remote sensing

Review

Satellite Earth Observation for Essential Climate Variables Supporting Sustainable Development Goals: A Review on Applications

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Abstract: Essential climate variables (ECVs) have been recognized as crucial information for achieving Sustainable Development Goals (SDGs). There is an agreement on 54 ECVs to understand climate evolution, and multiple rely on satellite Earth observation (abbreviated as s-ECVs). Despite the efforts to encourage s-ECV use for SDGs, there is still a need to further integrate them into the indicator calculations. Therefore, we conducted a systematic literature review to identify s-ECVs used in SDG monitoring. Results showed the use of 14 s-ECVs, the most frequent being land cover, ozone, precursors for aerosols and ozone, precipitation, land surface temperature, soil moisture, soil carbon, lakes, and leaf area index. They were related to 16 SDGs (mainly SDGs 3, 6, 11, 14, and 15), 33 targets, and 23 indicators. However, only 10 indicators (belonging to SDGs 6, 11, and 15) were calculated using s-ECVs. This review raises research opportunities by identifying s-ECVs yet to be used in the indicator calculations. Therefore, indicators supporting SDGs must be updated to use this valuable source of information which, in turn, allows a worldwide indicator comparison. Additionally, this review is relevant for scientists and policymakers for future actions and policies to better integrate s-ECVs into the Agenda 2030.

Keywords: SDG; sustainable development; satellite; Earth observation; review; essential variables; climate

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1. Introduction

The Agenda 2030 for Sustainable Development and its 17 goals (SDGs) are connected with the environment, economy, and society dimensions of sustainable development [1]. The 17 goals, their 169 associated targets, and 231 indicators are based on the first data-driven policy development framework, following the principle of "If you don't measure it, you can't manage it" [2] (p. 2). Despite the recognized importance of measuring the progress towards the SDGs, two-thirds of the indicators remain unreported, especially in low-income countries [3]. Moreover, less than 44% of the SDG indicators can be easily measured [4]. Therefore, it is a priority to boost the measuring and monitoring of the progress towards the SDGs. In our work, we focus on two key approaches to pursue this aim: (1) essential variables (EVs) that have been defined as an intermediate layer between observations and indicators [5] and (2) satellite Earth observation (sEO) data that gained particular attention as worldwide feasible, cost-effective, and analysis-ready data across scales in remote, non-accessible, and poorly monitored regions [6].

The EVs emerged in various social and environmental scientific communities related to specific domains such as climate, biodiversity, agriculture, and society [5,7–9]. Refer to [10,11] for detailed EV compendiums. These kinds of variables are "a minimal set of variables that determine the system's state and developments, [which] are crucial for predicting system developments and allow us to define metrics that measure the trajectory of the system" [12] (p. 8). In the climate arena, the EVs were first defined and standardized in the 1990s [5]. Here, 54 essential climate variables (ECVs) were selected by the Global Climate Observing System (GCOS) to improve the coordination of climate observations [13]. They have been defined by their critical relevance for the characterization of the climate and its changes, the feasibility of climate variables observed or derived at the global to local scales, and cost-effectiveness so that their generation is affordable [14]. ECVs have particular relevance in the context of SDGs since they build the intermediate layer between observations and indicators [5]. It was also pointed out that they contribute to 10 out of the 17 SDGs [15].

Since the emergence of the SDGs in 2015, the international Earth observation community has actively participated in defining indicators and methodologies to guarantee and expedite SDG monitoring. International organizations such as the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), the Committee on Earth Observation Satellites (CEOS), the Group on Earth Observation (GEO), the Food and Agriculture Organization (FAO), and the European Space Agency (ESA), among others, have actively identified in situ and sEO data to support the SDGs [2,3]. Some efforts have been made to map the contribution of sEO in this context [2,6,8,11,16–19].

However, beyond these efforts, challenges remain because of the still tricky access to sEO data, and open, transparent, and robust methodologies [3,18,20]. Additionally, the discovery of and access to data continue to be complicated in terms of time and money [18,21], requiring a high capacity to manage sEO data [22]. It is evidenced that accessing and managing such data require extensive know-how in handling both sEO and statistical calculations. This makes using sEO complex for decisionmakers within local and regional institutions [23], especially for institutions located in low-income countries. Therefore, using sEO in general, and ECVs in particular, has been delayed and not yet adequately integrated into the SDG indicator calculations. Thus, the bridge between ECVs, sEO, and SDGs must be strengthened.

Our contribution, in this regard, is to report the use of sEO for ECVs that supports the monitoring of SDGs. Therefore, we conducted a systematic literature review to identify satellite data applications for ECVs that have been used within the SDG context. From now on, the ECVs based on sEO will be abbreviated as "s-ECVs" and the applied research type studies of s-ECVs in the SDG context will be summarized as "applied" studies. The overall question guiding this systematic review is: Which are the s-ECVs supporting the measuring and monitoring of the progress towards SDGs? The review summarizes s-ECV data and applications reported for SDGs and their indicators. We also report the indicators that were calculated from s-ECVs. This work contributes to allowing scientists and policymakers to identify s-ECV sources for specific SDGs with their targets and indicators. Furthermore, SDGs that still need to be addressed with s-ECVs can be identified as priorities for future research. This review provides light to define actions and policies to better integrate s-ECVs into the SDGs.

This article is structured as follows. First, we justify our focus on satellite Earth observation and provide a detailed description of ECVs (Background, Section 2). The review method is presented in Section 3. Section 4 shows the results of the review process, the quantitative analysis, and a synthesis of the use of s-ECVs supporting SDG monitoring. Finally, discussion is provided in Section 5 and conclusions in Section 6.

2. Background

2.1. Satellite Earth Observation for SDGs

The importance of relying on sEO data sources for SDGs is related to (1) consistent and global monitoring over a long period; (2) reliable and verifiable product data; (3) transboundary data across scales, i.e., from global, regional, national, to basin scales; (4) transparent and well-reported methodologies with their weaknesses and strengths, including error metrics and quality flags; and (5) sustainable, open, and accessible operational data [3]. They are also relevant to allow feasible, cost-effective, and analysis-ready data in remote, non-accessible regions and poorly monitored regions [6]. In these scenarios, sEO becomes indispensable, being the only feasible source of information in many cases [23].

sEO contributes, directly or indirectly, to 30 (18%) of the SDG indicators [16,24]. However, the quantification of this contribution differs from author to author, publishing date, and focus of the work. This makes it challenging to provide a comprehensive comparison. For instance, Estoque [16] reported that 70% of EO-based indicators (21 out of 30) were added to the Global SDG Indicators Database and 33% (10 out of 30) were in the Sustainable Development Report 2019. A compendium of EO contributions to the SDGs reported that sEO contributes to 34 indicators, 29 targets, and 11 goals. Seventeen of such indicators have a direct contribution of EO, while the other seventeen have an indirect contribution [6]. Andries et al. [18] assessed a partial contribution from EO to 108 indicators, including a weak contribution to 19, a partial contribution to 67 and a strong contribution to 22, and for another 139, although there is no evidence, EO could have a potential use.

While sEO was the main focus in the works mentioned before, we want to provide a short note to clearly differentiate sEO (i.e., satellite Earth observation) from other EO data sources. Similarly to [18], we distinguish sEO from unmanned aerial vehicles (UAVs) (commonly known as drones), ground-based or in situ observations (e.g., meteorological stations), citizen science (e.g., participatory monitoring performed by a local community), and social networks (e.g., Twitter or Instagram) [19]. We also differentiate between sEO and reanalysis products (frequently used for mesoscale climate analysis). Reanalysis products encompass the assimilation of in situ, satellite, and modeling sources [25]. Although in situ data are essential, they can also be limited or even non-existent in poorly monitored areas of the Earth, such as Africa, Asia, and Latin America, making reanalysis data challenging. The particular viewpoint of our work is associated with the attempt to provide helpful information for low-income countries and poorly monitored regions [6], which present the most significant challenges to measuring the progress within the SDGs. In this sense, our work's focus is on satellite sources of EO that are feasible, cost-effective, global scale, and (for some of them) analysis-ready.

2.2. Essential Climate Variables

In the climate arena, the EVs were first defined and standardized in the 1990s [5]. Here, the Global Climate Observing System (GCOS) established 54 ECVs to improve the coordination of climate observations [13]. These ECVs are classified as physical, chemical, and biological variables that characterize the climate of the Earth and support the activities of climate monitoring, mitigation, and adaptation [14,21]. Lehmann et al. [11,13] defined some requirements for any essential variable, which are fulfilled by the ECVs [14], such as *Essentiality*, i.e., effectiveness and representativeness of an EV in a particular context or application; *Evolvability*, i.e., dynamism and evolution of an EV; *Unambiguity*, i.e., the unambiguous definition in terms of semantics, resolution, and accuracy; and *Feasibility*, i.e., feasible regarding its technology and the cost requirements.

The current 54 ECVs are organized into 3 domains and 9 subdomains: atmosphere (surface, upper-air, and atmospheric composition), land (hydrosphere, cryosphere, biosphere, and anthroposphere), and ocean (physical and biogeochemical). As an exemplification, only a few ECVs for each domain are listed. The complete list can be checked in Appendix A, Table A1. Some ECVs for the atmosphere domain are air temperature, wind direction and speed, water vapor, surface pressure, precipitation, solar radiation, cloud characteristics, carbon dioxide content, ozone, and aerosols. ECVs for the terrestrial or land domain are river flow, groundwater, land cover, biomass, soil carbon, and soil moisture. Finally, some representative variables for the ocean domain are associated with sea level, sea surface currents, sea surface temperature, nutrients, ocean color, and oxygen for ocean monitoring. Each ECV can have more than one ECV product, for instance, the lake ECVs have several products, such as water level, extent, or surface water temperature (Table A1 in Appendix A).

There has been a long-standing interest in mapping ECVs with sEO. For instance, Espinosa et al. [21] pointed out that data derived from sEO have significantly contributed to 30 ECVs. In 2015, when only 51 ECVs were defined, it was underlined that remote sensing had a significant contribution to 14 out of 17 ECVs for atmospheric ECVs, whereas 6 out of 18 ECVs for oceanic ECVs, and 11 out of 16 ECVs for land ECVs [26]. Furthermore, Giuliani et al. [7] (using only 52 ECVs and not the current 54) reported that 21 had a contribution from sEO, 21 had a partial contribution, and 10 received no contribution (sEO* column in Appendix A, Table A1).

Table A1 (Appendix A) summarizes the 54 ECVs and their products from https://gcos.wmo.int/en/essential-climate-variables, accessed on 22 May 2023; the contribution of each ECV to the SDGs from https://github.com/grumets/eneon-graph, accessed on 22 May 2023 [15]; and the contribution of sEO to the ECVs [7]. Even though this table is essential for our work, it was included in the Appendix A because of its length. We recommend checking the table before continuing to read the manuscript.

3. Methods

The review was conducted following the guidelines for systematic reviews provided by the Collaboration for Environmental Evidence (CEE) [27]. The overall question guiding this systematic review is: Which are the s-ECVs supporting the measuring and monitoring of the progress towards the SDGs? The critical components are:

- Population: scientific research articles in academic literature;
- Outcome: usage of satellite Earth observation for climate essential variables in the SDG context;
- Study types: any published research study, including primary research articles, case studies, and reviews.

This section describes the repositories, search processes, as well as inclusion and exclusion criteria for defining the eligible studies for this review. Additionally, we provide the main details of the selected studies included in the final sample of contributions for this systematic review.

3.1. Repositories and Searches

We performed bibliographic searches in Scopus and Web of Science, which are part of the core collections of bibliographic repositories for academic literature. These searches combined terms associated with five groups of keywords along with their respective alternatives or synonyms:

1. Sustainable Development Goals/SDG/SDGs;
2. Earth observation/remote sensing/satellite;
3. Climate;
4. Essential variables/EV; and
5. Essential climate variables/ECV.

The term groups mentioned above were concatenated using logical operators (*AND* and *OR*) that allowed finding relevant articles using a combination of search criteria. All these searches were carried out using the selected databases' sections: title, abstract, keywords, and all fields. The latter search option (all fields) was applied in Scopus to the groups of terms related to ECVs. By contrast, it was discarded in Web of Science given that during the preliminary analysis we discovered multiple off-topic results that did not match the selection criteria. Furthermore, we incorporated additional studies selected by the authors using the snowballing search criteria. However, we did not include gray literature in this review, that is, supporting Sustainable Development Goals publications outside the scientific databases such as theses and dissertations and government and international association reports. The time frame tool was not used, although we selected studies published between January 2015 and March 2022 (15 March 2022). Figure 1 details the diverse queries carried out in Scopus and Web of Science and the results thereof.

Figure 1. Query details in Scopus and Web of Science.

3.2. Inclusion and Exclusion Criteria

We defined a set of criteria to select the studies included or excluded in this systematic review. Thereby, we established the following inclusion criteria:

- Articles in the context of applications supporting SDGs;
- Studies making use of sEO for deriving data related to applications supporting SDGs.

Moreover, we defined exclusion criteria to discard off-topic studies, such as:

- Articles that were not digitally available;
- Duplicated studies (overlapping retrievals between Scopus and Web of Science);
- Works published before 2015;
- Contributions in a language different from English and Spanish. Spanish was chosen since it is the native language of some authors of this study;
- Conference and workshop proceedings.

Finally, further exclusion criteria were applied during the document screening phase:

- Articles that only mentioned the SDGs in the abstract or introduction/conclusions without further explanation about implementation, contribution, or implications;

- Articles related to the SDGs but out of the scope of this review. For instance, articles with a specific focus on technological platform implementation or contributions with a lack of sEO data application and analysis.

3.3. Data Extraction and Codification

The data extraction and codification were organized as citation details (author, title, and year), search details (keywords), and additional extracted data specifically for this review. For instance, SDGs and indicators, satellite source, and essential climate variable (Table 1).

Table 1. Data extraction and codification details.

Item	Definition	Codification
Keywords	It identifies the term group by which the study was discovered. Each contribution may have more than one keyword.	SDG, EO, EV, Climate, ECV
Snowballing	It indicates whether the snowballing criteria found the study.	Yes, No
Topic	Main thematic topic of the study, such as agriculture, urban, biodiversity, among others. Conceptual topics such as workflows, Earth observation, and essential variables were used for conceptual studies, reviews, and position papers.	Thematic topics, Conceptual topics
Type of research	Theoretical studies are reviews or position papers about SDGs and EO contributions. However, they did not calculate indicators or use sEO data to monitor SDGs. Applied studies calculate SDG indicators by using sEO data for ECVs in the context of monitoring, tracking, or developing new SDG indicators. They present applied examples or operational monitoring systems. The applied contribution was identified as related works with a direct contribution of sEO to SDGs.	Theoretical, Applied
SDG	It identifies the SDG scope of the study. There may be more than one SDG.	1 to 17, NS = Not specified
SDG target or indicator *	It identifies the SDG targets or indicators that the study contributes to. There may be no or more than one reported SDG target or indicator.	-
sEO	It answers the following question: Does the study explicitly make use of or promote the use of satellite EO data in the context of SDGs?	Yes, No
s-ECV *	It answers the following question: Does the study explicitly use climate data (ECVs) from satellite EO sources in the context of SDGs?	Yes, No
s-ECV details *	It details the ECVs from satellite EO sources (as named by GCOS https://gcos.wmo.int/en/essential-climate-variables/) mentioned in the study. It may have more than one ECV.	List of ECVs
Satellite source *	Product or source of the s-ECV used in the study.	As reported in the study
Spatial resolution *	The spatial resolution of the product or source of the s-ECV used in the study.	As reported in the study
Temporal resolution *	The temporal resolution of the product or source of the s-ECV used in the study.	As reported in the study

* They are reported only for "Applied" studies (type of research) and detailed in the Synthesis section.

3.4. Quantitative Analysis and Synthesis

With the extracted and coded data, we analyzed the articles and generated diverse results to summarize the temporal distribution of keywords, topics, types of research, reported ECVs from sEO sources, and their relation to the SDGs.

Then, the synthesis described the different applied studies regarding the direct contribution of s-ECVs for the SDG monitoring. In the synthesis, a short description is provided about the goals, targets, and indicators, which are mentioned only the first time they appear in the text. For instance, the first time, SDG 1—*No poverty* is used, and later only SDG 1.

Please access the SDG metadata repository (https://unstats.un.org/sgds/metadata/, accessed on 22 May 2023) for a complete description of goals, targets, and indicators.

4. Results

4.1. Review Process

A total of 371 papers were retrieved from the considered bibliographic databases (Scopus and Web of Science) and the snowballing criteria. After applying the exclusion criteria for the initial articles' collection, we selected 105 studies. Table 2 shows the details of the exclusion criteria.

Table 2. Summary of the selected studies and exclusion criteria.

	Retrieved Studies (371)	**Scopus/Web of Science**	**Snowballing**
		360	**11**
Exclusion criteria	Documents not available.	3	
	Documents repeated in previous searches and between Scopus and Web of Science.	151	
	Conference proceedings.	46	
	Older than 2015.	3	
	The language was different from English and Spanish.	2	
	Documents that only mentioned the SDGs in the abstract or introduction/conclusions, without further contribution or explanation.	48	
	Documents on the SDGs but out of the scope of this review. Too broad or topics not related to climate data.	13	
	Final selected studies (105)	94	11

4.2. Quantitative Analysis

4.2.1. Keywords, Topics, and Focus of the Contributions

Since SDG was a compulsory keyword in all searches, it appeared in all 105 selected studies. This keyword was closely followed by EO (91) and climate (70). Less frequent were ECV (26) and EV (21) (Figure 2a). Regarding the thematic topics, both natural and human systems were included, and frequently they were related to water (15), land degradation (14), biodiversity (10), urban (9), ocean (9), and agriculture (7) (Figure 2b, left side of figure). Twenty-one (21) studies did not focus on a specific thematic topic; instead, they described conceptual topics such as mechanisms, workflows, and opportunities for EO (9), data integration (6), and essential variables (6). This can be observed in the last three columns of Figure 2b. Additionally, we found that around 36% of the contributions were made in 2020 and 20% in 2021. In 2022, we found fewer publications because the search was carried out up to March. Most of the studies (57 out of 105) were of the theoretical research type on the SDGs (i.e., reviews, position papers, or workflows) and application opportunities for s-ECVs (Figure 2c). Moreover, 40 out of the 105 followed an applied research contribution in this regard, meaning they used s-ECVs in the SDG context by calculating indicators, developing new indicators, or generating knowledge that supports a specific SDG.

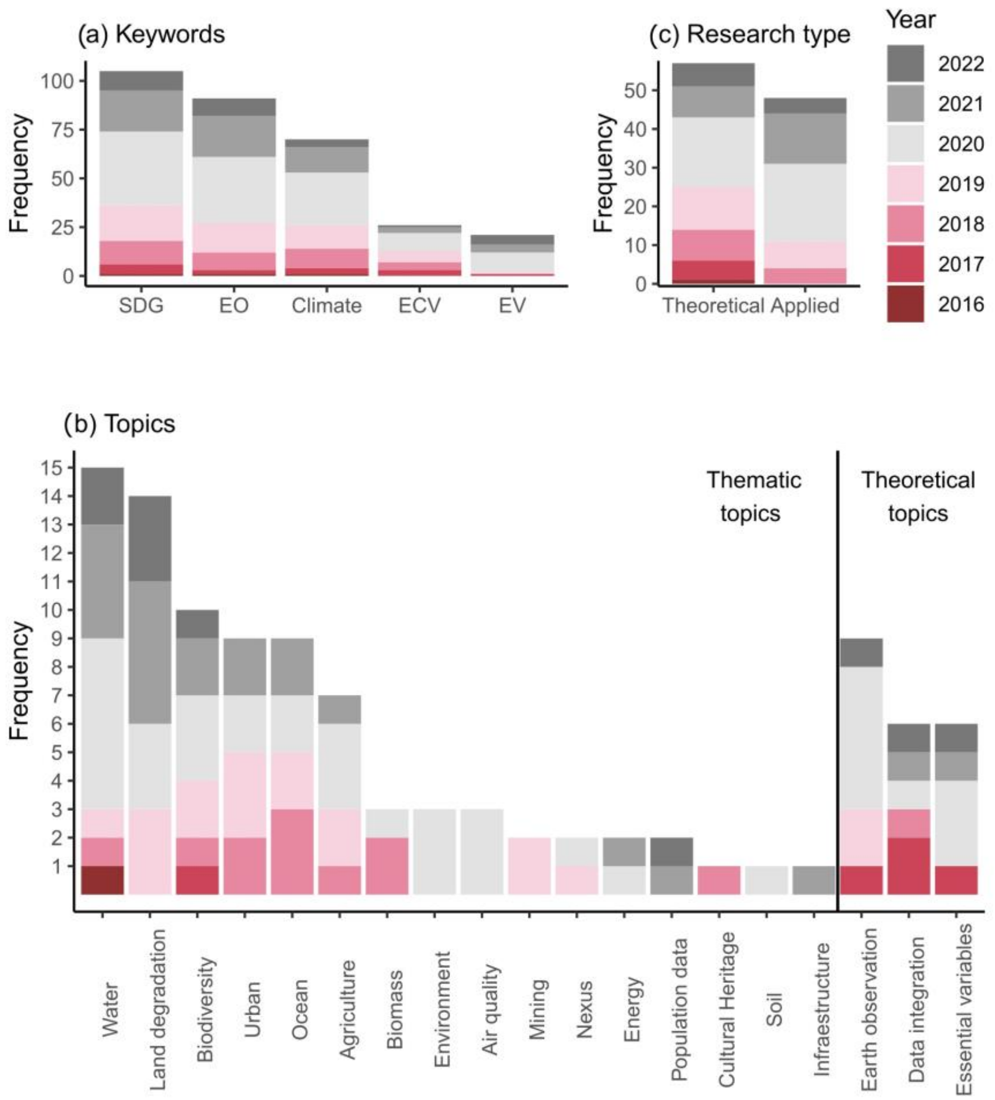

Figure 2. Summary of data codification by year of publication. It shows frequency data. (**a**) Searching keywords; (**b**) thematic topics (left part of the figure) and theoretical topics of the studies (3 rightmost bars in the figure); (**c**) theoretical and applied research type of the studies. Note that 2022 represents only 3 months of data.

4.2.2. Climate from Satellite Earth Observation: Theoretical and Applied Research for the SDGs

Among the selected studies, we found that 90% (94/105) of the contributions used sEO for both theoretical and applied research types (Figure 3a, *x*-axis Satellite Earth Observation—aggregation of Yes and No among the years). Within this group, 62% (58/94) addressed climate data from s-ECVs (aggregation of Yes among the years). The use of s-ECVs has been observed in the literature since 2018, increasing its presence in 2020 (Figure 3a). A similar increasing trend was found for both types of research, applied and theoretical studies (Figure 3b). Likewise, as we mentioned above, the low frequency registered in 2022 was related to the short period (3 months) included in this review.

Figure 3. Essential climate variables based on satellite Earth observation (s-ECVs). It shows frequency data. (**a**) Yearly distribution of theoretical and applied s-ECV studies and (**b**) s-ECV contribution to the SDGs. NS = Not specified. In (**b**), only studies using s-ECVs were selected.

Figure 3b shows the s-ECV contribution to the SDGs. Herein, only the studies using climate variables from sEO sources were represented. Thus, this result corresponds to a total of 58 studies (18 theoretical + 40 applied articles). The theoretical studies were related to all the 17 SDGs, although the most addressed were SDG 6—*Clean water and sanitation* (7 studies), SDG 15—*Life on land* (7), and SDG 13—*Climate action* (6). When focusing on the applied s-ECV studies, all SDGs were present except for SDG 17—*Partnership for the goals*. The most addressed were SDG 15 (23 studies), SDG 6 (13), SDG 11—*Sustainable cities and communities* (12), and SDG 13 (10). Additional SDGs with significant presence were SDG 2—*Zero hunger*, SDG 3—*Good health and well-being*, and SDG 14—*Life below water*.

4.3. Synthesis

4.3.1. Applied Satellite ECVs for the SDGs

Forty applied research studies that used s-ECVs were found to support SDGs, i.e., applied examples or operational monitoring systems. This synthesis describes these 40 studies that contribute to 16 SDGs, using 14 s-ECVs (See Table 3 and Figure 4—Summary section). Table 3 structures the synthesis of s-ECVs used to support SDGs. It organizes the information by ECV domain and subdomain, the variable (ECV) and product (ECV-P), SDGs and indicators for each ECV, and the respective satellite product. Indicators that were calculated are highlighted in gray. We refer to [18] for additional information and characteristics about satellite platforms, products, and EO data management and to [28] for climate remote sensing products available for some of the ECVs.

Table 3. Synthesis of essential climate variables from satellite Earth observation sources (s-ECVs) employed for supporting SDGs.

D	SD	ECV	ECV-P	SDG	SDG Ind.	Product	Sp-Res.	T-Res.	Citation
Atmosphere	Surface	Precipitation	Estimates of liquid and solid precipitation	6 15	6.4.2 NS	CHIRPS NESSDC	0.05° NS	Pentad Yearly	[29] [30]
	Atmospheric Composition	Ozone	Total column ozone	3 7 10 11	3.8.1 3.9.1 7.1.2 10.2.1 11.5.1 11.6.2	NEO	1 km	Time stamp	[31]
		Precursors for aerosols and ozone	Nitrogen dioxide concentration (NO_2)	3 7 10 11	3.8.1 3.9.1 7.1.2 10.2.1 11.5.1 11.6.2	Sentinel-5P OMI NEO	7 × 3.5 km NS 1 km	Monthly Time stamp	[32] [31]
			Total column sulfur dioxide (SO_2)	3 7 11	3.9.1 7.1.2 11.6.2	Sentinel-5P	7 × 3.5 km	Monthly	[32]
		Aerosols	Aerosol optical depth	3 8 11, 12 13, 14 15	NS 8.7 NS NS NS	MISR SeaWiFS	0.01°	Yearly	[33]
Land	Biosphere	FAPAR	Maps of FAPAR for modeling	15	15.2.1 15.3.1	Sentinel-2	10 m	Monthly	[34]
		Land surface temperature	Maps of land surface temperature	4, 6 11, 13 14, 15	NS NS NS	Landsat NESSDC	30 m NS	Yearly 16 days Yearly	[35] [30] [36]
		LAI	Maps of LAI for modeling	15	15.2.1 15.3.1	Sentinel-2 MODIS (MOD15A2H)	10 m 500 m	Monthly Yearly	[34] [37]
		Soil carbon	% Carbon in soil	2 3 6 11 13 15	2.3 2.4 3.9 6.4 6.5 11.3 13.2 15.3	EnMAP (1) Sentinel-2 (2)	30 m 10 m	NS	[38]
		Soil moisture	Surface soil moisture	6 15	6.4.2 NS	NASA-USDA Global soil moisture dataset (3) Landsat (OLI, TIRS, TM)	0.25° 30 m	3 days Yearly Seasonal	[29] [39]

Table 3. *Cont.*

D	SD	ECV	ECV-P	SDG	SDG Ind.	Product	Sp-Res.	T-Res.	Citation
		Fire	Burnt area	1, 2 3, 6 13, 14 15	NS NS NS NS	Landsat 8	30 m	Yearly	[40]
		Land cover	Maps of land cover	1, 2, 3 4, 5 6 7 8 11 12, 13, 14 15 16	NS NS 6.4 6.5 6.4.2 6.6.1 NS 8.7 11.B 11.1.1 11.3.1 NS 15.1 15.1.1 15.1.2 15.2 15.3 15.4.1 15.4.2 15.5 15.8 16.7	Landsat (OLI, TM, MSS, ETM+, NLCD, GFW)	15 m 30 m 0.09 ha 0.25°	Time series Time stamp Yearly	[41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [35] [29] [33] [36] [53]
				1, 3 2 6 8 11, 12 13, 14 15	NS 2.4 6.1 6.2 6.6 8.7 NS NS 15.1.1 15.1.2	MODIS (Land cover, MCD12Q1, MOD13A1, GLCNMO)	250 m 500 m 1 km 0.0083°	Time series Time stamp Yearly	[54] [52] [55] [56] [30] [33]
				2 6	NS 6.6.1	Sentinel-1	10 m 30 m	Time stamp Yearly	[43] [57]
				4, 6 11 13, 14 15	NS 11.1.1 11.2.1 11.3.1 11.6.2 NS 15.1.1 15.1.2	Sentinel-2	10 m 100 m	Time series Time stamp Yearly	[58] [52] [59] [36]
				15	15.3	IRS	5 m	Time stamp	[51]

Table 3. *Cont.*

D	SD	ECV	ECV-P	SDG	SDG Ind.	Product	Sp-Res.	T-Res.	Citation
				2 3 6 7 8, 9, 10 11 1315	2.4.1 NS 6.1.1 6.4.2 6.6.1 7.2.1 NS 11.5.1 NS 15.2 15.3.1 15.4.2 15.5.1	ESA land cover (4)	300 m	Yearly	[60] [37] [61] [53] [62] [63]
	Hydrosphere	Lakes	Water extent	6 11 16	6.4 6.5 6.6.1 11.B 16.7	Landsat (MSS, TM, GLAD, GSWE) MODIS (MOD44W)	30 m 250 m	Time series Yearly	[47] [43]
			Lake surface water temperature	3 6 14	3.3 NS NS	Sentinel-3A (LSWT) Sentinel-2A and 2B (MSI)	1 km 10 m 20 m		[64]
Ocean	Physical	Sea Level	Regional mean sea level	13 14	13.1 14.7	NOAA		Monthly	[65]
	Biogeochemical	Ocean color	Chlorophyll-a concentration	3 6 14	3.3 NS 14.3.1 14.1.1a	MODIS (Aqua) Landsat (OLI) Sentinel-2	1° 4 km	Monthly Yearly Time stamp	[66] [67] [64]

Acronyms. D = Domain, SD = Subdomain, ECV = Essential climate variable, ECV-P = Essential climate variable product, SDG = Sustainable Development Goal, SDG Ind. = SDG target or indicator, Sp-Res. = Spatial resolution (units as reported in the studies), T-Res. = Temporal resolution, OMI = Ozone Monitoring Instrument from EOS-Aura satellite, EnMap = Environmental Mapping and Analysis Program, German hyperspectral satellite mission, MSS = Multispectral scanner, TM = Thematic Mapper, ETM+ = Enhanced Thematic Mapper Plus, OLI = Operational Land Imager, MODIS = Moderate Resolution Imaging Spectroradiometer, GLAD = Global Land Analysis and Discovery Water Surface, GSWE = Global Surface Water Explorer, GLCNMO = Global Land Cover and National Mapping Organizations, IRS = Indian Remote Sensing, NLCD = USGS National Land Cover Database, CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data, OMI = Ozone Monitoring Instrument from EOS-Aura satellite, NEO = NASA Earth Observation, NESSDC = National Earth System Science Data Center (China), MISR = Multi-angle Imaging SpectroRadiometer. SeaWiFS = Sea-Viewing Wide Field-of-View Sensor, GFW = Global Forest Watch. Observations: cells for SDG Ind. are highlighted in gray means that they were calculated and reported. Sp-Res. units are shown as reported in the studies. (1) Simulated data from the forthcoming (at the time of the cited publication) EnMap were used. (2) Used to derive soil carbon. (3) Integrating the satellite-derived Soil Moisture Active Passive (SMAP) Level 3 soil moisture observations. (4) Trends.Earth using land cover data from the European Space Agency (ESA) and Climate Change Initiative Land Cover (CCI-LC) (https://www.esa-landcover-cci.org).

This section provides a synthesis of domains and subdomains. The short names of the addressed indicators are only made explicit the first time they appear in the text. Please notice that ECVs with long names were replaced by their acronyms (fraction of absorbed photosynthetically active radiation by FAPAR; leaf area index by LAI).

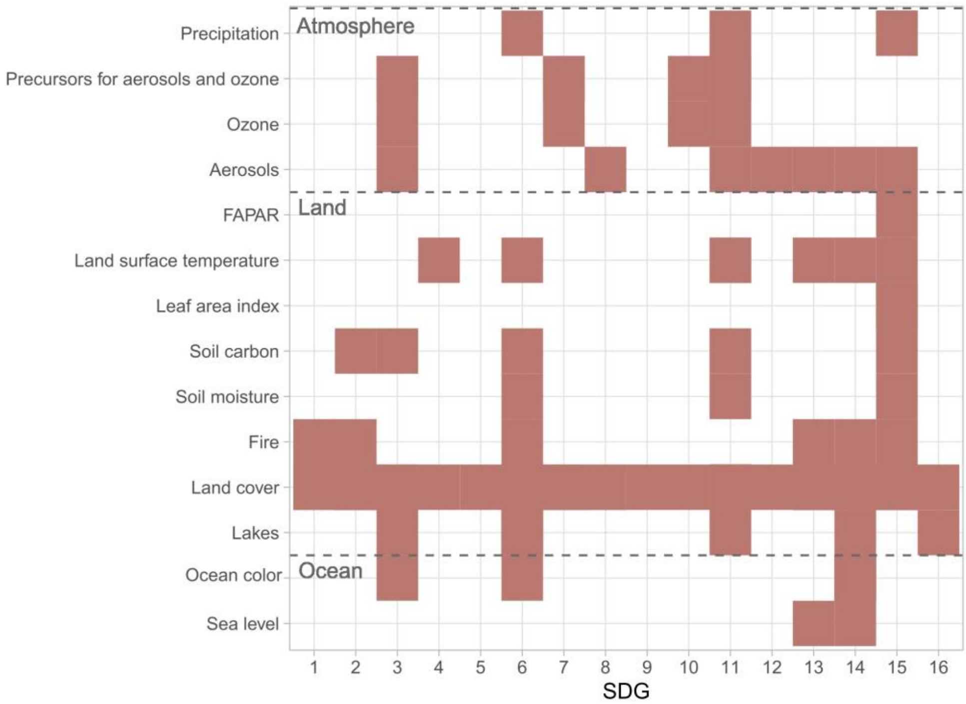

Figure 4. Applied contribution to SDGs that used 14 s-ECVs.

Atmosphere: Surface

In the atmosphere domain (surface), one ECV and one product were reported. For precipitation, we identified the use of CHIRPS product to inform about the SDG indicator 6.4.2 (*Water stress*) [29]. Although CHIRPS is not a pure satellite product, since it also uses rain gauge data, we considered it because of its detailed spatial resolution for rainfall data. Additionally, precipitation from the National Earth System Science Data Center (NESSDC—China), along with other types of information such as spatial, remote sensing, climate, and policies, were used in an integrated ecological security assessment that was related to SDG 15 [30].

Atmosphere: Atmospheric Composition

In the atmosphere domain (atmospheric composition subdomain), three ECVs and four products were reported. Regarding precursors for aerosols and ozone as well as ozone, three ECVs' products were used: total column nitrogen dioxide (NO_2), total column sulfur dioxide (SO_2), and ozone (O_3) [31,32]. In this subdomain, we found that the used s-ECV products were Sentinel-5 precursors (for NO_2 and SO_2), Ozone Monitoring Instrument from the EOS-Aura satellite (OMI, for NO_2), and NASA Earth Observation (NEO, for O_3 and NO_2, although no specific satellite product was mentioned in the study). These products contributed to diverse SDGs such as 3, 7—*Affordable and clean energy*, 10—*Reduced inequalities*, and 11, showing the interlinkages of air quality with different SDGs. Although no SDG indicator was calculated based on precursors, the studies were associated with indicators such as 3.8.1 (*Coverage of essential health services*), 3.9.1 (*Mortality rate of household and ambient air pollution*), 7.1.2 (*Population with primary reliance on clean fuels and technology*), 10.2.1 (*People living below median income*), 11.5.1 (*Deaths per 100,000 population*), and 11.6.2 (*Annual mean levels of fine particulate matter in cities*).

Moreover, aerosols through aerosol optical depth (AOD) were obtained from the Multi-angle Imaging SpectroRadiometer (MISR) and the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) [33]. This air pollution application used aerosols by combining remote sensing, EO, and machine learning to account for modern slavery (Goal 8—*Sustainable economic growth*, target 8.7—*End modern slavery*). The interlinkages of SDG 8.7 to urbanization (SDGs

11, 12—*Responsible consumption and production*), environmental degradation and pollution (SDGs 3, 14, and 15), and climate change (SDG 13) were mentioned.

Land: Biosphere

In the land domain (biosphere and hydrosphere subdomains), eight ECVs and seven products were reported. The most used s-ECV was land cover, and the most used satellite sensor was Landsat with all the archives (i.e., MSS = Multispectral Scanner, TM = Thematic Mapper, ETM+ = Enhanced Thematic Mapper Plus, OLI = Operational Land Imager, and NLCD = USGS National Land Cover Database) [29,33,35,36,41–53]. These approaches contributed to computing the indicators for SDGs 6, 11, and 15 by the following indicators: 6.6.1 (*Extent of water-related ecosystems*) [41,43], 6.4.2, 11.1.1 (*Urban population living in slums and informal settlements*), 11.3.1 (*Land consumption rate to population growth rate*) [29], 15.1.1 (*Forest area as a proportion of total land area*), and 15.1.2 (*Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type*) [52]. The aforementioned Landsat archives were also associated with SDGs 1, 2, 3, 4—*Education*, 5—*Gender equality*, 7, 8, 13, 15, 14, and 16—*Peaceful societies*, as well as with the following targets and indicators (however, no indicators were actually computed): 6.4 (*Water use and scarcity*), 6.5 (*Integrated water resources management*) [47], 6.6 (*Protect and restore water-related ecosystems*) [45], 8.7 [33], 11.B (*Adoption of policies and plans for mitigation and adaptation to climate change*) [47], 15.1 (*Sustainable use of terrestrial and inland freshwater ecosystems*) [45], 15.2.1 (*Sustainable forest management*) [49,53], 15.3 *(Restore degraded land and soil*) [51], 15.4.1 (*Coverage by protected areas of important sites for mountain biodiversity*) [49], 15.4.2 (*Mountain Green Cover Index*) [42], 15.5 (*Red List Index*) [45], 15.8.1 (*Legislation and adequately resourcing the prevention or control of invasive alien species*) [49], and 16.7 (*Effective, accountable and transparent institutions*) [47].

Another satellite sensor used for land cover was MODIS (i.e., land cover products, MCD12Q1, MOD13A1, GLCNMO—Global Land Cover and National Mapping Organizations) [30,33,52,54–56]. Such imagery was used to report indicators 15.1.1 and 15.1.2 [52]. Although not computed, they also were associated with SDGs 1, 2, 13, and 15 [56], target 8.7 [33], and indicator 2.4 (*Sustainable food production systems and resilient agricultural practices*) [55].

In addition, we also identified that land cover from Sentinel-1 and Sentinel-2 was also used in several works. Mainly, Sentinel-1 helped report indicator 6.6.1 [43], and it was also related to SDG 2 [57]. Meanwhile, Sentinel-2 was used to report indicators 15.1.1 and 15.1.2 [52], 11.1.1 and 11.3.1 [58], as well as new definitions for indicators 11.1.1, 11.2.1, 11.3.1, and 11.6.2 [59]. Polpanich et al. [36] used Sentinel-2 in relation to SDGs 4, 6, 11, 13, and 14 in their work for monitoring localized water changes.

Another reported land cover product was the Indian Remote Sensing (IRS) source used in the context of target 15.3 [51]. The European Space Agency (ESA) land cover was used in the platform Trends.Earth (https://www.esa-landcover-cci.org) to calculate indicators 15.3.1 (*Proportion of land that is degraded over total land area*) [60] and 15.4.2 [62]. Additionally, Cui and Li [37] related their work to indicator 15.3.1, and integrated various vegetation biophysical indicators by using, among other variables, the land cover product of the Climate Change Initiative Land Cover (CCI-LC) from the ESA. Antonarakis et al. [53] used this product to assess the relation of financial crises to deforestation (target 15.2—*Sustainable forest management*). Furthermore, a photovoltaic energy inventory at a global scale, which added land cover analysis based on the ESA product, was aligned with SDGs 7, 8, 9—*Resilient infrastructure*, and 13 as well as with the detrimental effects on different SDGs, such as SDG 2 by displacing croplands, SDG 3 by impairing ecosystem health benefits, SDG 10 by displacing community land use, and SDG 15 by impacting biodiversity [63].

The LAI and the FAPAR were obtained from Sentinel-2. This vegetation information was used as predictors for estimating above-ground biomass [34]. Cui and Li [37] used MODIS for a new global land productivity product. They contributed to the indicators 15.2.1

and 15.3.1. Similarly, soil carbon was estimated based on Sentinel-2 and simulated data from the forthcoming (at the time of publication) Environmental Mapping and Analysis Program (EnMAP), the German hyperspectral satellite mission [38]. This work referred to targets 2.3 (*Agricultural productivity and incomes*), 2.4, 3.9 (*Reduce deaths and illnesses from pollution and contamination*), 6.4, 6.5, 11.3 (*Inclusive and sustainable urbanization*), 13.2 (*Climate change measures into national policies, strategies and planning*), and 15.3.

Moreover, land surface temperature from Landsat contributed to SDG 11 [35] and SDGs 4, 6, 11, 13, and 14 [36] and that from National Earth System Science Data Center (NESSDC—China) to SDG 15 [30].

Soil moisture from the NASA-USDA Global Soil Moisture dataset, which integrates the satellite-derived Soil Moisture Active Passive (SMAP) Level 3 and soil moisture observations, was used to compute indicator 6.4.2 [29]. Landsat (OLI, TIRS, TM) was used to analyze drying conditions contributing to SDG 15 [39].

Finally, another reported ECV was fire. Landsat 8 was used to obtain burned areas in the context of SDG 15. It observed the vegetation and ecosystem changes from fire events and their impacts on climate, biogeochemical cycle, and human health [40].

Land: Hydrosphere

We found, in the land domain and hydrosphere subdomain, two reported ECV products. The water extent product from lakes was computed from Landsat (MSS and TM), and contributed to targets 6.4, 6.5, 11.B, and 16.7 [47]. Furthermore, Hakimdavar et al. [43] reported indicator 6.6.1 by using MODIS (MOD44W), and Landsat-derived products such as Global Land Analysis and Discovery Water Surface (GLAD) and Global Surface Water Explorer (GSWE). In addition, Anas et al. [64] addressed lake surface water temperature by making use of Sentinel-3A (LSWT) and Sentinel-2A and 2B (MSI) and contributed to SDGs 3 (concretely 3.3—*End epidemics*), 6, and 14.

Ocean: Physical

Regarding the ocean domain (physical subdomain), one ECV was reported using the regional mean sea level [65] from NOAA. It contributed to SDGs 13 (13.1—*Deaths, missing and affected persons attributed to disasters*) and 14 (14.7—*Increase economic benefits to small islands*). They analyzed the rise of the sea level in the context of coastal tourism development.

Ocean: Biogeochemical

In the ocean domain (biogeochemical subdomain), one ECV was reported using ocean color by the chlorophyll-a concentration product [64,66,67]. MODIS (Aqua) was used to understand the changes in the ocean carbon cycle and contributed to indicator 14.3.1 (*Average marine acidity—pH*) [66]; coastal eutrophication potential was a contribution to indicator 14.1.1a—*Index of coastal eutrophication* [67]. Additionally, Anas et al. [64] used Landsat (OLI) and Sentinel-2 to assess water quality for cholera disease in marine and freshwater ecosystems.

4.3.2. Summary

This section presents a straightforward summary of the main findings from the previous sections. From the literature review, we selected 40 studies that applied 14 ECVs from satellite sources (Figure 4) in the context of 16 SDGs, 33 targets, and 23 indicators (Table 4).

Table 4. Summary of SDGs, targets, and indicators associated with and reported using s-ECVs.

Targets				SDGs	Indicators			
			NS	1—No Poverty	NS			
		2.3	2.4	2—Zero Hunger	2.4.1			
	3.9	3.8	3.9	3—Good Health and Well-being	3.8.1	3.9.1		
			NS	4—Quality Education	NS			
			NS	5—Gender Equality	NS			
	6.6	6.4	6.1	6—Clean Water and Sanitation	6.4.2	6.6.1		
		6.5	6.2					
		7.2	7.1	7—Affordable and Clean Energy	7.1.2	7.2.1		
			8.7	8—Decent Work and Economic Growth	NS			
			NS	9—Industry, Innovation and Infrastructure	NS			
			10.2	10—Reduced Inequalities	10.2.1			
	11.B	11.3	11.1	11—Sustainable Cities and Communities	11.1.1	11.3.1	11.6.2	
		11.5	11.2		11.2.1	11.5.1		
			NS	12—Responsible Consumption and Production	NS			
		13.2	13.1	13—Climate Action	NS			
14.7	14.3	14.7	14.3	14—Life below Water	14.3.1	14.1.1a		
	15.5	15.3	15.1	15—Life on Land	15.1.1	15.2.1	15.4.1	15.5.1
	15.8	15.4	15.2		15.1.2	15.3.1	15.4.2	15.8.1
			16.7	16—Peace, Justice Strong Institutions	NS			
				17—Partnerships for the Goals				

The light gray highlighted goal was not covered by s-ECVs. The dark gray highlighted indicators were computed and reported using s-ECVs. NS means that although the SDG was related to the application, targets or indicators were not specified.

Four points summarize this information: (1) a summary of s-ECVs along with the related SDGs (Figure 4); (2) a list summarizing the main findings regarding the bridge between ECVs and SDGs; (3) an overview of SDGs, targets, and indicators associated and reported with the use of s-ECVs (Table 4). It highlights the indicators calculated using the s-ECVs; and (4) a list of the most used satellite products.

Visual inspection of s-ECVs by SDG. Figure 4 shows the 14 covered s-ECVs and their contribution to specific SDGs. In this context, the most used s-ECVs were related to land cover, whereas the SDGs that received the most attention were SDGs 3, 6, 11, 14, and 15.

List of s-ECVs and the related SDGs. The following list summarizes the main findings regarding the ECVs and their associated SDGs:

Atmosphere domain

- Surface subdomain: one ECV—precipitation (SDGs 6, 11, 15);
- Atmospheric composition subdomain: three ECVs—ozone (SDGs 3, 7, 10, 11), precursors for aerosols and ozone (SDGs 3, 7, 10, 11), aerosols (SDGs 3, 8, 11, 12, 13, 14, 15).

Land domain

- Biosphere subdomain: seven ECVs—FAPAR (SDG 15), land surface temperature (SDGs 4, 6, 11, 13, 14, 15), LAI (SDG 15), soil carbon (SDGs 2, 3, 6, 11, 15), soil moisture (SDGs 6, 11, 15), fire (SDGs 1, 2, 6, 13, 14, 15), land cover (SDGs 1 to 16);
- Hydrosphere subdomain: one ECV—lakes (SDGs 3, 6, 11, 14, 16).

Ocean domain

- Physical subdomain: one ECV—sea level (SDGs 3, 6, 14);

- Biogeochemical subdomain: one ECV—ocean color (SDGs 13, 14).

Overview of addressed SDGs, targets, and indicators. Table 4 summarizes the SDGs, targets, and indicators associated with the s-ECVs. Only 10 indicators (highlighted in dark gray) were calculated and reported by using s-ECVs. They are related to SDGs 6, 11, and 15. Additionally, this table shows that SDG 17 was the only SDG not addressed in the selected studies for this literature review.

Most used satellite products. Finally, we identified that the most used satellite products were Landsat (land surface temperature, soil moisture, fire, land cover, and lakes), Sentinel (precursors for aerosols and ozone, aerosols, FAPAR, LAI, lakes, and ocean color), and MODIS (LAI, lakes, and ocean color).

5. Discussion

5.1. Contribution to Previous Knowledge

Our study identified 14 s-ECVs (out of 54 ECVs). This might be considered as a modest number, especially considering several sEO products for climate variables are already operationally available. Espinosa et al. [21] reported that satellite Earth observation data significantly contributed to at least 30 of the 54 ECVs. Similarly, Giuliani et al. [7] stated (from 52 ECVs) that satellite EO had a full or partial contribution to 42 ECVs. Our study found a direct contribution from s-ECVs that Giuliani et al. [7] previously reported as having a partial contribution. Such a direct contribution is understood from the applied research they were used for. These ECVs were: precursors for aerosols and ozone, aerosols, FAPAR, LAI, soil carbon, soil moisture, and sea level. Masó et al. [15] reported that ECVs contributed (directly or indirectly) to 10 out of the 17 SDGs. Our work extends such results, showing evidence of a direct contribution to 16 out of the 17 SDGs. Furthermore, Avtar et al. [68] identified a group of SDGs on which minimal research had been carried out (SDGs 5, 8, and 10). Our review contributes to this work by reporting recent efforts to relate EO to the aforementioned SDGs.

Additionally, our work provides relevant evidence to update the previous work on ECVs to SDGs carried out by the projects GEOEssential and ConnectinGEO [15]. In fact, new evidence was reported for the following ECVs:

- Precipitation and soil moisture contributed to SDG 6 by computing indicator 6.4.2 [29];
- Ozone and precursors for aerosols and ozone contributed to SDGs 3 (3.8.1, 3.9.1), 7 (7.1.2), 10 (10.2.1), and 11 (11.5.1, 11.6.2). The use of Sentinel 5-P in this context is especially relevant [31,32];
- Lakes (water extent) contributed to SDG 6 by computing indicator 6.6.1 [43]. Additionally, it was linked as relevant to SDG 11 [47];
- Land surface temperature was related to SDG 11 [35] in the context of urban heat islands;
- FAPAR and LAI were related to indicators 15.2.1 and 15.3.1 [34]; and
- Soil carbon was predicted based on Sentinel-2 and EnMAP, contributing to SDGs 2, 3, 6, 11, and 15 [38]. Additionally, further uses of this ECV are expected from global products such as the Global Soil Organic Carbon map (GSOCmap) (http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-soilorganic-carbon-map-gsocmap, accessed on 22 May 2023) and Global Gridded Soil Information (SoilGrids) (https://www.isric.org/explore/soilgrids, accessed on 22 May 2023).

5.2. Most and Least Used s-ECVs

The most used s-ECVs were associated with the land–biosphere domain, with land cover being the most used s-ECV. In fact, this variable was used in 29 of the reported studies, where it was complementary to other s-ECVs in many cases.

The high presence of land cover might be related to the large EO community's experience in generating land cover products. For example, an extensive list of satellite products for the land domain is provided in [69]. Although not highly used in climate studies, land cover and other products from the land domain, such as biomass, have been integrated as ECVs because of their relation to the Earth's climate. For instance, the quantity of biomass and vegetation is related to the air temperature and water vapor, whereas land cover is related to water and energy exchanges to the atmosphere. Furthermore, while performing the literature review, it was not always made explicit whether the land cover was used from a climate or a geographic perspective. This made it challenging to differentiate the context for using land cover. Thus, we focused on the purpose of land cover being selected as an ECV.

Many domain-based EV groups have already been defined [11]. They overlap, entailing that some variables belong to more than one group. In this regard, land cover is one of the most frequent variables integrated with the different domains, such as in the essential biodiversity variables [70], essential water variables [71], essential agriculture variables [72], essential ocean variables [73], and essential energy variables [74], among others.

Other ECVs, especially in the atmosphere domain, have been hardly used for SDGs even if many of them are operationally available from sources such as https://www.eumetsat.int/, accessed on 22 May 2023, http://database.eohandbook.com/measurements/overview.aspx, accessed on 22 May 2023, or https://climatemonitoring.info/ecvinventory/, accessed on 22 May 2023. In this regard, variables from the cryosphere domain were not reported in the selected studies, although they can contribute to SDG 6 [15]. Similarly, variables from the biogeochemical domain are related to SDG 14 and those from the anthroposphere to several SDGs such as SDGs 2, 3, 6, 9, 11, and 12. This means that even if a significant number of available and operational satellite products exist, they still need to be integrated to support SDGs.

5.3. Limitations

Some limitations of this review are worth mentioning. Firstly, the review only considered a few months of 2022. Additionally, we only looked for literature after 2015 in order to consider the studies currently related to the Agenda 2030. However, this left out a considerable amount of literature, satellite EO products, and satellite-derived ECVs, that although not related to the Agenda 20230, might provide worthwhile information for the future integration of other s-ECVs within SDG monitoring.

Regarding the method used for the review, it focused on two repositories (Scopus and Web of Science), which are among the largest and most commonly used multidisciplinary repositories available. Only studies gathered from these databases were analyzed and no gray literature was used. Reviewing gray literature, mainly produced by official institutions, would also be worthwhile to review in future research. These works might evidence efforts to promote EO and SDG integration. As an example of these institutional initiatives, the published report "Compendium of Earth Observation Contributions to the SDG Targets and Indicators" describes the implementation of SDG indicators [6].

In addition, studies based on diverse keywords were collected. Therefore, this work may have excluded important contributions without these keywords. Similarly, we searched for English keywords. Only three studies were retrieved in a different language. The one in Spanish was included because it is the native language of some authors of our study. However, by searching in local repositories with different languages than English, the results of our study could be extended with further evidence. Despite these limitations, our study presents practical and updated insights about s-ECVs that have been used within the SDG context.

Our work carried out a systematic review, however, a meta-analysis reporting a quantitative analysis would be relevant as well as challenging. The challenge is because the reported indicators did not always follow the official methodologies and they were calculated with diverse (non-comparable) data sources. Nevertheless, this brings up an opportunity for future research to compare the performance of s-ECVs for the indicator calculations.

We focused on remotely sensed satellite data, omitting UAVs, in situ data, and reanalysis products. The reason for this choice was to report information that allows feasible, cost-effective, and analysis-ready data, especially on a global scale, in low-income countries and poorly monitored regions [6]. Nevertheless, useful information sources can also be obtained from UAVs, especially in tropical regions without cloud-free optical satellite imagery. Additionally, although with generally coarse spatial resolution, reanalysis data are instrumental in climate applications. We omitted this type of EO since it assimilates and model satellite data with in situ data, which is a significant limitation in many regions of the globe with scarce ground monitoring. However, we consider it extremely useful to complement this review with ECV reanalysis sources, and we also expect an increase in the ECVs reported from this source. Some of the reanalysis products mentioned in the studies selected for our review were MERRA-2 [32], Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System and Data Assimilation System (FLDAS) (combination of MERRA-2 and CHIRPS), MERRA-2 [29], Copernicus Atmosphere Monitoring Service [75], and precipitation and temperature (Era-Interim, CMIP5) [61]. Regardless of the EO data source, operational product access and validation are more important in order to choose the most reliable information for a specific region.

The applied studies selected for this study started to appear in 2018, and most of them were published in 2020. This increase in publications could be related to the launch of Sentinel 5-P in 2017, which allows the monitoring of the atmosphere. In this sense, the interest in using and diversifying the s-ECVs is expected to increase further during the following years, so it is recommended to provide an update of this literature review in the near future.

Moreover, we selected studies that utilized sEO sources for climate variables within the SDG context. Therefore, we intentionally omitted a much larger group of studies that used s-ECVs outside of the SDGs´ scope. We identified some studies that presented a lack of a clear description of material and satellite EO metadata. So, identifying satellite products and their spatial and temporal resolutions was challenging. In this regard, we accessed further citations in order to clarify these issues regarding the spatial and temporal resolution described in the studies. In this line, we call the EO community's attention to the relevance of contributing to science reproducibility by clearly reporting materials, sources, and processes [76] or, in other words, to follow the FAIR principles—Findability, Accessibility, Interoperability, and Reusability [11].

6. Conclusions

We systematically reviewed the essential climate variables from satellite Earth observation sources currently supporting the SDGs. By doing so, we searched for studies published between January 2015 and March 2022. From these searches, 40 studies fit the following criteria: (1) contributed to SDGs, (2) used ECVs from satellite EO, and (3) some were also used to calculate specific SDG indicators. With this framework, we established the following research question: Which are the s-ECVs supporting the measuring and monitoring of the progress towards SDGs? This was answered by reporting the used ECVs, their satellite sources, and the SDGs and indicators they contributed to.

Therefore, out of the 54 ECVs, we identified that 14 of them made an applied use of sEO products. They belonged to the (1) atmosphere domain, surface subdomain: precipitation; atmospheric composition subdomain: ozone, precursors for aerosols and ozone, aerosols; (2) land domain, biosphere subdomain: FAPAR, land surface temperature, LAI, soil carbon, soil moisture, fire, and land cover; hydrosphere subdomain: lakes; and (3) ocean domain, physical subdomain: sea level; biogeochemical subdomain: ocean color.

This literature review provides relevant evidence for scientists and policymakers in order to boost a better integration of satellite-based ECVs into SDG monitoring. It summarizes the s-ECVs used for specific SDGs along with their targets and indicators. However, further actions and research are needed. For instance, it is required to ensure that all countries have access to EO data, software tools, and services to promote the use of EO to support the SDGs and that EO-based analysis-ready data are openly available [22]. Therefore, common access mechanisms to EO data must be provided [21], and further efforts must be made to achieve so-called "EO literacy" [6]. Although we found that s-ECVs contributed to 16 SDGs, 33 targets, and 23 indicators, only 10 indicators were calculated and reported using s-ECVs. These were associated with SDGs 6, 11, and 15. Thus, there is still a gap regarding SDG indicator calculations to further utilize ECVs from satellite EO sources, allowing a worldwide indicator comparison. Additionally, we suggest a revision of the methodologies to calculate indicators and to identify ready-to-use climate variables in support of the SDGs.

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Abbreviations

SDG	Sustainable Development Goal
EO	Earth Observation
sEO	Satellite Earth Observation
EV	Essential Variable
ECV	Essential Climate Variable
s-ECV	Essential Climate Variable from Satellite Earth Observation source

Appendix A

Table A1 summarizes the 54 ECVs and their products from GCOS (https://gcos.wmo.int/en/essential-climate-variables, accessed on 22 May 2023). Additionally, it displays the contribution of each ECV to the SDGs, obtained from ENEON (https://github.com/grumets/eneon-graph, accessed on 22 May 2023). These connections between ECV and SDGs were previously mapped in the context of the GEOEssential and ConnectinGEO projects [15]. The use of sEO as a contribution to the ECVs was obtained from Giuliani et al. [7]. Finally, a valuable repository to further explore available s-ECVs is the ECV Inventory (https://climatemonitoring.info/ecvinventory/, accessed on 22 May 2023), which was implemented by the Coordination Group of Meteorological Satellites (CGMS) and CEOS. This work allowed setting the Working Group on Climate (WGClimate) and provided access to 496 existing products for ECVs [21] from both sEO and reanalysis data. ECV—Variables highlighted in gray represent s-ECVs identified as results of our study.

Table A1. ECVs, products, and their relation to the SDGs.

D.	S.D.	ECV—Variable	ECV—Product	sEO *	SDG **
Atmosphere	Surface	Precipitation	Estimates of liquid and solid precipitation	Y	6
		Pressure	Pressure	N	
		Radiation budget	Surface ERB (longwave, shortwave)	Y	13
		Temperature	Temperature	Y	
		Water vapor	Water vapor (relative humidity, dew point)	Y	
		Wind speed and direction	Surface wind speed and direction	Y	
	Upper-air	Earth radiation budget	Top-of atmosphere ERB (longwave, shortwave-reflected), total solar irradiance, solar spectral irradiance	Y	
		Lightning	Number of lightnings	Y	
		Temperature	Tropospheric and stratospheric temperature profile, temperature of deep atmospheric layers	P	
		Water vapor	Water vapor (total column, tropospheric and lower stratospheric profiles, upper tropospheric humidity)	P	
		Wind speed and direction	Upper-air wind retrievals	Y	
	Atmospheric composition	Aerosols	Aerosol (optical depth, layer height, extinction coeff. profile), single-scattering albedo	P	
		Carbon dioxide, methane, and other greenhouse gases	Tropospheric column (CO_2, CH_4), tropospheric (CO_2, CH_4), stratospheric CH_4	P	3, 7, 9, 13
		Clouds	Cloud (amount, top pressure, top temperature, optical depth, water path –liquid/ice, effective particle radius -liquid + ice)	P	
		Ozone	Ozone (total column, tropospheric, profile in upper troposphere, lower stratosphere, upper strato- and mesosphere)	Y	
		Precursors for aerosols and ozone	Tropospheric column (NO_2, SO_2, HCHO, CO) and profile (CO)	P	
Land	Hydrosphere	Groundwater	Groundwater (storage change, level, recharge, discharge, wellhead level, quality)	P	6
		Lakes	Lakes (water level, water extent, surface water temperature, color, ice thickness and cover)	Y	6, 15
		River discharge	River discharge, water level, flow velocity, cross-section	N	6
	Cryosphere	Glaciers	Glacier area, elevation change, mass change	Y	6
		Ice sheets and ice shelves	Surface elevation change, ice velocity, ice mass change, grounding line location, and thickness	P	6
		Permafrost	Thermal state of permafrost, active layer thickness	P	
		Snow	Area covered by snow, snow depth, snow water equivalent	Y	6
	Biosphere	Above-ground biomass	Maps of above-ground biomass	P	15
		Albedo	Maps of directional hemispherical reflectance (DHR) albedo for adaptation, bihemispherical reflectance (BHR) albedo for adaptation, DHR and BHR albedo for modeling	Y	13
		Evaporation from land	Latent heat flux, sensible heat flux	P	
		Fire	Burnt area, active fire maps, fire radiative power	Y	15
		Fraction of absorbed photosynthetically active radiation (FAPAR)	Maps of FAPAR for modeling and adaptation	P	15
		Land cover	Maps of land cover, high resolution land cover, key IPCC land use, related changes, and land management types	Y	2, 6, 11, 15
		Land surface temperature	Maps of land surface temperature	Y	
		Leaf area index (LAI)	Maps of LAI for modeling and adaptation	P	15
		Soil carbon	% carbon in soil; mineral soil bulk density to 30 cm and 1m Peatlands' total depth of profile, area, and location	P	15
		Soil moisture	Surface soil moisture, freeze/thaw, surface inundation, root-zone soil moisture	P	

Table A1. *Cont.*

D.	S.D.	ECV—Variable	ECV—Product	sEO *	SDG **
	Anthroposphere	Anthropogenic greenhouse gas fluxes	Emissions from fossil fuel use, industry, agriculture and waste sector; emissions/removals by IPCC land categories; estimated fluxes by inversions of observed atmospheric composition—continental; estimated fluxes by inversions of observed atmospheric composition—national; hi-res CO2 column concentrations to monitor point sources	N	3, 9, 11, 12
		Anthropogenic water use	Volume of water use	N	2, 3, 6
Ocean	Physical	Ocean surface heat flux	Latent heat flux, sensible heat flux, radiative heat flux	P	
		Sea ice	Sea ice (concentration, extent, thickness, drift)	Y	
		Sea level	Global mean sea level, regional mean sea level	P	
		Sea state	Wave height	N	
		Sea surface currents	Surface geostrophic current	P	
		Sea surface salinity	Sea surface salinity	Y	
		Sea surface stress	Surface stress	N	
		Sea surface temperature	Sea surface temperature	Y	
		Subsurface currents	Interior currents	N	
		Subsurface salinity	Interior salinity	NR	
		Subsurface temperature	Interior temperature	NR	
	Biogeochemical	Inorganic carbon	Interior ocean carbon storage. At least 2 of: dissolved inorganic carbon (DIC), total alkalinity (TA), or pH; pCO2	N	14
		Nitrous oxide	Interior ocean N2O, N2O air–sea flux	N	
		Nutrients	Interior ocean concentrations of silicate, phosphate, nitrate	P	14
		Ocean color	Water leaving radiance, chlorophyll-a concentration	Y	14
		Oxygen	Interior ocean oxygen concentration	N	14
		Transient tracers	Interior ocean (CFC-12, CFC-11, SF6, tritium, 3He, 14C, 9Ar)	N	
	Biological ecosystems	Marine habitats	Coral reefs, mangrove forests, seagrass beds, macroalgal communities	P	15
		Plankton	Phytoplankton, zooplankton	P	

D.—domain; S.D.—subdomain; ECV—variables and products adapted from https://gcos.wmo.int/en/essential-climate-variables/table; accessed on 22 May 2023; * sEO: satellite Earth observation adapted from [7] (Y = Yes; N = No; P = Partial; NR = Not reported; ** SDG adapted from https://github.com/grumets/eneon-graph, accessed on 22 May 2023.

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