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Essential earth observation variables for high-level multi-scale indicators and policies

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ABSTRACT

Several holistic approaches are based on the description of socio-ecological systems to address the sustainability challenge. Essential Variables (EVs) have the potential to support these approaches by describing the status of the Earth system through monitoring and modeling. The different classes of EVs can be organized along the environmental policy framework of Drivers, Pressures, States, Impacts and Responses. The EV concept represents an opportunity to strengthen monitoring systems by providing observations to seize the fundamental dimensions of the Earth system

The Group on Earth Observation (GEO) is a partnership of 113 nations and 134 participating organizations in 2021 that are dedicated to making Earth Observation (EO) data available globally to inform about the state of the environment and enable data-driven decision processes. GEO is building the Global Earth Observation System of Systems, a set of coordinated and independent EO, information and processing systems that interoperate to provide access to EO for users in the public and private sectors. The progresses made in the development of various classes of EVs are described with their main policy targets, Internet links and key references

The paper reviews the literature on EVs and describes the main contributions of the EU GEOEssential project to integrate EVs within the work plan of GEO in order to better address selected environmental policies and the SDGs. A new GEO-EVs community has been set to discuss about the current status of the EVs, exchange knowledge, experiences and assess the gaps to be solved in their communities of providers and users. A set of four traits characterizing an EV was put forward to describe the entire socio-ecological system of planet Earth: Essentiality, Evolvability, Unambiguity, and Feasibility. A workflow from the identification of EO data sources to the final visualization of SDG 15.3.1 indicators on land degradation is demonstrated, spanning through the use of different EVs, the definition of the knowledge base on this indicator, the implementation of the workflow in the VLab (a cloud-based processing infrastructure), the presentation of the outputs on a dedicated dashboard and the corresponding narrative through a story map.

Abbreviations: EO, Earth Observation; EV, Essential Variable; GEO, Group on Earth Observations; GEOSS, Global Earth Observation System of Systems; SBA, Societal Benefit Areas of GEO; VLab, Virtual Earth Laboratory.

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The concept of EV started in the climate sphere and spread to other domains of the earth system but less so in socio-economic activities. More work is therefore needed to converge on a common definition and criteria in order to complete the implementation of EVs in all GEO focus areas. EVs should screen the entire Earth's social-ecological system, providing a trusted and long-term foundation for interdisciplinary approaches such as ecological footprinting, planetary boundaries, disaster risk reduction, and nexus frameworks, as well as many other policy frameworks such as the SDGs

1. Introduction

Several holistic approaches have been developed to link the social and biophysical parts of socio-ecological systems in order to address the sustainability challenge (Lehmann et al., 2017). Approaches such as the planetary boundaries (Rockstrom et al., 2009; Steffen et al., 2018), ecological footprints (Fang et al., 2015), natural disaster risk reductions (UNDRR, 2019), ecosystem services (Millennium Ecosystem Assessment, 2005) and the nexus and socio-ecological system metabolism (Giampietro et al., 2009) are aiming to explicitly link environmental, social and economic dimensions.

Essential Variables (EVs) have the potential to support these approaches by fully describing the socio-ecological Earth system for its monitoring and modeling in order to track progress towards sustainable development (Fig. 1) and by exploring simultaneously the essential Earth system variables and the essential socio-economic system variables, in order to define a full set of Essential SDG Variables (Reyers et al., 2017; Lehmann et al., 2020a; Plag and Jules-Plag, 2020). Furthermore, the different classes of EVs can be organized along the well-known environmental policy framework of Drivers, Pressures, States, Impacts and Responses (DPSIR)(Masò et al., 2020) for improved policy monitoring.

First the State and Evolution of the Earth system can be described by its Atmosphere characterized by the Essential Climate Variables (Bojinski et al., 2014), its Hydrosphere characterized by the Essential Water Variables (Lawford, 2014) and Essential Ocean Variables (Miloslavich et al., 2018), its Biosphere characterized by the Essential Biodiversity Variables (Pereira et al., 2013), and its Geosphere characterized by Essential Geodiversity Variables (Schrodt et al., 2019). The state of these variables will then affect and modify their potential Benefits and Impacts on the Socio-Economic System. This system will modify its Responses and Activities that can be decomposed into Essential Variables for Urban environment (Patias et al., 2019), Energy (Ranchin et al., 2020) and Minerals, Transport and Infrastructure, Health, Population (Ehrlich et al., 2018) and Agriculture (Whitcraft et al., 2015). Finally, variations and levels of intensity of human activities will modify the Drivers and Pressures on the Earth system. The aim of sustainable development can clearly be defined as an attempt to secure the provision of benefits from the Earth system towards the socio-economic system, while minimizing the changes in drivers and pressure on the Earth system (Biggs et al., 2015).

Sustainability research efforts are advancing and identifying critical

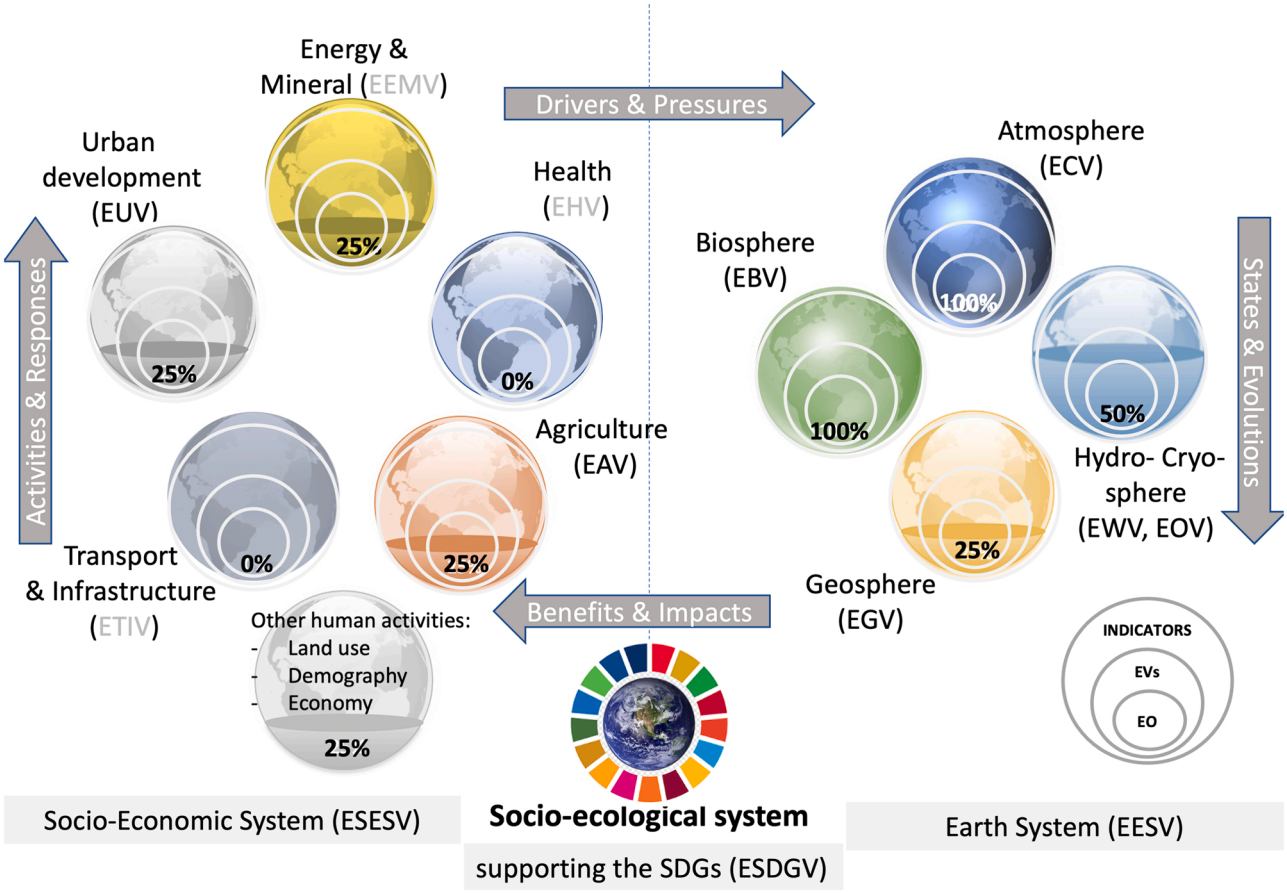

Fig. 1. Status in 2021 of Essential Variables development in the different GEO SBAs in support of SDGs and in relationship with the DPSIR policy framework. Percentages represent level of development of EV classes from EO to indicators.

drivers of change and evolution in social, economic, and environmental systems. The concept of EVs represents an important opportunity to strengthen monitoring by providing more effective observations and to capture fundamental dimensions of the Earth system. An EV can potentially contribute to multiple SDG indicators, and a given observation can be linked to more than one class of EV (e.g., land use, temperature). This can allow for a potential reduction in the number of observations needed to provide indicators, moving from a Big Data set of candidate observations to a Smart Data set of observations used to describe selected EVs (Reyers et al., 2017). EO is not restricted to the data obtained by remote sensing from satellites and is considered in its different forms that include also data from sensors on Earth, in-situ observations, data from citizen sciences and social networks. The estimated percentages of development of the different classes of EVs are represented graphically in Fig. 1.

The objective of this paper is to review the literature on EVs and to explore their integration in the framework of the GEO work plan (GEO, 2017, 2019) as well as their potential contributions for addressing the SDGs and other environmental policies.

2. Group on earth observations

The Group on Earth Observations (GEO: www.earthobservations.org) is a partnership of 113 nations and 134 participating organizations in February 2021 that are dedicated to making Earth Observation (EO) data available globally to inform about the state of the environment and enable data-driven decision processes for a more sustainable World. GEO was created in 2005 and grew up as a unique global network of governmental, research and private organizations. GEO activities can be monitored through its Work Programme for 2020–2022 (GEO, 2019). GEO is the relevant organization to promote and coordinate the development of EVs through its three priority engagement areas (PEAs) and eight societal benefit areas (SBAs) that are described below. The relationships between GEO SBAs, global policies, EVs and SDG are represented below and in Fig. 2. Most SBAs correspond to a clearly identified global policy and a set of dedicated EVs, which are connected directly to nine of the seventeen SDGs. All EVs sets are contributing indirectly to several SDGs (Fig. 3).

2.1. The three main global priority engagement areas of GEO

First, GEO brings its members and EO together in order to contribute to the seventeen Sustainable Development Goals (SDGs) (UN, 2015). It is indeed recognized that EO can help assessing the progress toward many of the 169 targets of the SDGs by monitoring the changes on our planet with space and Earth observing systems that are based on both natural science and socio-economic data (Anderson et al., 2017; Kavvada et al., 2020). While monitoring the progress of every nation is instrumental, the importance of EO probably resides even more in its capacity to inform decisions on the ground at finer temporal and spatial scales, in a consistent and standardized manner (Dhu et al., 2019). Each country should now be capable of gathering important information from various data sources to monitor its progress towards its targets and furthermore guide its sustainability policy (Gregg and Rajabifard, 2017; Giuliani et al., 2020b). The EO in Service of the 2030 Agenda for Sustainable Development Initiative (EO4SDG) strives to bring EO into practice to support the SDGs (GEO, 2017).

Second, in the climate change policy agenda, GEO actively collaborates through its members with the UN Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization (WMO), the United Nations Environment Programme (UN Environment), and the Committee on Earth Observation Satellites (CEOS) to help implementing the 2015 Paris Agreement. The use of EO represents indeed a unique opportunity to inform mitigation and adaptation policies at various spatial scales in near real-time. Carbon storage and sequestration,

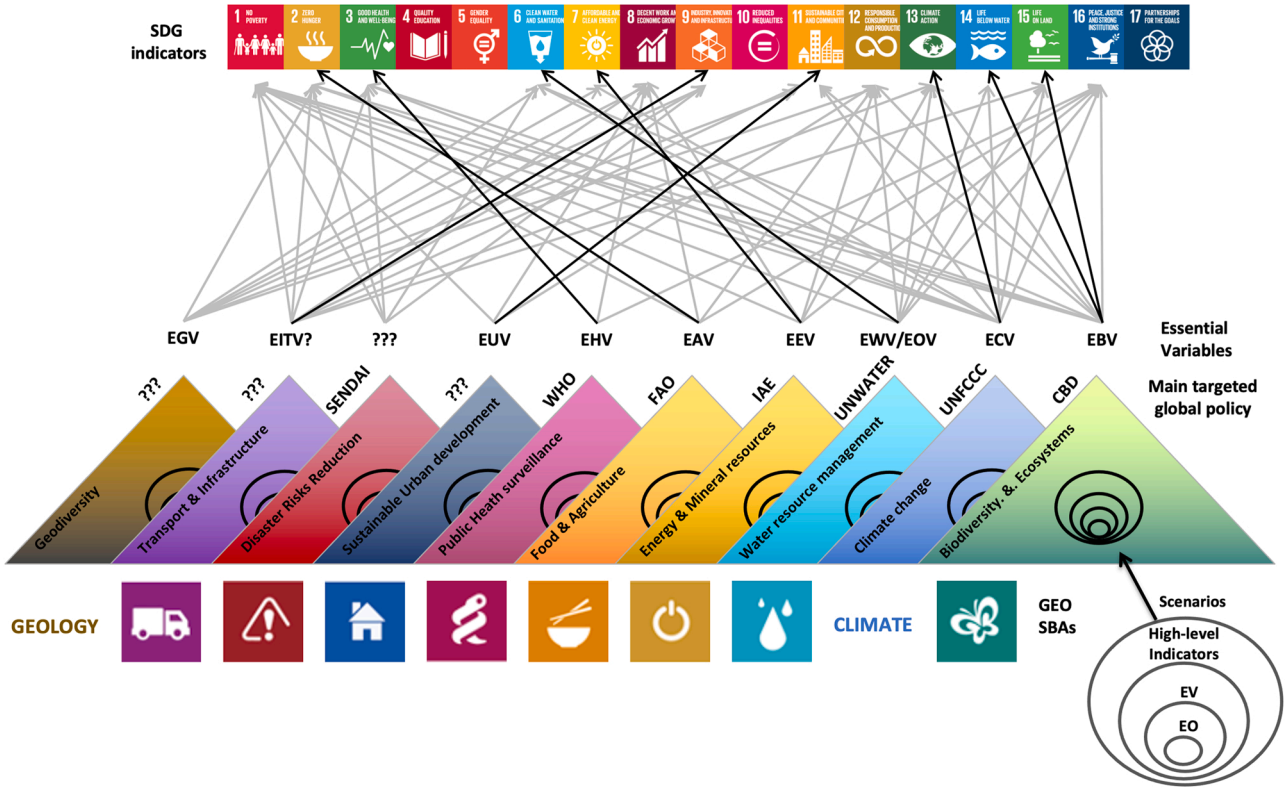

Fig. 2. Main relationships between GEO SBAs, global policies, EVs and SDGs. Bold arrows represent direct links between set of EVs and SDGs. Grey arrows represent indirect links.

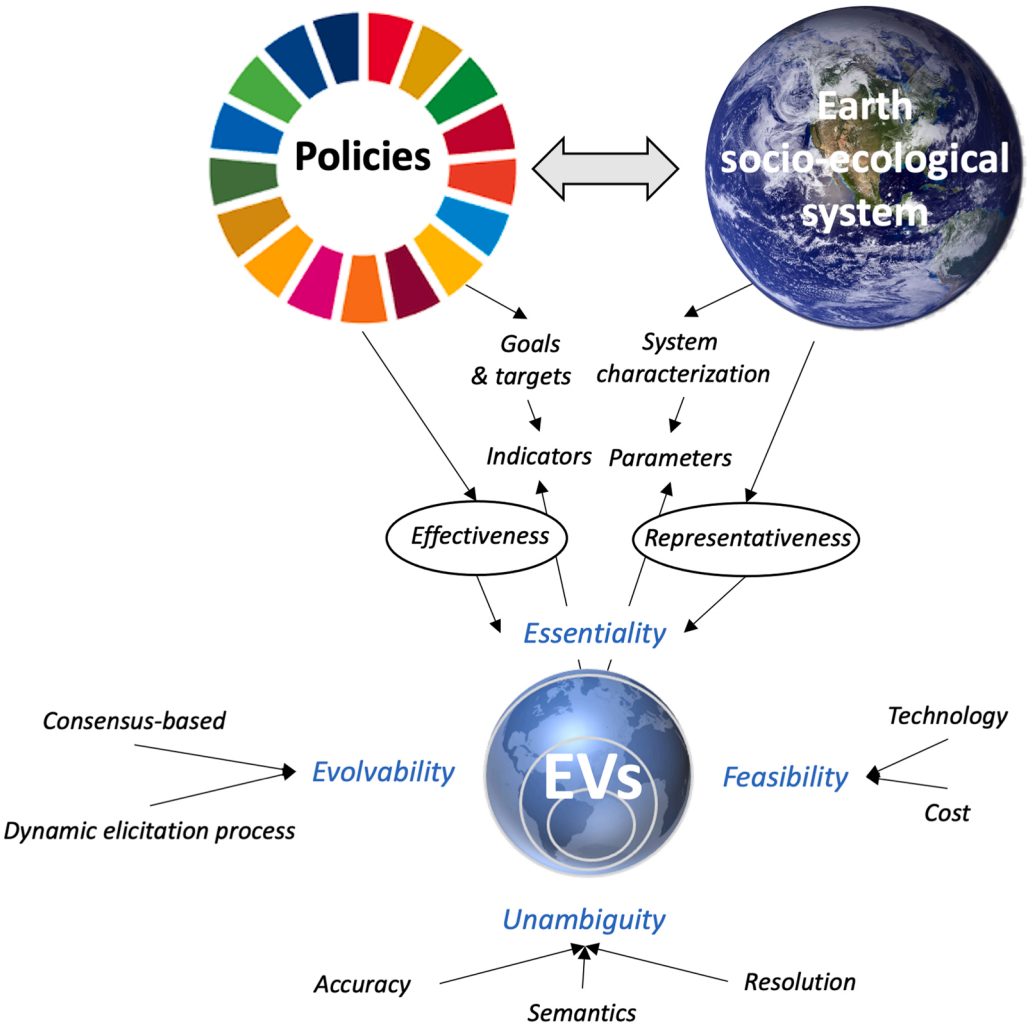

Fig. 3. EVs traits and selection criteria.
(modified from Lehmann et al., 2020a).

greenhouse gasses emissions and concentrations, sea levels, land use cover changes such as snow and ice extent, urban sprawl, desertification or land degradation are all examples of key variables that can be readily measured and estimated from available remote sensors. Combined with socio-economic data, this knowledge can be used to assess risks, vulnerabilities, impacts and resilience. This newly available information is central to the deployment of dedicated climate services for driving mitigation and adaptation actions in most human activities. Several activities in the GEO work programme are supporting these efforts (GEO, 2019).

Third, EO is also central to the implementation of the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) to forecast and prepare for disasters, to mitigate damage and to better manage and recover from disasters. In summary, the objective is to protect a significant number of lives and properties from the hazards of natural disasters such as wildfires, tsunamis, landslides, avalanches, floods, droughts, volcanoes and earthquakes. The GEO initiative on Data Access for Risk Management (GEO-DARMA) is fostering the use of EO in the disaster risk reduction community to bring more accurate risk data and improve decision making.

2.2. Principal GEO Societal Benefit Areas

Among the GEO SBAs, four can be associated to the description of the Earth's natural spheres (atmo-, hydro-, geo-, and bio- spheres) where the others are rather associated to the socio-economic spheres (health, energy, agriculture, transport and cities) (Lehmann et al., 2020a). Altogether, spheres depict the global socio-ecological system of the Earth (Fig. 1).

First, the activities of GEO in relationship with the atmosphere have been described above in the paragraph on climate change. This topic is probably the most active in EO and many initiatives exist that feed into the achievement of SDG 13 on climate (Bojinski et al., 2014).

The study of the hydrosphere has a long tradition in EO from ground to space, as water is central for life on Earth. GEO is very active in coordinating the access of EO that can be calibrated with data from hydrological gauges in order to provide the necessary inputs for the assessment and modeling of the water cycles at various spatial and temporal scales. This is crucial to guide Integrated Water Resource Management for a sustainable use of water (SDG 6) in agriculture, households, industries, energy production and biodiversity support (Lawford, 2014). Another dimension of the hydrosphere is the oceans, and the observation of them is covered by the Global Ocean Observing System (GOOS) (UNESCO, 2012).

The observation of the geosphere (soils and geology) is less prominent in EO. A good example of activities in this direction is the One-Geology project that aims at serving standardized geological data to address global challenges such as the three main GEO policies described above (Laxton et al., 2010).

The SBA on biodiversity and ecosystems is focusing on the

monitoring of the biosphere, through several initiatives such as the Global Ecosystem (GECO), the Global Forest Observation (GFOI), the Global Network for Observation and Information in Mountain Environments (GEO GNOME) and the Biodiversity Observation Network (GEO-BON). Key information and knowledge are gathered on genes, species and ecosystems past, present and future states in order to inform local, national and international conservation policies. This SBA is closely linked to the post 2020 targets of the UN Convention on Biological Diversity and SDG 14 on water and 15 on terrestrial biodiversity (Scholes et al., 2012).

The next five SBAs are related to the observation of the socio-economical activities taking place on the Earth system.

Sustainable energy and mineral resources provision belong to another central SBAs of GEO. In order to preserve the climate of the Earth while sustaining human activities, new sources of clean energy must be identified, quantified and forecasted in order to increase their proportion in the energy mix until a zero emission of greenhouse gasses is reached. Both the public and private sectors are engaged in this race. EO can bring valuable information to assess the potential of new sources of clean energy, to improve their management and to increase their efficiency. This effort is carried by the GEO-VENER initiative in support of various international policies and SDG 7 on Sustainable energy (Ranchin et al., 2020).

EO combined with crop monitoring bring valuable information to address the challenge of food security and sustainable agriculture to reach SDG 2 on Zero Hunger. The challenge is to provide accurate and timely information to farmers on crop productivity status, potential and outlooks in the context of global changes. The contribution of EO can be seen here as a way to help farmers and decision makers to improve their crop productivity while preserving the environment. This is achieved through the monitoring of past and present crops and the forecast of their productivity in near and far futures, providing early warning system, in case of extreme events, and long-term forecast as function of global changes. The GEO activity in this SBA is done within the GEO-GLAM initiative (Whitcraft et al., 2015).

The development of key infrastructures is essential to maintain a sustainable and equitable distribution of resources and opportunities. EO can provide very useful information to monitor, manage and plan infrastructures such as industries, dams, roads, railways, ports and pipelines as well as transportation activities on air, land and seas. The aim of the GEO is to minimize environmental impacts with low-carbon footprints. This activity is closely related to SDG 9 on industry, innovation and infrastructures.

EO is helping to achieve SDG 3 on good health and wellbeing by monitoring for instance the air quality and environmental pollutants (e.g., Anenberg et al., 2020), the climate conditions that facilitates the outbreaks of diseases (e.g., Parselia et al., 2019), or the exposome linked to non-communicable diseases (e.g., Sogno et al., 2020). The relationships between environment quality and health issues are getting more and more attention with the outbreaks of various diseases that can potentially result in pandemics. EO variables include airborne, marine, and water pollutants; stratospheric ozone depletion; land-use change; persistent organic pollutants; food security and nutrition; noise levels; weather-related stresses and disease vectors; and many others. These observations combined with models can help to predict the outbreaks and trends of diseases such as meningitis, cholera and malaria (e.g., Weiss et al., 2019). As seen during the COVID-19 pandemic, the access to reliable information is key to better-informed decision making and increase public awareness that can potentially save millions of lives (Sathe et al., 2021). The EO4HEALTH and GOS4M activities are typically addressing these challenges under the GEO umbrella.

Finally, EO is important to improve the design of future urban areas in a more sustainable way (SDG 11). This is a huge challenge as a majority of the human population is now living in urban areas and their environmental impacts are therefore increasing. EO can help rethinking the urban agenda by promoting sustainable and resilient solutions to make cities more inclusive and safer, through identifying economic externalities, and by managing environmental, climate and disaster risks (e.g. Prakash et al., 2020; Giuliani et al., 2021).

While GEO activities are functioning well within each thematic community, driving the Earth towards sustainability requires an intensive exchange of knowledge and information across all SBAs. An analogy can be made with the pilot of a plane that would have access to all the parameters of his plane instrumentation, versus a pilot looking only at his altimeter. Continuing with the same metaphor, in EO domain the altimeter could be replaced by Gross Domestic Product, for instance, while the whole set of parameters can be represented by the SDG indicators. The pilot of the "SDG" plane is typically a national government that has reporting obligations but also the private sector that is more and more interested in the assessment of its impacts of SDGs.

2.3. Global earth observation system of systems

GEO is also building the Global Earth Observation System of Systems (GEOSS), a set of coordinated and independent EO, information and processing systems that interact with each other and provide access to diverse information to a wide range of users in the public and private sectors (Nativi et al., 2013, 2020). GEOSS facilitates the sharing of environmental data and information collected by the many observing systems maintained by countries and organizations within the GEO (Giuliani et al., 2011). In addition, GEOSS ensures that these data are accessible, of a certain quality and origin, and are interoperable to support the development of tools and the provision of information services. GEOSS promotes common technical standards so that data from thousands of different sources can be combined into consistent data sets. The GEOSS Portal (www.geoportal.org) is a single Internet access point for users seeking data, images and analysis software relevant to all regions of the world. It connects users to existing databases and portals and provides reliable, up-to-date and user-friendly information - essential for the work of decision-makers, planners and emergency managers. A capacity building package to bring GEOSS into practice has been developed (Giuliani et al., 2017a).

3. GEO relationships with EVs

3.1. Set of EVs used in GEO

In Table 1, the progress made in the development of various classes of EVs is described. The concept of EVs was first defined by the climate community through the efforts of the Global Climate Observing System (GCOS), which established a set of 50 Essential Climate Variables (ECVs) (Ostensen et al., 2008). ECVs were selected for their relevance to characterizing the Earth's climate system and for their technical and economic feasibility for systematic observations (Giuliani et al., 2017b). Although the ECV concept covers some areas other than the atmosphere, approaches have been taken to extend the concept to the ocean and biodiversity. Other communities are currently working to define a common set of key variables such as water, agriculture, sustainable energy, geology, extractives, urban areas, air quality, and ecosystems. Essential Biodiversity Variables (EBVs) further clarify the role of EVs, which fall between primary observations and indicators (Geijzendorffer et al., 2016) to address both the diversity of data providers and the changing demand for indicators in different regions and different policy needs (Reyers et al., 2017).

3.2. Objectives of the GEO EVs community activity

Now that the stock has been taken on the development of EVs (Table 1), it is the time to strengthen the definition of EVs across domains to allow the development of interdisciplinary research and applications. Based on the findings of two EU research projects, ConnectinGEO (www.connectingeo.net) and ERA-PLANET/

Table 1
GEO priority engagement areas (PEAs) and societal benefit areas (SBAs), EO activities, Essential Variables, policy goals, level of progress of EVs, links and references.

GEO PEAs and SBAs	EO activities	Existing EV classes	Targeted policy goals	Level of progress on EVs	Links	References
SDGs	EO4SDG	ESDGV	All SDGs	50%	www.earthobservations.org/documents/gwp20_22/EO4SDG.pdf	Brende and Hoie (2015);GEO (2017);Reyers et al. (2017)
Disaster resilience	GEO-DARMA	NA	Sendai frameworkUNDRR	0%	www.preventionweb.net/sendai-framework/sendai-framework-monitor/indicators	NA
Climate action	GCOS	ECV	IPCC, UNFCCCSDG 13	100%	gcos.wmo.int/en/essential-climate-variables	Hollmann et al. (2013);Bojinski et al. (2014); Miranda Espinosa et al. (2020)
Water resource management	GEOGLOWS	EWV	SDG 6	50%	www.earthobservations.org/documents/gwp20_22/GEOGLOWS.pdf	Leonard and Duffy (2013);Lawford (2014)
Water resource management	GOOS	EOV	SDG 14	50%	www.goosocean.org	UNESCO (2012);Hayes et al. (2015);Miloslavich et al. (2018)
Biodiversity and ecosystem sustainability	GEOBON	EBV	IPBES, CBDSDG 14,15	100%	www.geobon.org/ebvs	Pereira et al. (2013);Skidmore et al. (2015); Geijzendorffer et al. (2016);Pettorelli et al. (2016);Kissling et al. (2018);Hardisty et al. (2019);Jetz et al. (2019);Dantas de Paula et al. (2020)
Geology and pedology resource management	Geodiversity OneGeology	EGV	SDG 7	25%	www.researchgate.net/project/Essential-Geodiversity-Variables www.onegeology.org	Schrodt et al. (2019)
Energy	GEO-VENER	EREV	UNFCCCSDG 7	25%	www.earthobservations.org/documents/gwp20_22/GEO-VENER.pdf	Ranchin et al. (2020)
Mineral resource management	NA	EMV	SDG 7	25%	https://www.earthobservations.org/documents/gwp20_22/EO4MIN.pdf	Ambrosone et al. (2019)
Food security and sustainable agriculture	GEOGLAM	EAV	SDG 2	25%	earthobservations.org/geoglam.php	Whitcraft et al. (2015);GEOGLAM (2018)
Public health surveillance	EO4HEALTH GOS4M	NA	SDG 3	0%	www.geohealthcop.orgwww.gos4m.org	NA
Infrastructure and transport management	NA	NA	SDG 9	0%	NA	NA
Sustainable urban development	GUOI	EUV	SDG 11	25%	www.earthobservations.org/documents/gwp20_22/GUOI.pdf	Weng (2018);Patias et al. (2019)
Societal	NA	ESV	All SDGs	25%	NA	Ehrlich et al. (2018)

NA: not available; ESDGV: SDG; ECV: Climate; EWV: Water; EOV: Ocean; EBV: Biodiversity; EGV: Geodiversity; EREV: Renewable Energy; EMV: Mineral; EAV: Agriculture; EUV: Urban; ESV: Societal.

GEOEssential (www.geoessential.eu), a new GEO-EVs community (www.eneon.net/CommunityActivityEV.htm) has been set with the vision to achieve the challenging task of generalizing EVs (GEO, 2020). A panel of experts will be set to discuss about the current status of EVs, exchange knowledge, experiences and methodologies, finding the gaps to be solved, and avoiding duplicated work. GEO-EV does not have the intention to replace or constrain the on-going actions of communities already working on the definition of EVs. Instead, it aims to become a forum allowing to share expertise and experiences, address multidisciplinary aspects of EVs, and speak with a single voice about EVs inside GEO. More specific objectives have been set:

- Exchange experiences, methodologies and knowledge regarding the development of EVs in several GEO communities;
- Monitor the evolution of the EV definition in different domains;
- Discuss multidisciplinary aspects of EVs, including harmonization of EV definitions, mapping of cross-domain EVs, etc.
- Consolidate the EV in the themes that has not completed a list of EVs;
- Generate a roadmap to generalize and complete the definition of EVs in other EO communities;
- Ensure that the identified EVs support the generation of the entire set of SDG indicators; and
- Collect EV requirements (e.g. spatial and temporal resolutions) for different purposes and user scenarios of policy related decision-making.

4. Main contributions of GEOEssential to strengthen EVs in GEO

4.1. From connectinGeo to GEOEssential

ConnectinGEO and GEOEssential have recognized the necessity to promote the generation of EVs across GEO SBAs. ConnectinGEO (2015–2018) aimed at linking existing coordinated EO networks with the scientific communities, the industry sector and the EO stakeholders. The goal was to facilitate a broader and more accessible knowledge base to support the needs of the GEO priority engagement areas. GEO-Essential (2017–2020) is demonstrating the benefit of EVs by implementing full dedicated workflows from available data sources to policy indicators. Existing EVs, data sources and platforms were analyzed in order to identify substantial gaps and synergies for addressing the needs of environmental policies in agriculture, water, biodiversity, energy, light and raw materials. GEOEssential is developing workflows based on EVs with data sources available in GEOSS to derive policy relevant indicators. GEOEssential is one of the four EO projects of the ERA-Planet program (www.era-planet.eu) described in this special issue (Pirrone

et al., 2021, this issue).

4.2. Criteria for defining EV classes

As demonstrated in Table 1, the concept of EVs has spread relatively quickly across topics but with little coordination. Essential Climate Variables have been developed to characterize the climate system according to 3 criteria: Relevance to characterize the climate system, Feasibility with proven scientific methods, and Cost effectiveness with affordable solutions. For the Biodiversity community, Essential Biodiversity Variables[1] "should be able to capture critical scales and dimensions of biodiversity to inform high-level policy indicators, a state variable of biological conditions, sensitive to change, ecosystem agnostic, technically feasible, economically viable and sustainable in time".

In order to reconcile these two positions, Lehmann et al. (2020a) integrated these criteria by putting forward a set of four traits to characterize an EV: Essentiality, Evolvability, Unambiguity, and Feasibility.

Essentiality is related to the capacity of EVs to be an effective indicator of policy targets as well as a representative parameter to characterize a system. Unambiguity with a full semantic, accuracy and spatio-temporal resolution. Feasibility is driven by technology, methodological and cost considerations. Evolvability requires knowledge of the evolving policy contexts and the need to result from a community consensus. Considering these criteria, EVs should be based on a co-design approach involving different science-technology-policy communities. This is one of the strengths of GEO that already includes those different communities.

Furthermore, the experience gained in the development of different classes of EVs demonstrated the need to follow a certain number of steps:

- Consulting the scientific community – setting initial EV list based on above criteria;
- Defining EV classes and sub-classes – using the criteria described above;
- Identifying observational sources at various scales – linking EV classes with potential data sources at various scales;
- Processing EVs – harmonizing several observational sources into the EVs framework;
- Validating outputs – consulting the scientific community;
- Disseminating EVs – making available the approved set of EVs on Internet in machine and human readable formats;
- Publishing EVs – making the harmonized set of observational data available and labeled with the approved set of EVs terms.

This process has been followed in most of the efforts for defining the different classes of EVs, but not systematically. The GEO-EV community activity described in Section 3.2 aims at standardizing this approach across GEO activities.

4.3. Recent developments of EVs from GEOEssential

GEOEssential edited recently a special issue entitled "toward integrating Essential Variables for sustainability" (Lehmann et al., 2020a). The editorial paper proposed a new comprehensive typology of EV classes describing socio-ecological systems on the basis of GEO focus areas and priorities (Fig. 1). The first papers aim at setting the scene of high-level use of EVs to inform policy indictors. Plag and Jules-Plag (2020) are advocating for a goal-based approach for establishing EVs for the implementation of the SDG agenda (ESDGV). Nativi et al. (2020) explore how EVs can be used for knowledge generation. Maso et al. (2020) introduce how EVs can link EO Observatory with policy indicators and monitoring using the Drivers, Pressures, State Impact and Response (DPSIR) framework. The next papers are exploring the development of EVs in different GEO focus areas. Miranda Espinosa et al. (2020) reviewed the current status of Essential Climate Variables (ECVs) and their accessibility. Ranchin et al. (2020) show how Essential Renewable Energy Variables (EREVs) are currently being developed. EBVs for ecosystem modelling are at the heart of Dantas de Paula et al. (2020). The interest of developing air quality EVs in cities is demonstrated in the city of Kiev in Ukraine (EUV) by Koloti et al. (2019). The following articles focus on integrated approaches across domains. The interest of EVs in transdisciplinary approached such as the food-water-energy nexus is tackled in McCallum et al. (2020). A case study for monitoring several SDG indicators from high-resolution land use maps is presented for Ukraine (ESDGV) in Kussul et al. (2020). In the last paper, Lehmann et al. (2020b) discuss how the EV concept can be generalized and how it can be used with different tools provided by the GEOSS Platform to create cross-thematic workflows to evaluate, predict and monitor our progress towards policy targets such as the SDGs.

4.4. Overlaps and gaps among EVs lists

The ConnectinGEO project catalogued the existing classes of EVs and detected gaps and overlaps. A tool developed to find and illustrate these gaps and overlaps was the ENEON graph that connected the EVs with the observation networks producing and maintaining EVs. Within GEO-Essential, the dynamic ENEON graph has been updated incorporating information on SDGs and indicators. This way, the graph[2] relates SDG indicators with potential EVs for monitoring and with EO networks and infrastructures (data sources) to retrieve them (Fig. 4).

By showing this interrelation, gaps and overlaps can be more easily detected (Serral et al., 2019). Overlapping, duplication and redundancy could be perhaps minimized if more "thematic" or topic oriented EVs were defined in line with the classes proposed in this paper (Fig. 1). In terms of gaps in EVs definition, most of them come from the Socio-Economic arena. Despite the amount of socioeconomic data collected by statistical agencies, only a few institutions are organizing their observations in terms of EVs (see Section 2.2). A full list of EVs that have already been proposed in the literature is available in Appendix A.

4.5. GEOEssential workflows from data to indicators

The scientific process for knowledge generation from geospatial data can be implemented as a workflow that specifies a sequence of geospatial processes with their data inputs and parameters (Nativi et al., 2020). The execution of scientific models requires processing large amounts of data, which can imply a long execution time. Implementing such a workflow is not a simple task despite the availability of cloud technologies addressing many of the data challenges. In fact, this requires addressing several barriers including cloud services management and interoperability (for data and scientific models). Automating as much as possible this highly technical task is therefore necessary to lower these barriers and allow scientists and modelers to focus on their specific tasks (Lehmann et al., 2017).

The Virtual Earth Laboratory (VLab) framework was developed to help addressing the above issues in the context of several EU H2020 projects (including ECOPotential, ERA-PLANET, and EOSC-hub). The VLab framework is in charge of implementing the orchestration functionalities to enable the execution with the needed input data and parameters and finally saving the generated output. Through the VLab, modelers can publish their existing models, developed in different programming environments (e.g., Python, Java, R, NetLogo) solve the interoperability issued, and allow external users to easily run the models and explore the results.

Another noticeable feature enabled by the VLab is the support of

[1] https://geobon.org/ebvs/what-are-ebv.

[2] www.eneon.org/graph-ev-sdg/index.htm.

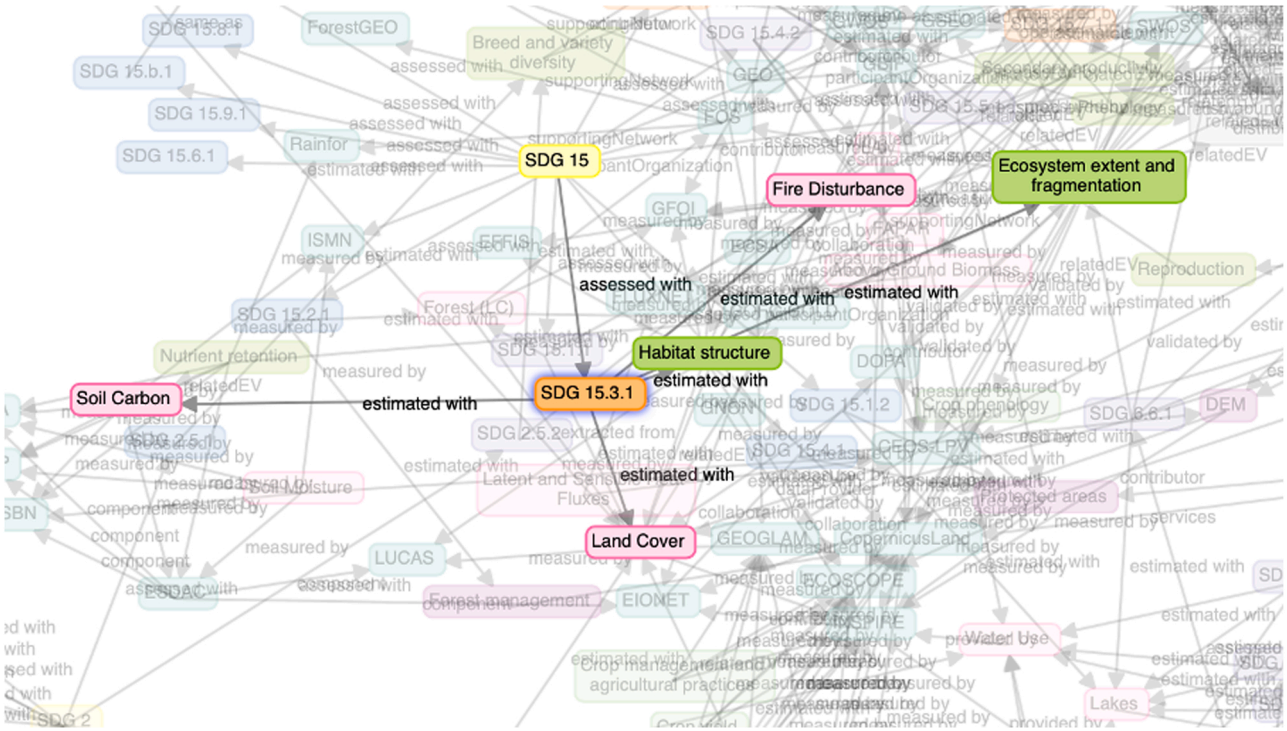

Fig. 4. Representation of the Land degradation indicator (SDG 15.3.1) with related EBV in green and ECV in pink.

multiple cloud platforms for model execution, allowing moving the source code to the platform where data is stored to reduce network traffic and improve performance. This was experimented with different cloud providers such as the ones used in some Copernicus DIAS platforms (Creodias, ONDA, Sobloo), the European Open Science Cloud and the commercial Amazon Web Services (AWS) cloud.

During the ERA-PLANET project, the VLab framework was used to develop and test several workflows that are listed in Appendix B (several other public or private models are available in the VLab from other projects and initiatives). In the VLab, the connection of data and models is based on the simple syntactic interoperability, i.e., it is based on the data structure. Therefore, the user must take care of providing meaningful data as inputs to a specific model. This represents a barrier, especially for non-scientist users. To address this issue, a proof of concept integrating the VLab and the ERA-PLANET Knowledge Base (Mazzetti et al., 2022) functionalities was developed, based on the SDG 15.3.1 Indicator generation use-case (Fig. 5).

The system architecture and implementation are described in detail in Giuliani et al. (2020c). The source data combines remote sensing imagery and some ECVs that are provided by various data repositories such as the Copernicus Open Access Hub, the Copernicus data and Information Access Services (Copernicus, 2018), the GEOSS (Craglia et al., 2017), the Google Earth Engine (Gorelick et al., 2017), or national data infrastructures such as Data Cubes (Giuliani et al., 2020a). These data are then used to compute the three sub-indicators in accordance with the UNCCD Good Practice Guidance. Finally, the three sub-indicators feed the SDG15.3.1 model available in the VLab and outputs are published and documented using interoperable web services for further visualization and aggregation of the results in dedicated dashboard as described in the next section.

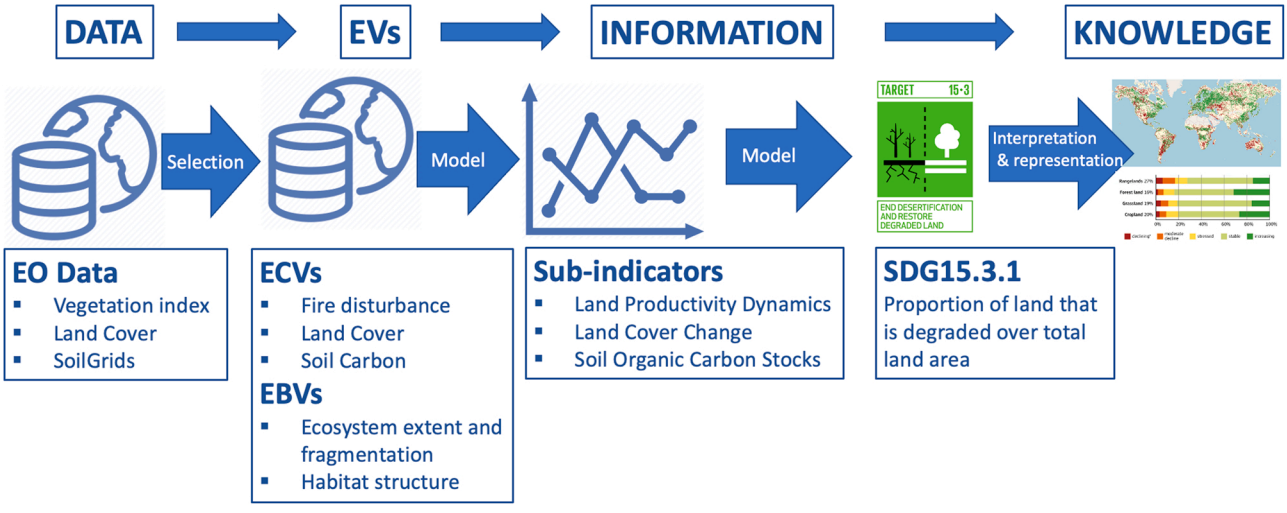

Fig. 5. Description of the workflow for a SDG indicator on Land degradation from data sources, essential variables, information and finally knowledge.

4.6. End user interfaces

The use of standardized web services in the VLab opens the possibility to directly reuse the outputs of the workflows in various web interfaces. One of them is the GEOEssential Dashboard that allows users to explore model outputs in a consistent and comprehensive one-page document (Fig. 6). Continuing with the land degradation example, end-users can quickly look at selected area showing whether land is considered either more degraded, stable or improved according to the SDG15.3.1 indicator. The dashboard dynamically aggregates data in graphs, counters at different administrative levels, as well as pixel-based maps allowing one to capture where and when degradation is happening. In addition, textual explanations on the results are provided as well as various documentation and products allowing one to obtain a detailed understanding on the methodologies, products, and related resources. This suit of data and information can help understanding a specific issue and guide decision making.

When users are in front of a graphical interface that has a geospatial component, friendliness and simplicity in the navigation are often strong requests, as many of them are not experts in Geographic Information System (GIS) – see for example the GEOEssential dashboard page on land degradation (Fig. 6) or on monitoring the impacts of mining activities on forest cover in the Democratic Republic of the Congo.[3] To converge into a visually attractive interface, user experience and user interface testing should be iteratively conducted with early adopters and the finding included as requirements at the different steps of its development.

In the case of MapX[4] (Lacroix et al., 2019), the possibility to deal with a high heterogeneity of data types, the capacity to provide dashboards for monitoring environmental information, to support multiple languages and to tell stories are perceived by the MapX user community as key functionalities. The MapX story map engine used on monitoring deforestation by mining activities provides another way to explore the data.[5] Instead of presenting a user with a dashboard with no predefined way to explore the data, a story map combines a more linear narrative with dynamic snapshots of maps, graphs and statistics to guide the user into its learning process.

5. Discussion

5.1. Lack of socio-economic data

With the environmental component of sustainability increasingly characterized by the EV approach, the socio-economic component (generally collected by national statistical agencies) lags behind and is not adequately connected to the environmental dimension (Lehmann et al., 2020a). This makes it increasingly difficult to effectively track progress towards sustainable development targets that depend on both environmental and socio-economic monitoring (ConnectinGEO, 2016). Furthermore, there are large geographic differences in monitoring capabilities. On average, countries in Africa and Asia have data available to monitor only about 20% of SDG indicators (SDSN, 2019). The gaps in statistical data coverage mentioned above need to be filled. Increasing national statistical capacity is one approach, but this requires large investment (OECD, 2018). Another approach would be to complement official systems for SDG reporting with modern, non-traditional data sources (e.g., EO and Citizen Science) (Fritz et al., 2019). Hence, increasing efforts are focused on the role that EO data can play in closing some of the gaps, along with a variety of non-traditional sources of data and new data science methods. While the definition of Essential Socio-Economic System Variables (Lehmann et al., 2020a) is important, we must still address the lack of data in the socio-economic domain.

5.2. Working at geographically different policy scales

Although the focus of EVs has been primarily on the climatic dimension of the Earth system, the extension of EVs in other SBAs will improve the monitoring capacity to inform the SDGs at the local, national, regional, and global scale. One of the major challenges of developing tools for tracking the progress of policy implementations, is ensuring the quality of the used data, its accessibility, and redundancy in generating indicators and outputs. At the core of the EVs are observations, which will condition the temporal and spatial scales of the environmental data collected. While indicators are typically developed by statistical offices at regional or national levels, EO has the potential to bring valuable information at a much finer spatial and temporal scale to guide the implementation of the solutions on the ground.

At the national level, the implementation of SDGs will depend on their integration with the national strategy, practical policy initiatives, and local actions. Although a lot of work is still required to develop EVs, especially regarding the socio-economic aspects of sustainability, the clear definition of EVs could support the development of cross-sectional instruments to enhance SDGs objectives. Furthermore, EVs were developed to avoid duplication of efforts across platforms and networks and adopt common data collection standards and dissemination to maximize data utility. The level of organization proposed by the GEOEssential project (Lehmann et al., 2020b), has contributed to crafting a platform offering accessible and consistent data sets and models and workflows that generate output to inform environmental policies at various scales.

5.3. Need of reproducible digital solutions (FAIR principles)

All the generated information and knowledge (EVs and resulting indicators) can be exposed on the Internet with well-recognized interfaces such as Open Geospatial Consortium (OGC) standards, for efficient discovery, access and use. This makes data Findable, Accessible, Interoperable and Reusable (FAIR: Wilkinson et al., 2016; Stall et al., 2019), and contributes to major initiatives such as GEOSS. Such approaches enable a movement towards a more open and reproducible EO-based science (Giuliani et al., 2019). Indeed, there is an increasing interest in making scientific research more collaborative and transparent (open science) and to make knowledge accessible by using digital technologies and new collaborative tools (open learning). Open science is aiming to remove barriers to sharing data, methods, algorithms, results and publications. Such an approach is fundamental in effectively embedding science into decision and policy-making processes.

In GEOEssential, open science practices have been fundamental in making data, results and methods open and reproducible. Workflows published in the VLab allow to reproduce the applied methods developed within each thematic area. Using the VLab platform, users can access and execute workflows to produce quantified variables and indicators, and knowledge towards monitoring the Earth system.

5.4. The need for coordination

Making EVs operational requires globally interoperable, transnational information systems from local to global extent (Hardisty et al., 2019). GEOSS could provide this framework where most EVs operate and interact. The challenge is to agree on how to build a dependable and stable body of sufficiently comprehensive data, and how to package and deliver it in the easiest manner to facilitate assessment and forecasting. Such an agreement must be based upon cooperation, practicality and interoperability among those collecting, mobilizing, processing, modelling organizing, publishing and preserving data that

[3] https://geoessential.unepgrid.ch/mapstore/#/dashboard/9.

[4] MapX (https://www.mapx.org) is an open geospatial platform for the management, analysis and visualization of environmental data, which was used to disseminate some of the results of GEOEssential

[5] https://app.mapx.org/static.html?views=MX-E3R1W-BIVO7-FGU3N&zoomToViews=true&language=en&.

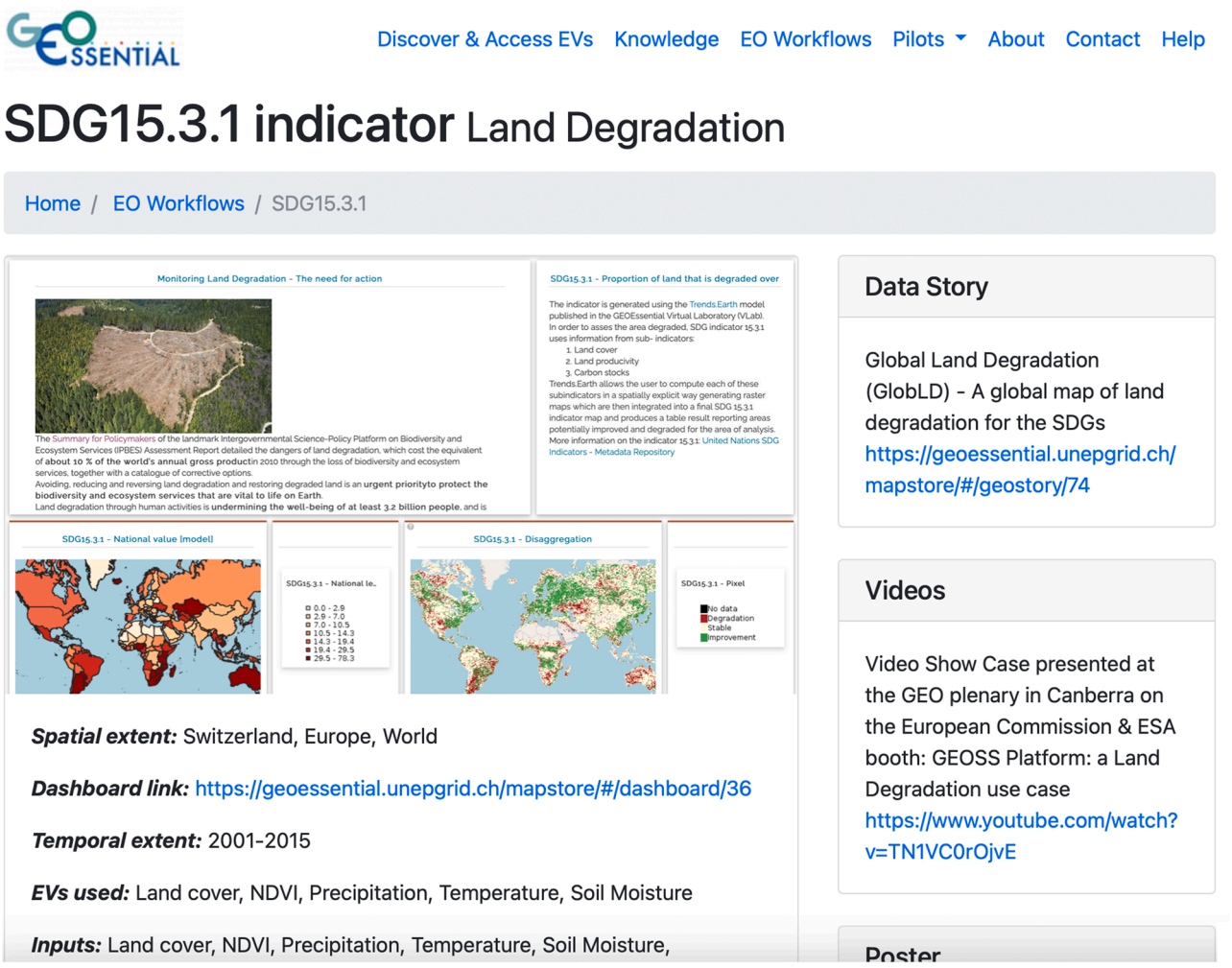

Fig. 6. GEOEssential web page dedicated to the representation of the knowledge gained on SDG indicator 15.3.1 on Land degradation. https://geoessential.unepgrid.ch/mapstore/#/dashboard/36.

can potentially be considered EVs (Kissling et al., 2015). This can be compared with the situation currently prevailing for climate data, where stable, dependable Essential Climate Variables (ECV) data are managed by the Global Observing System for Climate (GCOS) (Hardisty et al., 2019).

The GEO-EV community aims to provide this general framework where Earth system and Socio-Economic system EVs experts meet and coordinate for a better understanding and monitoring of the complete system, thus contributing to the implementation of SDGs in a comprehensive Socio-Ecological Earth manner. Current global challenges threatening the planet need a holistic view coming from scientists, policymakers and citizens.

In order to reach its challenging tasks more efficiently, the EO community would benefit from building a converging set of EVs in order to address simultaneously the needs of several policies at various scales (Fig. 7). One of the first tasks pursued in GEO-EV is to end up with a name-harmonized list of EVs. A first attempt of this is shown in Appendix A. This is a proposal encompassing the new appeared EVs and that still needs to be discussed and agreed by the communities involved.

It is worth noting that, in the presented approach, no specific EV is suggested as a result of a science-policy interface. Nevertheless, it is possible that new indicators require parameters of subsystems not yet considered and that a process to identify new EVs should start. The science-policy interface should define the proper indicators and indices based on the goals expressed by the policy component, while the scientific component is responsible of the process of their estimation from selected existing community EVs. Therefore, it is important to distinguish among EV as subsystem essential descriptors ("EV of" Ocean, Atmosphere…) defined by the scientific communities, and EV as a tool ("EV for" scientific simulation, engineering, policy making…) selected from users and stakeholders. Although a selection of EVs for a specific usage scenario is an important action (e.g. for SDGs in Reyers et al., 2017), the definition of EVs should be based on the more comprehensive "EV of" approach, taking into account the majority of possible scenarios for an efficient mobilization of resources. Focusing on specific use cases generates the risk of spending time and effort on defining EVs and later generating quality datasets of parameters that are relevant for a few short-term targets but missing the collection of more general parameters that could be relevant for major or critical future challenges.

6. Conclusions

The EV concept, which was initiated in the climate observation domain, has quickly spread to other SBAs and is now partially implemented across GEO activities mostly in the Earth system side and less so in the socio-economical system side. EVs have the potential of providing the basis for interdisciplinary approaches related to policy making such as ecological footprint, planetary boundaries, disaster risk reduction, or nexus frameworks. High quality datasets of EVs could be generated integrating multiple sources, including EO, and then used for the estimation of reliable multidisciplinary policy indicators and indices, with the potential to provide also high resolution spatially explicit solutions

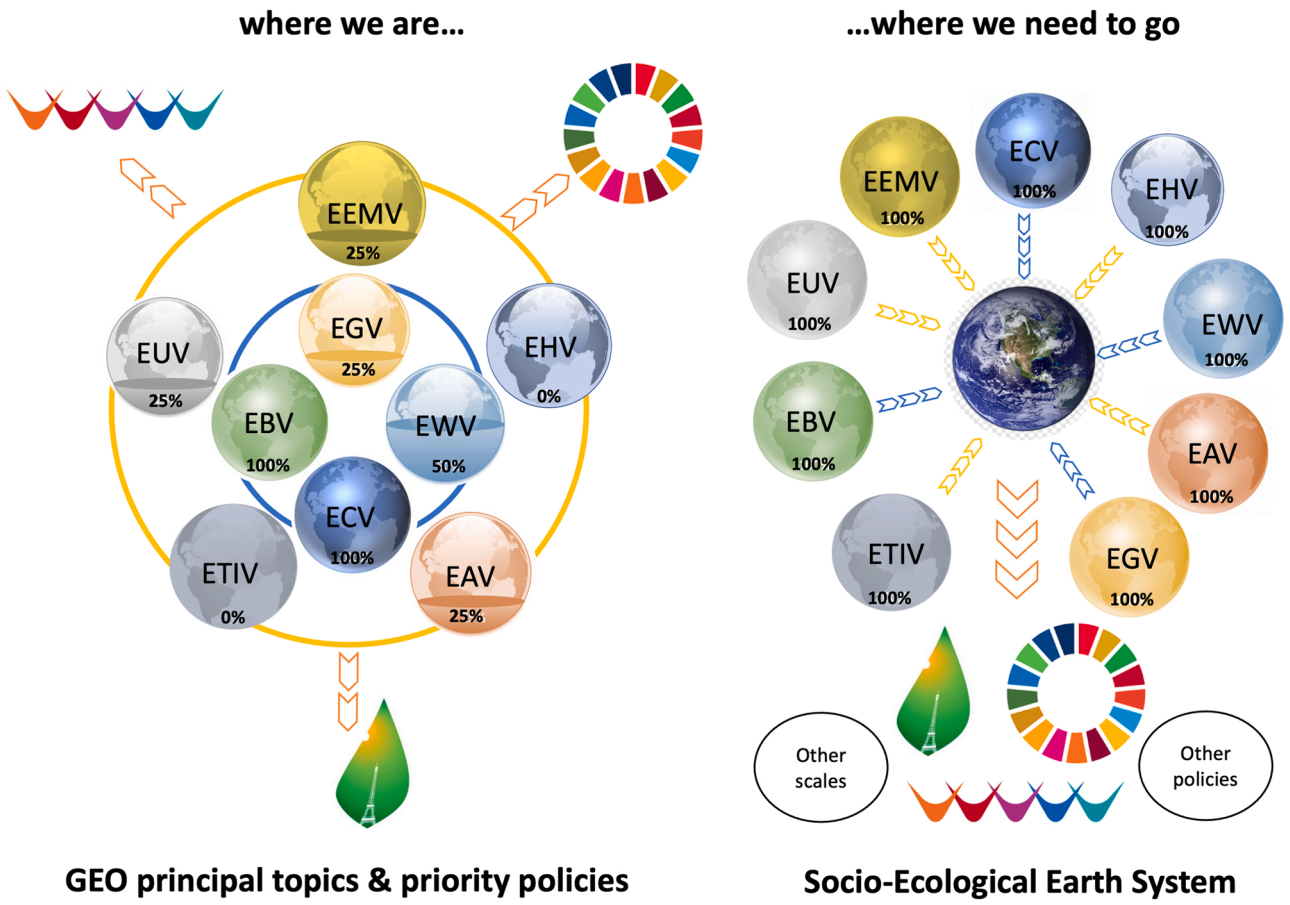

Fig. 7. Where we are and where we need to go with EVs in order to fully address the environmental policy needs in a coherent manner through the full monitoring of the Earth socio-ecological system.

for a more sustainable world.

However, to make this scenario happen, an effort is required to converge towards a common definition and implementation of EVs across GEO SBAs. Semantic harmonization must be carefully evaluated and implemented to identify homonyms and synonyms in EV classes definitions. Moreover, pragmatic aspects should be considered, taking into account the different contexts where EVs are defined and used. This implies different requirements in terms of accuracy, spatial/temporal coverage, and resolution for the same EV in different usage scenarios. The description of an EV should be based on as many heterogeneous use cases as possible to make high quality datasets usable for different applications.

These are all aspects where the multidisciplinary and multi-organizational nature of the GEO-EV community activity can play a significant role: harmonization of existing EVs, identification of new relevant Earth subsystems to be characterized with EVs, gap analysis on EO and in-situ monitoring systems for generation of EV quality datasets, and estimation and acknowledgment of EO value for EV dataset generation for policy decision-making.

Technical solutions are ready to implement EVs across all GEO SBAs in order to make available the necessary data sources (such as metadata catalogues exposing EVs observations) and also to provide workflows to transform the EVs data into policy indicators (such as the VLab). GEO-Essential is providing several demonstrations of full functional EV workflows that can be now improved and replicated for many policy indicators at various scales. With the use of data sharing and data visualization web services, this knowledge can be spread in different forms (e.g., dashboards and story maps).

Time is counted. As shown with the COVID-19 pandemic, sound scientific information can help make better decisions. While pandemics cause immediate threats to our well-being, economy and even survival, environmental threats on climate and biodiversity play on longer time periods and may become one of the main concerns, if not the primary challenge, for the human society before the end of this century. We have the potential to bring all the necessary information at the fingertips of decision-makers at all scales and we should increase our efforts to gain time in the search to mitigation and adaptation solutions.

EVs should screen the entire Earth's social-ecological system, providing a trusted and long-term foundation for interdisciplinary approaches such as ecological footprinting, planetary boundaries, disaster risk reduction, and nexus frameworks, as well as many other policy frameworks such as the SDGs.

CRediT authorship contribution statement

Anthony Lehmann: Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Paolo Mazzetti:** Writing – review & editing parts on the knowledge platform. **Mattia Santoro:** Writing – review & editing parts on the knowledge platform. **Stefano Nativi:** Writing – review & editing parts on the knowledge platform. **Joan Masò:** Writing – review & editing parts on the gap analysis. **Ivette Serral:** Writing – review & editing parts on the gap analysis. **Daniel Spengler:** Writing – review & editing parts on essential variables and workflows. **Aidin Niamir:** Writing – review & editing parts on essential variables and workflows. **Pierre Lacroix:** Writing – review & editing parts on essential variables and workflows. **Mariapaola Ambrosone:** Writing – review & editing parts on essential variables and workflows. **Ian McCallum:** Writing – review & editing parts on essential variables and workflows. **Nataliia Kussul:** Writing – review & editing parts on essential variables and workflows. **Petros Patias:** Essential variables

and dissemination. **Denisa Rodila:** Writing, Supervision and Project management. **Nicolas Ray:** Writing, Supervision and Project management. **Grégory Giuliani:** Writing – review & editing parts on data sharing, dashboards and story maps.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2021.12.024.

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