraction has on the social, economic and environmental fields and propose some indicators to assess their influence in each of these three fields.

Different methodologies are used to estimate the impact of mineral extraction on natural systems. One of the approaches used, sees the integration of GIS and geoprocessing on aerial images to detect the changes on the landscape. Considering the vast extent of mining sites and the extent of the impacted zones, the use of satellite images can facilitate the assessment of the changes on the soil occupation. Relevant in this field is the study carried out by Santo et al., 2002 in Brazil where a detailed workflow is implemented to assess the changes on the landscape subsequent the installation of sand mining facilities. This workflow uses satellite images previous and following the installation of the mine thus considering the temporal dimension of the changes. The indicators selected to measure the environmental changes of the area are:

- total mining area;

- former agricultural land converted into open pits, open water ponds and mining ancillary installations;

- deforested areas;

- channel river morphology modifications;

- vegetation growth in reclaimed areas;

- mining encroachments on legally protected riverside zones.

A similar and more recent study using satellite images as a tool, gives information on the changes on the hydrology of the area impacted by mining activities. The study conducted by Padmanaban et al., 2017, explores the use of remote sensing and vegetation indexes (NDVI) to assess the changes on the vegetation

and the landscape over a reclaimed area. Remote sensing and GIS have proven themselves as advantageous over field monitoring to assess long to short term landscape dynamics. The study aims to:

- examine the short-term land use and land cover dynamics in a reclaimed area;

- quantify the emergence and growth of wetlands in the area interested by the mine and identify potential subsidence spots;

- examine the vegetation dynamics following ground water table fluctuation and ecological stress.

Both studies include image processing, image classification and indices calculations to assess the impact of mineral extraction on the landscape components.

Based on the knowledge shared by previous publications, this work aims to develop Extractive Essential Variables and bridge the gap existing between the scientific researches conducted to assess the degree of environmental impacts and the targets imposed by the Sustainable Development Goals (SDGs). Environmental indicators for the extractive industry will represent the final output of a process unifying field- based observations and the political will for a sustainable and conscious use of natural resources for the social, economic and environmental welfare.

2.3 Possible candidates for Extractive Essential Variables (EEVs)

A list of variables to observe the impacts of mining activities on the environment, was compiled by answering to three questions: "why is it changing?", "what is it changing?" and "what are the impacts?". Based on these questions some workflows were developed and essential variables were derived.

The answer to the first question - "Why is it changing" – allows to determine two essential variable classes: "Extraction method" and "Nature of the mineral deposit". Depending from the nature of the mineral deposit and the mineral to be extracted, the extraction and processing methods can vary, as variable are the impacts on the environment. To these a third class was added considering the footprint of mines on the landscape ("Mine footprint").

"What is changing" - helps to determine what function of the ecosystem is affected consequently mineral extraction. By answering to this question, essential variable categories will be determined.

Once these two questions answered, some general classes defining key mechanisms involved in the functioning of ecosystems, are defined. Ultimately these classes will help in the development of different workflows which outputs quantify the disturbances on the ecosystems in terms of surface loss, changes in the hydrology of the area and alterations of the chemical and physical properties of land and water.

Essential variable class

Mine footprint

	Essential variable category	Products
Hydrology	**Mining related water use**	Data on water extraction per year
	Groundwater	Groundwater volume changes
	Lakes and other superficial water	Changes in water surface, lake extent

Land	**Land use agriculture**	Surface of crop lost
	Forest	Surface of forest lost
	Species habitat	Surface of natural habitat lost

Essential variable class

Extraction method

Essential variable category

Land	**Ecosystem structure**	Degree of fragmentation
	Endemic species	Extinction risk index
	Avian species	Population abundance
	Terrestrial species	Population abundance

Essential variable class

Nature of the

mineral deposit

Essential variable category

Water resources	**Superficial water pollution**	Water quality and chemistry
	Underground water pollution	Water quality and chemistry
Land	**Soil chemical pollution**	Soil chemical composition
Atmosphere	**Atmospheric composition**	Content of greenhouses gas and/or pollutants deriving from extractive activities such as blasting

Table 1. Group of potential Extractive Essential Variables (EEVs) proposed as part of this work.

The different components of the Earth's systems – lithosphere, hydrosphere, biosphere and atmosphere, are interdependent and mutually affecting each other so that a change in one sphere results in changes in one or more of the other spheres. This interconnection is perceived in the overlapping of essential variables created for other domains. In the case of mineral extraction, in order to assess the impact of mining on the biodiversity and ecosystem structure, the use of existing biodiversity essential variables was considered. In the same way, the essential variables proposed for assessing the impact of extractive activities on the atmosphere, are shared with the climate essential variables (ECVs). The interconnection between EVs will reduce the amount of new and redundant indicators and highlight the cooperative aspect SDGs should have in targeting multiples aspects of the same system.

The schema below is a graphical representation of the logic used to develop different workflows and derive Extractive Essential Variables (fig. 3).
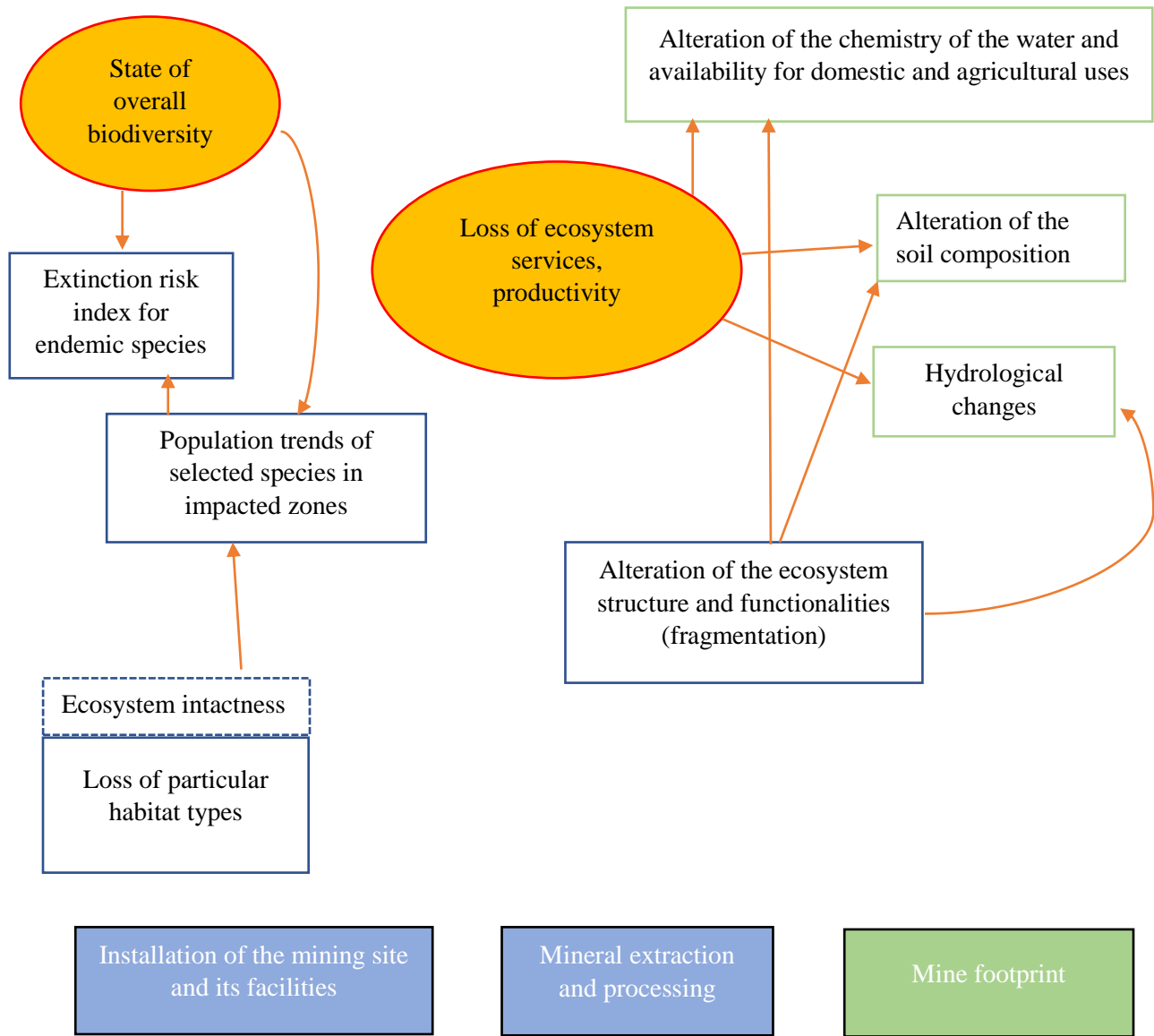
Figure 3. Chart-flow for the development of essential variables. In blue boxes the anthropogenic processes responsible for ecosystem deterioration. Mining activities are responsible for habitat loss which will impact the species population and ultimately pose a threat to the overall biodiversity. In the same way extraction can alter ecosystems structures and functionalities with a consequent loss of ecosystem services and productivity. The impact of the mine can be determined in term of the footprint it has on the ecosystems hydrology, soil quality and chemistry (green box).

2.4 Definition of proposed essential variables

The following section includes a brief description of the essential variables listed above:

Mine footprint – Hydrology

1. mining related water use: 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 they will have on the overall hydrology, depends on the type of the 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: Some mining relative activities can influence the groundwater volume. In 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 baseflow of surface water courses.

3. lakes and other superficial water: mineral activities are responsible for alterations of the hydrology of the region and consequently the surface water will be affected.

Mine footprint - Land

1. land use agriculture: Mineral extraction requires the use of great surfaces often creating conflicts of interest between different soil occupations. Despite the temporal economic benefits associated with the mine, greater are the economic loss for the local communities depending on agriculture for their livelihoods. For the regions where, agricultural production represents the main economic activity, an increase in land degradation will affect the communities' ability to sustain themselves.

2. forest: Vegetation will be gradually and incrementally removed to accommodate mining. Impacts associated to vegetation removal could include increase in soil erosion and differences between pre-mining and post-mining vegetative communities.

3. species habitat: direct impact of surface mining would occur on wildlife. 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; increased noise, dust and human presence (Frelich, 2014).

Extraction method – Land

1. ecosystem structure: a large proportion of the world's mineral and energy resources are found in forested regions, which are consequently subjected to severe disturbance by surface mining. This can lead to alterations in the ecosystem structure, function and services (Layman et al., 2007). One measure of the alteration is represented by the degree of fragmentation of ecosystems.

2. endemic species: as the availability of accessible mineral deposits decreases, the exploration of remote areas holding minerals of interest increases. This can represent a threat for the conservation of isolated species. In particular extractive practices requiring blasting, can irreversibly damage unique ecosystems and biodiversity. Metallophyte plants are an example of threatened species because thriving on mineral deposits (Ginocchio et al., 2004; Saad et al., 2011).

3. avian species: the loss or alteration of avian population habitats, can lead to a decrease in the population abundance. Disturbances on habitat results in nesting sites loss, increased noise, habitat fragmentation (Kociolek et al., 2010).

4. terrestrial species: 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 stressors negatively affecting the growth of the population which can be reflected in a decrease in the population abundance.

Nature of the mineral deposit – Water resources

     1. <u>superficial water pollution:</u> mineral processing is related to the risk of acid drainage. Acid generation takes place in the pH range when iron sulphide minerals are exposed to and react with oxygen and water. If leaking in water body or transported by run off it can pose a threat to aquatic life and make water unfit for human consumption.

     2. <u>underground water pollution</u>: ground water pollution can occur directly or indirectly as a consequence of surface mining. Direct pollution can derive from diversion of contaminated drainage from the mine or acid mine drainage. This pollution will pose a danger for the entire basin.

Nature of the mineral deposit – Land

     1. <u>soil chemical pollution:</u> environmental issues representing a threat for the soil integrity are erosion, decline in organic matter content and biodiversity, contamination and compaction.

Nature of the mineral deposit – Atmosphere

     1. <u>atmospheric composition:</u> activities such as blasting, excavation, loading and hauling of overburden and coal, and wind erosion of disturbed land, all produce fugitive dust. Nitrogen oxides are the principal fugitive gaseous emissions produced during surface coal mining operations.

3. Use of Earth observation products and GIS tools in the field of mineral exploitation to support the development of Extractive Essential Variables

The application of Earth Observation products to investigate the impact of mining on the environment, showed to be of use to determine the footprint of the mine and assess its impacts on forests and biodiversity. The use of remote sensing data combined with ancillary data on the topography of the area, its hydrology, into a geographic information system (GIS), can facilitate the development of Extractive Essential Variables. Remote sensing techniques and Geographic Information Systems allow to assess long term and short-term landscape changes and dynamics (Padmanaban et al., 2017).

3.1 Mineral exploitation and forest preservation. EEVs and SGS15 "life on land"

Degradation of the land represents one of the major consequences of mining activities. Considering the vast surface occupied by the mine and its facilities, physical disturbances such as landscape changes directly impact the area surrounding the mined area. Whether it's an open pit mine or an underground mine, vegetation clears up is needed to host the infrastructure, connecting roads and machinery, to support the extraction and processing of ores. By allowing the installation of mines, forest ecosystems will be negatively impacted. The SDG15, "life on land", aims to preserve and restore key terrestrial habitats for biodiversity as well implements sustainable land management in order to combat desertification, restore degraded forests and halt the destruction and unsustainable exploitation of existing forests.

As mentioned above mineral extraction has an important impact on terrestrial ecosystems and in view of attaining the targets fixed by the SDGs for terrestrial biodiversity and ecosystem conservation, a workflow assessing the impact of mines on forest was developed. The following workflow will allow to quantify the surface of forest lost as a consequence of the mine installation by comparison of two sets of data prior and subsequent the mineral exploitation.

3.2 Monitoring the influence of mines installation on forest area in the Democratic Republic of Congo (DRC): EEVs proposal and workflow

The workflow implemented will allow to estimate the surface of forest lost because of the expansion of the mining site. The indicator was developed starting from the assumption that mining sites and forests cannot coexist for the same site; the presence of the mine will correspond to the loss of an area of the forest. The region chosen for this work is the Democratic Republic of Congo (DRC). This indicator does not exist yet but similarities can be found with the indicator 15.3.1 "*proportion of land that is degraded over total land area*" proposed for the SDG15 and available on the UN SDG metadata repository (https://unstats.un.org/sdgs/metadata/files/Metadata-15-03-01.pdf).

The indicator is calculated from 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 (fig. 4). The value of the indicator, given in km^2, is computed as the ratio of the surface occupied by mining concessions and the total surface of the forest cover. Both tree cover and mining concessions are for the year 2015.
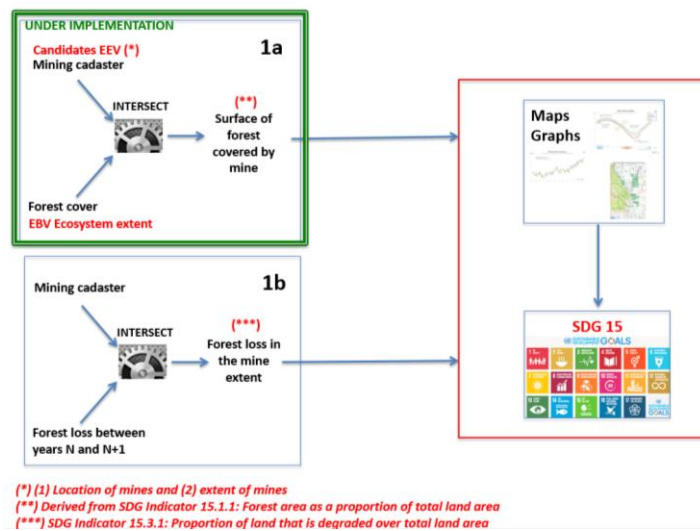
Figure 4. Conceptual framework for the workflow assessing the impact of mining concessions on forest cover.

The data for the forest cover are obtained from the website Global Forest Change from University of Maryland, Department of Geographical Sciences (https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.2.html). 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 which values range between 0 and 100. The size of the pixel is 25*25 m.

The data for mining concessions are provided by the Mining cadaster from Democratic Republic of Congo, provided by Ministry of Mines in DRC. Each concession is represented as a polygon (fig. 5).
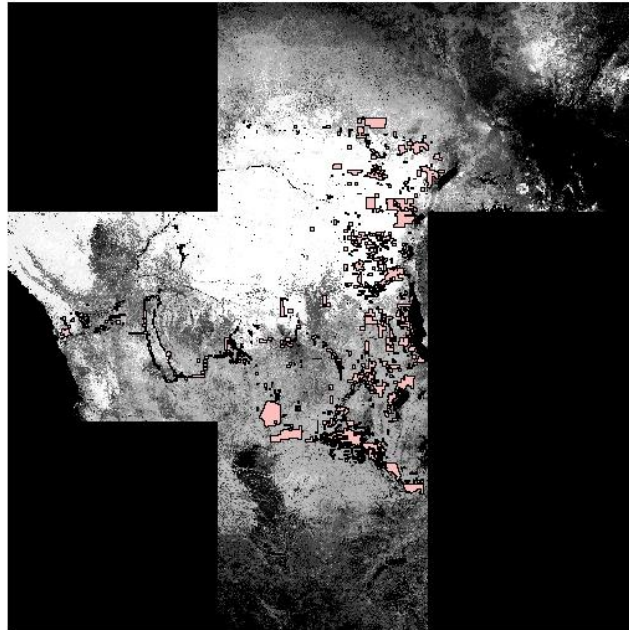
Figure 5. Raster representing the extent of the area considered for the workflow. The mining concessions are represented by the pink polygons overlapping the forest area.

3.3 Method

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 script was successively conceived to automatize the process of data treatment (see Appendix 1). The accuracy of the results of the workflow was tested by comparing the outputs obtained from ArcMap and the outputs of the script.

The geotools used for the data treatment are:

- Data management tools → Raster → Mosaic Dataset → Mosaic to New Raster. This tool is going to aggregate the five TIFF images containing the forest data into a unique raster file;
- Data Management tool → Generalization →Dissolve. This tool will fusion together in one unique polygon all the polygons contained in the "concessions" shapefile;
- Spatial Analyst → Extraction → Extract by Mask. The raster containing the forest surface and the shapefile containing the surface occupied by the mines will be overlapped to obtain a new raster with the surface of the forest on which mine concessions were granted;
- Data Management tools → Fields → Add Field. A new field "surface" is added to the raster attribute table of the newly created raster;
- Data Management tools → Fields → Calculate Field. Calculate the values of the field "surface" containing the value of the surface of forest overlapping the mines. The surface is given in km^2.
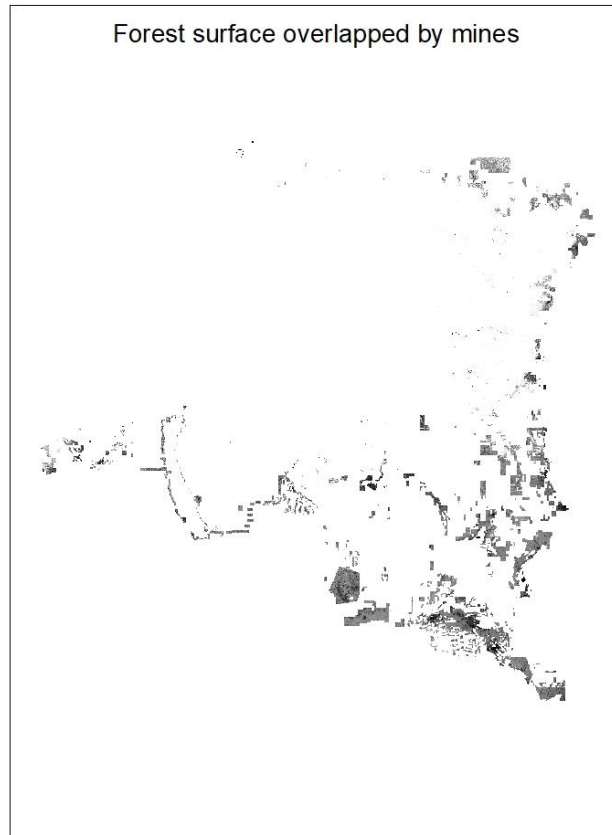
Figure 6. Output of the "Extract by mask" tool on ArcMap representing the surface of the forest overlapped by mining concessions.

The language chosen to develop the script to automatize the data treatment is Unix. The GDAL library (Geospatial Data Abstraction Library) for reading and writing raster and vector geospatial data, was chosen to develop the script. A bash approach was privileged over a python script to avoid the installation of complex libraries for data treatment. The script is conceived to work exclusively on raster dataset to avoid any bug related to topological errors when working on vector datasets. The outputs are computed and printed in a text file.

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 are 0 for absence of polygons and 1 for presence of polygon. At the end of this steps a raster with the same extent and resolution of the TIFF image of the forest is obtained. The command `gdal_calc.py` allows to combine 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 ArcMap, a new raster is created containing the area of the forest overlapping the concessions (masked_$RAST);

19

The extent of the surface occupied by the mines is finally calculated in the newly created raster (masked_$RAST). This value is obtained by calculating the mean value of pixels present in the raster, multiply it for the total of pixels of the raster, multiply for the size of each pixel (25m*25m) and divided by 10^{-6} to obtain the surface of the forest in km^2;

- **a for loop**. The TIFF files selected to test the indicator are insert into a for loop which allow to automatically execute the central part of the script for each image in the input variable.
- **the outputs**. A variable containing the results of every 'for loop' is created, `detailed_rast_sum.txt`. The results obtained for the dataset provided are:

```
9230
76038
36247
3424
18678
```

- The total of the area of forest lost on the total extent of the area considered, is obtained by summing up the outputs of every single loop in the variable `rast_sum.txt`. The result obtained for the dataset provided is:

```
143617
```

3.4 VLab a web service-based platform to share and access workflows and resources

This work is inscribed in the context of the Ecopotential and GEOEssential project for which different resource types such as satellite data, analysis and modelling tools, model/workflows, are generated. Moved by the need of sharing all these resources in an accessible way, a Virtual Laboratory Platform (VLab), providing a web service based access, was developed by the Consiglio Nazionale delle Ricerche (CNR).

Through this platform it is possible to access and use:

- Open Earth Observation and in-situ monitoring data, metadata, scientific models and results, semantic engines and analytics' provision;
- Ecosystems modelling (including ecosystem services, upscaling and future protected areas)
- Knowledge to analyze ecosystems services and to obtain climate and land-use change scenarios, upscaling to larger areas and definition of the requirements of future protected areas

The VLab will allow different resource users to access the resources through an intermediate service layer that will harmonize the various type of resources and expose them as a web service.

3.5 EEVs proposition: technical aspects

ArcMap represented a useful resource for the development of the workflow, allowing to test, through trial and error, the consistency of the workflow and the usefulness of the indicator. The geoprocessing tools available, allowed to combine the sets of data for mining concessions and forest cover and determine the best approach to assess the impact of mineral extraction on forest. The workflow developed on ArcMap represented the guideline for the development of the script.

The script was tested on a Linux 4.9 operative system on which all the input data and the output were stored. The PuTTy open source software was used to access the virtual machine alongside with WinSCP file

transfer software to manage the input and output data on the virtual machine. Ultimately the workflow was tested and published on a web service-based access platform, Virtual Laboratory Platform (VLab). The process of upload of the final script on the VLab platform required its publication on the cloud where the input data and the code were stored. The intermediate platform used for this purpose are GitHub and Docker.

GitHub is an open source project which allows to manage and store revisions of projects. Each project requires the creation of a repository where all the input data and the code are stored. The repository can be access through a URL. A desktop version of GitHub is downloaded. Changes done on the code locally are directly made on the relative repository on GitHub. The Git-hosted code is then transfer on Docker Hub and finally published on the VLab.

Docker Hub is a cloud-based registry service which allows to create code repository, build and test images and share and manage them. The use of Docker for the purpose of this work is to create the image supporting the model based on the implemented script. With the term image it's intended a virtual environment containing an Operative System (OS), data files and the libraries needed to run the code. The model developed for this work runs on an Ubuntu derived image containing GDAL library. The installation of the Docker toolbox was necessary to run the software on Windows systems. The first step is the creation of a docker container for which three .json files are required:

- iodescription.json file which contains two elements, *input* an array of JSON objects representing the input of the model and the *outputs* representing the model outputs. The name assigned to each object need to correspond to the names assigned in the related script.
- dockerimage.json contains the image on which the container will be built. The image used is geodata/gdal 2.1.3;
- script.json contains an array of JSON objects representing the model script to be executed.

The docker container and its files are uploaded on GitHub which now contains all the elements necessary to run the model.

4. Mineral extraction and its surrounding: workflow propositions to determine the interaction of mineral extraction on ecosystems.
When considering the sustainability of mineral activities, two aspects should be taken into account:

- the life cycle of natural products including the extraction and processing of the natural resource;
- the life cycle of the mine and the production facilities.

At this regard a series of workflows will be proposed to ensure that mineral extraction won't correspond to a loss of net environmental continuity and ecosystem integrity and at the same time be the foundation for the development of extractive essential variables in the context of SDGs.

Some of the data source that could be considered for the development of these indicators and for the monitoring of ecosystem changes are:

- direct *in situ* biological and ecological monitoring and data collection to assess the abundance of species, their distribution and their behavior in their natural habitat;

- remote sensing for the collection of data relative to the ecosystem attributes;

- maps of land use and land occupation to determine the different uses of the study area.

The following workflows are not implemented yet, but they are proposed as possible candidates in support of new Extractive Essential Variables.

4.1 Mineral extraction and biodiversity: surface of a species habitat lost due to the presence of the mine

The present workflow is proposed to build an indicator addressing the SDGs goal 15 "life on land" in the attempt to preserve the forest ecosystems and the role they play as habitat for terrestrial species. This indicator can also apply to the target 5 of the Aichi biodiversity targets aiming to reduce the loss of natural habitats. The workflow proposed quantify the habitat of avian species lost after the installation of a mining site. The consequences of habitat loss are species specific: some avian species avoid edge habitat created from segmentation for reasons such as microclimatology or increased predation and other species, preferring early successional habitats, will thrive as a consequence (Kociolek et al., 2010).

The indicator derived from the workflow will be the result of a spatial overlap between polygons representing the habitat of an avian species and a raster or other data type identifying the surface occupied by the mine and its facilities.

Inputs

- Mining site surface
- Birds' habitat surface: One possible data source are the data from the Boreal Avian Modelling Project (http://www.borealbirds.ca/index.php/avian_data), available previa request with additional information on the abundance. Another source of layer is represented by the IUCN website which provide shapefiles on the distribution area of a species (http://www.iucnredlist.org)

Algorithm

- Download input layers
- Intersect of the input data (ArcMap analysis tools → overlay → intersect)
- Perform zonal statistic between the two areas to obtain the area of the habitat intersecting the mine facilities (ArcMap spatial analyst tools → zonal → zonal statistics)

Outputs

A number representing the surface of habitat lost and the map of the mining area overlapping the natural habitat.

4.2 Mineral extraction and agricultural activities of the surrounding area

The present workflow aims to create an indicator suitable for the SDG 2 "*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*" and in particular it could address the target 2.3 which aim to *"double the productivity and incomes of small scale food producers [...] through secure and equal access to land [...]"*.

Mining is responsible for subtracting land devoted to farming activities and to turn soil unproductive and not usable on the long term. In some regions mining activities are responsible for the loss of livelihood for local communities, their displacement and affect their independency in terms of food production. The indicator will provide information on the surface of crop lost over the total extent of the cultivated area. The value obtained will be given as a percentage and derived by the ratio of the extent of the mining surface

over the total extent of the farmed land. By providing information on the type of crop present in the area of interest, is possible to determine the percentage of the loss per crop type.

The most standard method used for land use - land cover change detection is the post classification comparison method, which entails the comparison of independently produced classified images

$$\text{change percentage (\%)} = \frac{(\text{present LULC area} - \text{previous LULC area}) * 100}{\text{previous LULC area}}$$

This method could be implemented in the proposed workflow.

Inputs

- Agricultural surface. It can either be a single crop variety or multiple crops which will give as output the percentage of lost surface per crop type. An example of data type is available for South Africa showing the surface occupied by agricultural area (Waldner et al., 2017). https://figshare.com/articles/Updated_cropland_map_of_South_Africa_for_the_2013-2015_period_/5322970 ;
- Mining concessions or mining surface extent

Algorithm

- Download input layers
- Intersect of the input data (ArcMap analysis tools → overlay → intersect)
- Perform zonal statistic between the two areas to obtain the area of the habitat intersecting the mine facilities (ArcMap spatial analyst tools → zonal → zonal statistics)

Outputs

The surface of crop land lost express as a percentage.

4.3 Mineral extraction and areas of interest for the protection of mountain ecosystems

This workflow is conceived to assess the impact of mineral extraction on hotspots areas for the preservation of mountain ecosystems biodiversity and integrity. The present workflow is targeting the SDG15 aiming to "ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development". The indicator proposed is in line with the SDG 15.4.1 "*Coverage by protected areas of important sites for mountain biodiversity*" which estimates the mean percentage of mountain ecosystems dedicated to protected areas (https://unstats.un.org/sdgs/metadata/files/Metadata-15-04-01.pdf).

Mountain top ecosystems where Mountain Top Removal is practiced, are the most exposed to a decline in biodiversity (Castro Pena et al., 2017). Mountain Top Removal Mining is a form of surface mining at the summit of a mountain. The mineral deposit is accessed through consecutive blasts to expose underlying deposits. This practice is usually employed for coal mining (Bernhardt et al., 2011).

The indicator is calculated from data derived from a spatial overlap between digital polygons indicating the extent of mountain top habitat and the extent of the surface affected by the extractive activities. The

expected output will be the surface of mountain ecosystem disappeared or compromised by mining activities. The output can either be a measure of the habitat lost in km^2 or a measure of the degree of fragmentation of the habitat following the blasting and the extraction.

Inputs

- Mining concessions/ancillary data on the surface occupied by the mine;
- Satellite image prior and subsequent mineral exploitation to assess the changes in the habitat. An affected area can be identified and an appropriate satellite image can be downloaded from the Earth Explorer website (https://earthexplorer.usgs.gov/) ;
- Ancillary data on the ecosystem to identify the presence of important sites for biodiversity conservation. Georeferenced data containing information on key biodiversity areas can be find on the World Database on Key Biodiversity Areas and could be considered as a data source for this workflow (http://www.keybiodiversityareas.org/site/requestgis)

4.4 Mineral extraction and the hydrography of the landscape

The present workflow aims to determine the extent of the impacts of mineral extraction on the hydrology of the impacted area. The workflow objective is to create an indicator suitable for the SDG 6*"Ensure availability and sustainable management of water and sanitation for all"* and in particular for the target 6.3 which aims to "ensure water-use efficiency and ensure sustainable withdrawals and supply of freshwater to reduce the number of people suffering from water scarcity".

Through the comparison of satellite images of a given area, acquired at different years, it is possible to reveal the scale of the impact of mineral extraction on the hydrology of the area and to identify alterations such as buried streams, the creation of ponds and other mining related surface of water (Padmanaban et al., 2017, Akiwumi et al., 2008).

The approach chosen for this indicator is based on satellite images treatments to obtain a thematic map categorizing the different objects in the image and distinguish superficial water. The comparison between images taken in different years will allow to make an estimation of decrease or alterations of superficial water patterns since the installation of the mine.

Inputs

- Landsat images or other satellite images of the area of interest. After examination of the interested area, satellite images can be downloaded from the Earth Explorer website (https://earthexplorer.usgs.gov/) ;
- Ancillary data on the hydrology and topography of the region (hydrological and biophysical data). These data can be obtained from literature research, archival mining company records for Environmental Impact Assessment (EIA);
- Data on the nature of the mining site and it extent to validate the image classification.

Algorithm

- Land use change estimation can be made from multi date satellite images collected in different years, preferably choosing those years where intense mining activities are recorded. The creation of a composite image based on infrared bands can help to classify the biophysical parameters and mine features.

-   The ancillary data on the extent of the mine help in the classification process to accurate select the training fields for the use of the Maximum Likelihood Classification.
-   The classification will then help in the estimation of the surface dedicated to each category and make comparison between the images of previous years. The difference between the classes is made based on different spectral reflectance of the objects on the ground. For example, the distinction between natural and man-made water bodies can be based on different concentration of suspended particles or hydro-chemical properties (Akiwumi et al., 2008).

Outputs

The surface occupied by each category in the classified image for each of the considered years.

4.5 Mineral extraction and habitat fragmentation

The present workflow is conceived as an indicator toward SDG 15 "life on land" and in particular the target 15.3.1. "*Proportion of land that is degraded over total land area*" and Aichi biodiversity target 5. The parameter considered is habitat fragmentation, intended as a landscape level process in which a specific habitat is progressively divided into smaller fragments as a result of both natural and human activities (McGarigal et al., 2005; Didham).

The use of the FRAGSTATS software can be considered to provide the degree of fragmentation of the habitat. FRAGSTATS is a spatial pattern analysis program for quantifying the structure of landscapes. The landscape is used defined and can represent any spatial phenomenon (McGarigal, 2015).

The degree of fragmentation and so the impact of the mine on the integrity of the habitat can be assess by defining a scale going from "low fragmentated" to "highly fragmentated". Another metric that can be considered to assess the degree of fragmentation posterior the installation of the mine, is connectivity. This can be achieved by determining the extent to which movements between patches are facilitated or discouraged in relation to the matrix and the distance occurring between patches.

4.6 Mineral extraction and endemic species: the case of metallophyte plants

The workflow is intended to measure the impact of mineral extraction on the endemic species inhabiting the area of concern, in particular metallophyte plants which survival is strictly dependent from mineral deposits. The indicator derived from the workflow addresses the Aichi biodiversity target 12, "prevent extinctions and improve and sustain species most in decline" and the SDG 15.5.1 "*Red list index*" to reduce the degradation of natural habitats and protect and prevent the extinction of threatened species.

Classified as metallophyte are those plant species that can tolerate high levels of heavy metals. Such plants range between "obligate metallophytes" which can only survive in the presence of the metals they are dependent on, and "facultative metallophytes" which survivor is not strictly dependent from the presence of the metal (Faucon et al., 2010; Ginocchio et al., 2004).

This indicator is calculated from the intersection of spatial data on the distribution of a metallophyte plants and data on the surface occupied by the mine. The result obtained from the intersection of the two layers will provide a measure of the habitat loss and can be used for conservatory purposes to assess the changes in the species abundance when mining activities are present.

Inputs

- Surface of the area occupied by the mine as surface allocated to mining concessions or the surface of individual mines.
- Surface designated to be the habitat of a given species. IUCN Red list spatial data http://www.iucnredlist.org

Algorithm

- Intersect of the input data (ArcMap analysis tools → overlay → intersect)
- Perform zonal statistic between the two areas to obtain the area of the habitat intersecting the mine facilities (ArcMap spatial analyst tools → zonal → zonal statistics)

Outputs

Area of the species habitat occupied by the mine and surface of the habitat lost because of the presence of the mine in km^2.

5. Technical difficulties and future perspectives

The major difficulties encountered in the development of the workflows was the lack of up-to-date data on mineral concessions and their locations. Despite most nations provide a cadaster of the mines present on their territory, the data are not available for download. 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.

Equally difficult was to find recent data on forest cover and data for species distribution and their habitat. Concerning the avian species, data on their habitat, distribution and abundance are available on the Boreal Avian Modeling Project but not as an open source (http://www.borealbirds.ca/index.php/avian_data). The IUCN website provides a good platform where is possible to obtain shapefiles on the distribution of a determine species but no additional information on the abundance are available. This data source was of use in trying to implement the workflow assessing the metallophytes species distribution but the lack of information on the abundance, rendered complicated the identification of species hotspots to quantify in what measure a mine overlapping a portion of the habitat will be dangerous for the survival of the species.

The collection of in situ data represent a necessary source of data for the development of useful indicators helping in monitoring the changes on the ecosystems over time. Thus, it is essential to make the resources available and accessible for those intended to use them. Another essential step to take, is to coordinate the data collection effort in order to obtain reliable data compiled according standard sampling method which will facilitate the exploitation, updating and sharing of information.

With this work we tried to explore the possibilities to implement workflows able to support indicators to assess the impact of mineral extraction on the environment. At the same time, we tried to make the indicators ready-to-use tools by translating the workflow into an automated process through the development of a script. Different components of the ecosystems were considered and related to extractive activities that are known to represent a threat to their functioning.

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 Sustainable Development Goals. The workflows were proposed based on the literature review conducted in order to understand the problematic and the impact mineral extraction has on the environment. The methodology proposed, partially based on scientific publications and on personal reasoning, need to be tested and improved. Thus, the following steps

in the implementation of these workflows is to identify areas sufficiently impacted by extractive activities where good quality data are available and develop coherent data treatment.

The workflow developed for the assessment of the impact of mineral extraction on forest cover can have different applications depending on the input data used. The outputs and thus the information from the indicator are related to the type of mine that is present on the area, for example, an open pit mine will have a major impact in term of forest loss compared to an underground mine. Other factors that can influence the outcome of mineral activities on the forest are the mineral being extracted requiring 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 lost by using the indicator to calculate the surface of forest lost 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 rhythm of deforestation as a consequence of the mine and obtain useful information for the purpose of environmental monitoring in relation to mineral extraction.

6. Conclusion

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 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 is still the privileged approach. For this reason, the mineral industry need to take all the necessary measures to prevent or reduce at the minimum the loss of net environmental continuity and ecosystem integrity. Amongst the aspects to be considered for a more sustainable exploitation of mineral deposits should be:

- Measures to act after the closing of the mine in terms of waste handling and disposal;
- The environmental legacy left by the mine in terms of contamination of water resources, forest and soil;
- The loss of biodiversity as a consequence of ecosystem disturbances and alternations.

In this context the concept of Extractive Essential Variables represents a valuable instrument to create a framework for efficient monitoring able to capture key aspects of natural ecosystems and their functioning.

The use of Essential Variables as sustainable development indicators will help to translate the sustainability issues linked to mineral extraction into a concrete measure of environmental performances which will ultimately lead to the compliance of the SDGs and other political framework looking towards a more attentive approach to natural resources exploitation.

7. References.

Akiwumi et al., 2008. *Mining and environmental change in Sierra Leone, West Africa: a remote sensing and hydrogeomorphological study*. Environmental Monitoring and Assessment, 142:309-318. doi: 10.1007/s10661-007-9930-9;

Awuah-Offei et al., 2011. *Application of cycle assessment in the mining industry*. International Journal of Life Cycle Assessment, 16, pp. 89-89;

Azapagic, 2004. *Developing a framework for sustainable development indicators for the mining and minerals industry.* Journal of Cleaner Production, 12, pp. 639-662;

Bernhardt et al., 2011. *The environmental costs of mountaintop mining valley fill operations for aquatic ecosystems of the Central Appalachians.* Annals of the New York Academy of Science, 1223, pp. 39-57;

Blonda et al., 2016. *Current status of the Essential Variables as an instrument to assess the Earth Observation Networks in Europe.* EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, id. EPSC2016-16692;

Bojinski et al., 2014. *The concept of essential climate variables in support of climate research, applications and policy.* American Meteorological Society. *https://doi.org/10.1175/BAMS-D-13-00047.1;*

Breaking new ground. The report of the Mining, Minerals and Sustainable Development Project, 2002. Earthscan publications Ltd London;

Brummitt et al., 2017. *Taking stock of nature: Essential Biodiversity variables explained.* Biological conservation, 213, pp. 252-255;

Castro Pena et al., 2017. *Impacts of mining activities on the potential geographic distribution of eastern Brazil mountaintop endemic species.* Perspectives in ecology and conservation, 15, pp. 172-178;

Constable et al., 2016. *Developing priority variables ("ecosystem Essential Ocean Variables – eOEVs) for observing dynamics and change in Southern Ocean ecosystems.* Journal of Marine Systems, 161, pp. 26 – 41;

Didham. *The ecological consequences of habitat fragmentation.* Encyclopedia for life sciences;

Drielsma et al., 2016. *Mineral resources in life cycle impact assessment – defining the path forward.* Life Cycle Sustainability Assessment, 21, pp. 85-105;

Durucan et al., 2006. *Mining life cycle modelling: a cradle to gate approach to environmental management in the minerals industry.* Journal of cleaner production, 14, pp. 1057-1070;

Faucon et al., 2010. *Copper endemism in the Congolese flora: a database of copper affinity and conservational value of cuprophytes.* Plant ecology and evolution, 143(1), pp. 5-18;

Ferreira et al., 2015. *A life cycle assessment study of iron ore mining.* Journal of Cleaner Production, 108, pp. 1081-1091;

Frelich, 2014. *Forest and terrestrial ecosystem impacts of mining.* Report from University of Minnesota Center for Forest Ecology. September 2014;

Geijzendorffer et al., 2015. *Bridging the gap between biodiversity data and policy reporting needs: an Essential Biodiversity Variables perspective.* Journal of Applied Ecology. doi: 10.1111/1365-2664.12417;

Ginocchio et al., 2004. *Metallophytes in Latin America: a remarkable biological and genetic resources scarcely known and studied in the region.* Revista Chilena de Historia Natural, 77, pp. 185-194;

Hendryx, 2009. *Mortality from heart, respiratory, and kidney disease in coal mining areas of Appalachia.* International Archives of occupational and environmental health, 82: 243-249;

Karmakar et al., 2012. *Impact of mining on ground and surface waters.* International Mine Water Association, 2012. www.IMWA.info ;

Kociolek et al., 2010. *Effects of road networks on bird populations.* Conservation Biology, 25(2), pp. 241-249;

Layman et al., 2007. *Niche width collapse in a resilient top predator following ecosystem fragmentation.* Ecology Letters, 10, pp. 937-944;

Lindahl, 2014. *Towards better environmental management and sustainable exploitation of mineral resources.* SGU Geological Survey of Sweden;

Macdonald et al., 2015. *Forest restoration following surface mining disturbance : challenges and solutions.* New Forests, 46, pp. 703-732;

Marnika et al., 2015. *Sustainable development indicators for mining sites in protected areas: tool development, ranking and scoring of potential environmental impacts and assessment of management scenarios.* Journal of cleaner production, 101, pp. 59-70;

McGarigal et al., 2005. *Quantifying terrestrial habitat loss and fragmentation: a protocol.* Department of Natural Resources Conservation, University of Massachusetts;

McGarigal, 2015. *FRAGSTATS help.* Fragstats documentation. University of Massachusetts, Amherst;

Padmanaban et al., 2017. *A remote sensing approach to environmental monitoring in a reclaimed mine area.* International Journal of Geo-Information, 6, 401. doi:10.3390/ijgi6120401;

Prior et al., 2011. *Resource depletion, peak minerals and the implications for sustainable resource management.* Global Environmental Change. doi: 10.1016/j.gloenvcha.2011.08.009;

Reyers et al., 2017. *Essential Variables help to focus Sustainable Development Goals monitoring.* Current Opinion in Environmental Sustainability, 26-27:97 – 105. *http://dx.doi.org/j.cosust.2017.05.003* ;

Saad et al., 2011. *Investigating the vegetation-soil relationships on the copper-cobalt rock outcrops of Katanga (D.R. Congo), an essential step in a biodiversity conservation plan.* The Journal of the Society for Ecological Restoration International. doi: 10.1111/j.1526-100X.2011.00786.x;

Santo et al., 2002. *GIS applied to determine environmental impact indicators made by sand mining in a floodplain in southeastern Brazil.* Environmental Geology, 41 (6), pp. 628-637;

Sumaila et al., 2017. *Investments to reverse biodiversity loss are economically beneficial.* Current Opinion in Environmental Sustainability, 29, pp. 82-88;

Turak et al., 2016. *Using the essential biodiversity variables framework to measure biodiversity change at national scale.* Biological Conservation, http://dx.doi.org/10.1016/j.biocon.2016.08.019 ;

Van Wilgenburg et al., 2013. *Estimated avian nest loss associated with oil and gas exploration and extraction in the Western Canadian Sedimentary Basin.* Avian Conservation and Ecology, 8(2) :9. *http://dx.doi.org/10.5751/ACE-00585-080209* ;

Vela-Almeida et al., 2016. *Lessons from Yanacocha: assessing mining impacts on hydrological systems and water distribution in the Cajamarca region, Peru.* Water International http://dx.doi.org/10.1080/02508060.2016.1159077;

Waldner et al., 2017. *National scale cropland mapping based on spectral-temporal features and outdated land cover information.* PLoS ONE 12(8): e0181911. https://doi.org/10.1371/journal.pone.0181911

8. Appendix 1

```bash
#!/bin/bash

tar -zxvf concessions.tar.gz

VECT="concessions_agregees_2015_one.shp"

vec_RAST=("Hansen_GFC2015_treecover2000_00N_010E.tif"
"Hansen_GFC2015_treecover2000_00N_020E.tif" "Hansen_GFC2015_treecover2000_10N_020E.tif"
"Hansen_GFC2015_treecover2000_10N_030E.tif" "Hansen_GFC2015_treecover2000_10S_020E.tif")
```

```bash
vec_OUT=("concessions1.tif" "concessions2.tif" "concessions3.tif" "concessions4.tif"
"concessions5.tif")
```

 # Create a counter to dynamically create vect_OUT

```bash
cnt=0
```

 # Create an empty rast_sum variable

```bash
sum_sum=0
```

 # Create an empty detailed_sum_rast.txt file

```bash
echo "" > detailed_rast_sum.txt


for i in "${vec_RAST[@]}"

do
```

    # increment the counter

```bash
    ((cnt+=1))

    RAST=$i

    echo "* processing: $RAST"
```

 # Get extent

```bash
    meta=`gdalinfo $RAST | grep 'Lower Left' | sed 's/Lower Left  (//g' |  sed 's/) (/,/g'`

    w=`echo ${meta}| awk -F ',' '{print $1}'`

    s=`echo ${meta}| awk -F ',' '{print $2}'`

    meta=`gdalinfo $RAST | grep 'Upper Right' | sed 's/Upper Right (//g' | sed 's/) (/,/g'`

    e=`echo ${meta}| awk -F ',' '{print $1}'`

    n=`echo ${meta}| awk -F ',' '{print $2}'`
```

 # Get resolution (necessary to use the -tap option to guarantee proper overlay with RAST)

```bash
    meta=`gdalinfo $RAST | grep 'Pixel Size' | sed 's/Pixel Size = //g' | sed 's/(//g' | sed
's/)//g' | sed 's/ - /, /g'`

    rez=`echo ${meta}| awk -F ',' '{print $1}'`
```

 # RASTerize VECT as 1 overlaying perfectly RAST using information just collected

```bash
    rm -f concessions$cnt.tif # Remove the file if it already exists

    gdal_rasterize -te $w $s $e $n -tr $rez $rez -tap -burn 1 -init 0 -co COMPRESS=LZW $VECT
concessions$cnt.tif
```

 # Combine both rasters

```bash
    rm -f masked_$RAST # Remove the file if it already exists

    gdal_calc.py -A $RAST -B concessions$cnt.tif --co COMPRESS=LZW --outfile=masked_$RAST --
calc="A*B"
```

 # Calculate pixels sum, multiply by surface (km2) and take percentage into account

```
    stat=`gdalinfo -stats masked_$RAST | grep 'Size is ' | sed 's/Size is //g' |  sed 's/)
(/,/g'`

    xpx=`echo ${stat}| awk -F ',' '{print $1}'`

    ypx=`echo ${stat}| awk -F ',' '{print $2}'`

    cellmean=`gdalinfo   -stats   masked_$RAST   |   grep   'STATISTICS_MEAN='   |   sed
's/STATISTICS_MEAN=//g' |  sed 's/) (/,/g'`

    rast_sum=`echo $cellmean*$xpx*$ypx*625/100/1000000 | bc`
```

 # Write the sum of each loop in a detailed file

```
    echo $rast_sum >> detailed_rast_sum.txt
```

 # Sum up the result of each loop

```
    sum_sum=`echo $sum_sum+$rast_sum | bc`

done
```

 # write the total sum in a file

```
echo $sum_sum > rast_sum.txt
```