Review

Open and Consistent Geospatial Data on Population Density, Built-Up and Settlements to Analyse Human Presence, Societal Impact and Sustainability: A Review of GHSL Applications

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Abstract: This review analyses peer-reviewed scientific publications and policy documents that use built-up density, population density and settlement typology spatial grids from the Global Human Settlement Layer (GHSL) project to quantify human presence and processes for sustainability. Such open and free grids provide detailed time series spanning 1975–2015 developed with consistent approaches. Improving our knowledge of cities and settlements by measuring their size extent, as well as the societal processes occurring within settlements, is key to understanding their impact on the local, regional and global environment for addressing global sustainability and the integrity of planet Earth. The reviewed papers are grouped around five main topics: Quantifying human presence; assessing settlement growth over time; estimating societal impact, assessing natural hazard risk and impact, and generating indicators for international framework agreements and policy documents. This review calls for continuing to refine and expand the work on societal variables that, when combined with essential variables including those for climate, biodiversity and ocean, can improve our understanding of the societal impact on the biosphere and help to monitor progress towards local, regional and planetary sustainability.

Keywords: anthropogenic impacts; hazard risk and impact; international frameworks; city size; GHS-BUILT; GHS-POP; GHS-SMOD; urban; rural; cities

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1. Introduction

Planetary sustainability in the Anthropocene [1]—an epoch of increasing societal resource use—is a global concern [2]. Planetary sustainability addresses human development, while safeguarding Earth's life support system [3] and fulfilling human societal needs for current and future generations [4]. It is related to the societal impact of cities, which is where most resources are consumed [5]. Measuring the size and shape of cities and settlements resulting from urbanisation [6–9]—made possible through the analysis of satellite image archives [10]—and the human activities occurring within them—as referenced in this review—is a precondition to understanding societal processes [11], their impact on planet Earth at a local, regional and global scale. In fact, cities and settlements have been identified as key players in the transition towards a sustainable future [12].

The societal use of resources continues to increase, due to population growth and affluence, both of these largely occurring in cities [7]. Between 1950 and 2020, five billion people have been added to Planet Earth, and the carbon related energy emission has increased 5 fold [13]. Anthropocene is the new term referring to this epoch of unprecedented resource use, urbanisation and global environmental changes [2]. One of the direct impacts of urbanisation and economic growth is the conversion of natural land into built-up land and the increase in the concentration of greenhouse gases in the atmosphere. The indirect, cumulative impact of human activities is centred on modifying the land and marine ecosystems for societal use [14]. As the cumulative impact of local scale human activities may

affect planet Earth, settlement data need to be available at fine scale in addition to having global coverage.

This work reviews the use of three GHSL information layers generated within the Group on Earth Observation—Human Planet Initiative, that satisfy these requirements of spatial detail and global coverage over a temporal timespan of decades. The layers include the Global Human Settlement Built-Up Areas spatial grid (GHS-BUILT), the Global Human Settlements Population spatial grid (GHS-POP) and the Global Human Settlement Model (GHS-SMOD) spatial grid. The GHS-BUILT was produced by inferring the presence of buildings [15,16] from satellite imagery alone. It uses artificial intelligence techniques and the satellite image archives from Landsat, Sentinel-1 and Sentinel-2 [17,18]. The GHS-POP combines census data with that of the global built-up area to generate gridded population density layers over time [19]. The GHS-SMOD partitions the global built-environment into settlement types (including cities, towns and suburbs, and rural areas) based on population density, size and geospatial contiguity based on the Degree of Urbanisation methodology [20] that was recently endorsed by the UN Statistical Commission [21].

The three datasets, covering the period 1975–2015, are co-produced and are part of the same lineage of GHS products [22]. The technical description of the products subject of this review are provided in Supplementary Table S1.

Consistency across the three layer types is of value in itself as a number of applications rely on diverse themes that need to be analysed jointly in a consistent manner (e.g., quantifying population by settlement type). The open layers are used to support science and policy in a variety of operational services.

A number of global Earth Observation derived information products—key global geospatial information sources—map the global built-environment [23] in a homologous way to GHS-BUILT. These information products can differ in the semantics they use (e.g., impervious, settlement footprint, “urban”); the type of EO data used as input, as well as the use of different techniques of information extraction [23]. These include the Global Urban Footprint [24] and World Settlement Footprint [25]. Moreover, global land cover maps use the class “urban” to represent settlements on a global scale [26], while other information products map impervious surfaces that include the built-environment [27].

A number of population grid products—key global geospatial information sources—are analogous to GHS-POP [28]. Some population grids differ from GHS-POP as they use different definitions (i.e., “ambient” population [29]) that are less well suited for outlining cities and settlements—and thus, measuring their shape and size—that is key in understanding settlements [28]. In fact, GHS-POP is part of the methodology to generate GHS Settlement Model (GHS-SMOD) used to spatially outline settlements.

This review analyses scientific publications (peer-reviewed), reports and policy documents that quantify human presence and processes for sustainability, enabled by the free availability of GHSL global geospatial data. These documents are grouped based on the geographical scope of the analysis, the geographical region covered, and the type of GHS datasets used. The reviewed publications are grouped and related thematically to a simplified Earth System diagram to highlight the relevance of this body of literature for Earth System Science. We use these findings to assess the potential for supporting indicators used to monitor international frameworks, to generate new scientific knowledge on human presence, societal processes and hazard impact on societies. This article complements a policy-focused review of GHSL data applications in Disaster Risk Management, Urbanisation, Development and Environment and Sustainability [30].

2. Background

Cities and settlements are centres of production and consumption that drive global environmental change [5]. Cities and settlements are at the centre of the sustainability debate, and their consumption patterns define the societal demand for resources. In fact, to maintain themselves and prosper, societies have evolved by organising a continuous flow of energy and materials from their natural environments [31] that are consumed in

cities and settlements. That societal demand varies greatly based on societal development/affluence [14]. Resource and energy use are reflected in the physical characteristics of settlements, including its form and shape, built-up and population density—the settlement patterns, and that influences the unfolding of human activities—the societal processes [32].

Local settlement sustainability patterns can be scaled up to generate regional, national and global sustainability trajectories. Settlement sustainability studies at the local scale use settlement perimeters to determine the spatial area of analysis [33–35]. Cities and settlements are also functional nodes of national, regional and global networks that exchange people, goods and resources [36]. Sustainability trajectories will have to address resource demand displacement through teleconnections [37] that are starting to be measured and quantified [38]. For planetary boundary concerns, the cumulative throughput of energy and materials will then need to be aggregated in national, regional and global scale assessments to estimate the overall trajectory of the Anthropocene [39].

Population and built-up density are the essential societal variables that provide the spatial skeleton of human presence on planet Earth. This review is organised around a conceptual and schematic Earth system diagram [40] that identifies Earth's subsystems, including the atmosphere, land, oceans and biosphere with its land and ocean component (Figure 1).

The settlement perimeters include built-up and landscape elements, such as green areas or transport infrastructure, and are represented schematically by the larger human settlement box in Figure 1. Societies use resources, material and energy that are largely consumed within settlements. The arrows in Figure 1 represent systems of resources, material, or energy flows that are occurring at different geographical scales. We indicate the demand for resources with grey arrows, the production of waste with black arrows and the process impact of natural hazards with yellow arrows. The waste produced needs to be either assimilated within settlements or exported outside settlements [41]. Resources used in settlements sustain their populations and built-environment, and generate the goods and services that improve the quality of life of their citizens.

Human activities are largely occurring within settlements, an environment modified for human habitation. Resource use and demands in settlements modify the environment beyond the physical space occupied by settlements (Figure 1). Societal primary economic sectors (agriculture, forestry, extraction) are put in place and evolve as systems to supply the food, fibre, energy and materials to meet the needs of human societies [42]. Ecosystem resource appropriation modifies the natural ecosystem to different degrees. Semi natural ecosystems provide services and are often transformed into simplified agricultural ecosystems with completely different structures from the original, and at different degrees [43]. This transformation process typically weakens ecosystem resilience and reduces biodiversity, issues at the core of the Sustainable Development Goals (SDGs) [44], planetary boundaries [45] and European Green Deal [46]. Settlements also rely on water supply from outside the perimeter of the settlement when it is not available to a sufficient degree within, and this is becoming a major concern for larger cities, and not only in dry environments. Similarly, using different resource appropriation systems, oceans are put under stress and are recipients of waste originating from settlements. Finally, the natural processes governing planet Earth generate extreme high-energy events that impact negatively on the built-environment and people living within it (fast-onset natural hazards), or impact the resource base (crops, access to water and energy) and the systems that supply human societies (yellow arrow) with food, water, energy and materials.

Figure 1. The simplified Earth system diagram (redrawn from [40]) shows with arrows the societal and natural processes that connect human settlements with Earth system subcomponents. The 51 reviewed papers are clustered into five thematic groupings (A–E) of 13 thematic areas (1–13). Human presence (A) is defined by the spatial size of human settlements and their components; and the spatial settlement growth (B). The impact of human activities on the Earth subsystems (C) is represented by black arrows, and the societal demand for resources by grey arrows. The impact of natural hazards on society (D) is indicated with yellow arrows. The resulting patterns and trajectories are then captured/assessed through spatial aggregation indicators used for reporting to international frameworks and in policy reports (E) indicated with white arrows.

The thematic reference groupings are also relevant for generating indicators for reporting on international frameworks. In fact, Human Presence on Planet Earth—location, size and densities of settlements, and Settlement Spatial Growth (Figure 1 thematic grouping A and B)—are central to the New Urban Agenda (NUA) [47], and urbanisation issues are addressed in SDG 11. Accurate estimates of built-up and population are also key in quantifying the impact of exposure to natural hazards (thematic grouping D). Understanding societal impact within and beyond settlements is central to The Paris Agreements [48] and European Green Deal, and is also addressed in SDG 12, which has carbon emission reduction as one of its goals (thematic grouping C). Key negative societal impacts are also Land degradation (central to the United Nation Convention to Combat Desertification (UNCDD) [49]) and biodiversity reduction, also central to the European Green Deal. Hazard impact and risk is key to understanding damage and losses, as well as to “understand disaster risk” (first priority in Sendai Framework for Disaster Risk Reduction—Sendai FDRR [50]). Regarding climate-related hazard impact, assessments of risks and adaptation are then the focus of The Paris Agreement. Framework indicators are typically generated at

a national scale using the administrative boundary of the countries [51] for communication to the relevant framework custodians.

The reviewed publications also address the generation of variables that may contribute to the goals of the European Green Deal. The European Green Deal addresses in different ways the sustainability of societies with a time horizon longer than that of the 2030 Agenda for Sustainable Development. Its main priority is eliminating fossil fuel emissions by mid-century and building a sustainable green economy [52] (European Commission, 2020). The European Green Deal prioritises a number of thematic areas that overlap, complement or refine the ambition of The Paris Agreement, that of the SDGs and that of other international frameworks. For example, the goals of supplying clean energy or reducing emission from the building stock are directly centred on the priority of The Paris agreement. The objectives of mobilising industry for a circular economy, moving towards sustainable transport, improving food consumption and making the agricultural system more efficient, as addressed in SDG goals 7, 8, 9 and 12, respectively.

3. Results

The results are presented based on five thematic groupings for a total of thirteen thematic areas against the structure of Figure 1. The human presence thematic group includes sections related to (a) the outlining of settlements, (b) the characterisation of settlements (Table 1) and (c) the measurement of the built-up spatial growth (Table 2). The societal thematic grouping includes sections addressing the direct and indirect impact of built-up growth on other land cover types (Table 3) and measuring demand for resources, energy and emissions (Table 4). The hazard impact thematic grouping addresses the increased exposure to hazards (Table 5). The indicators thematic grouping addresses the generation of indicators for the post-2015 International Framework Agreements, as well as policy documents that use indicators aggregated across larger spatial units for policy analysis (Table 6).

Table 1. Sizing and understanding human settlements.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
A.1 Settlement delineation	1	Urbanisation in USA	Outlining settlements	Conterminous United States	GHS-BUILT	[53]
	2	Urban spatial extent of Indian cities	Outlining settlements	Indian cities	GHS-BUILT (Nightlights)	[54]
	3	Urbanisation in India	Comparing urbanisation	Indian cities	GHS-POP	[55]
	4	Detecting urban markets with satellite imagery	Partition metropolitan areas into subsections	Indian cities	GHS-BUILT	[56]
	5	Delineation and population trends in metropolitan areas of the world	Outlining worlds metropolitan areas	Global	GHS-SMOD (HDC) FUAs	[57]
A.2 Built-up patterns within settlements	6	Green in urban areas of the world	Green in urban areas	Global	GHS-SMOD; GHS-BUILT	[58]
	7	Characterising urban infrastructural transitions	Characterising the changes in built-up population and infrastructure	India	GHS-BUILT Marble Nightlights	[59]
	8	Internal displacement in urban and rural areas	Internally displaced in settlement classes	Nigeria, Ethiopia	GHS-SMOD	[60]

Table 2. Built-up spatial growth.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
A.3 Built-up spatial growth	9	Global urbanisation	Spatial settlement growth	Global	GHS-BUILT	[10]
	10	Megacities population growth and density	Megacities population growth	30 Megacities of the world	GHS-BUILT; GHS-POP; GHS-SMOD	[61]
	11	Spatial growth in Latin American cities	Spatial settlement growth	Latin American Cities	GHS-POP	[62]
	12	Urbanisation and sustainability in Asian Russian cities	Urbanisation in Six Siberian cities	Six Asian Russian cities	GHS-BUILT	[63]
	13	Urban sprawl in Dar Es Salaam	Spatial Settlement Growth	Dar Es Salaam	GHS-BUILT; GHS POP	[64]
	14	Characterising urbanisation in greater Saigon 2000–2009	Spatial settlement Growth	Greater Saigon	GHS-BUILT	[65]
	15	Urbanisation in Uttarkhand (India)	Built-up growth in Himalayas	Uttarkhand (India)	GHS-BUILT; GHS-POP; GHS-SMOD	[66]
	16	Urban growth in settlement of different sizes	Population growth in settlements over time	Global	GHS-POP; GHS-SMOD	[67]

Table 3. Built-up growth Impact on other land covers.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
B.4 Encroaching on other land covers	17	Urban change 1985–2015 and impact on other land cover	Consumption of agricultural land	Global	GHS-BUILT	[68]
	18	Urban change trajectories and impact on food production	Settlement growth and loss of crop yields	Jangsu province (China)	GHS-POP	[69]
	19	Spatio-temporal analysis of urbanisation	Loss of agricultural land	Yangtze River (China)	GHS-BUILT; GHS-POP	[70]
B.5 Impact on other natural and/or societal assets	20	Settling conservation priorities based on the Global Human Modification Gradient	Global Human Modification Gradient	Global	GHS-POP	[71]
	21	Forest degradation around Dar Es Salaam	Impact of urbanisation on deforestation	Dar Es Salaam (Tanzania)	GHS-POP	[72]
	22	Built-up within and around protected areas	Built-up impact on protected areas	Global	GHS-BUILT	[73]

Table 4. Climate, emissions and energy use in settlements.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
C.6 Urban climate	23	World Urban Data and Web portal for Local Climate Zones	Characterising urban patterns to assess urban climate	Framework for global analysis	GHS-BUILT	[74]
	24	Mapping Europe in Local Urban Zones	Characterising urban patterns to assess urban climate	European Cities	GHS-BUILT	[75]
	25	Greenness in 486 urban Centres with more than 1 million people	Greenness as an indicator to reduce heat in Cities	Globe	GHS-SMOD (Urban Centres)	[76]
C.7 Emissions	26	Emissions from cities	Emissions	130,000 cities worldwide	GHS-SMOD	[77]
	27	Global assessment of Asthma incidence due to NO ₂	Spatially disaggregate NO ₂ emission in settlements	Global	GHS-SMOD	[78]
	28	Emissions and air pollution	Air pollution/Emissions	250 cities world wide	GHS-SMOD	[79]
	29	Air pollution for 20 Indian cities	Air pollution	20 Indian Cities	GHS-BUILT	[80]
	30	Vehicle emissions and air pollution in urban areas	Modelling Air pollution/Emissions based on GHS-BU	China	GHS-BUILT	[81]
C.8 Energy use and demands	31	Spatial patterns of energy use	Uneven energy access across the globe	Globe	GHS-POP; GHS-BUILT	[82]
	32	Assessment of the rooftop solar photovoltaic, potential in the European Union geospatial	Rooftop to estimate electricity production potential from solar panels	European Union	GHS-BUILT GHS-ESM	[83]
	33	Electricity autarchy in Europe	Energy sufficiency	European Union	GHS-POP; GHS ESM	[84]
C.9 Economic variables	34	Global grids of GDP	Gridded GDP	Global	GHS-POP	[85]
	35	Mapping GDP using 1 km VIIRS data	Night-time lights as proxy for GDP in urban clusters	Global	GHS-SMOD; GHS-POP	[86]
C.10 Access indicators	36	Global time access indicators	Travel access time to cities (HDC)	Global	GHS-SMOD;(HDC)	[87]
	37	Global time access indicator	Travel time to settlements	Global	GHS-SMOD	[88]
	38	Urban rural catchment and access to services	Urban rural catchments	Global	GHS-POP;GHS-SMOD	[89]
	39	Access to mass rapid transit in OECD urban areas	Access to mass transit based on Functional Urban Areas	OECD urban areas	GHS-POP	[90]

Table 5. Exposure and hazards impact and risk.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
D. 11 Exposure to hazards	40	Global Exposure Model for the Global Assessment Report 2015	Contribution to computation of exposure in GAR 2015	Global Exposure to measure risk	GHS-BUILT_Ref. (precursor of GHS-BUILT)	[91]
	41	Changes in global built-up and population exposure	Increase in global exposure for 5 hazards	Global (Country aggregates)	GHS-BUILT; GHS-POP	[92]
	42	Population distribution in the proximity of active volcanoes	Exposure to volcano hazards	Global with focus on Asia and Central America	GHS-POP	[93]
	43	Global projections of flood risks in a warmer climate	Population flood impact	Global	GHS-POP	[94]
	44	Heat waves in Africa 1981–2015	Population impacted by Heat waves	Africa	GHS-POP	[95]

Table 6. Indicators for science, policy and International Frameworks.

Thematic Area	Sequential	Short Title	Use of GHS Spatial Grids	Geographical Scope	GHS Layer	References
E.12 SDGs Indicators	45	Principle and applications. The SDG 11.3.1	SDGs indicators	Global (per city)	GHS-BUILT; GHS-POP; GHS-SMOD	[96]
	46	Multi-scale estimation of land use efficiency	SDGs indicators	Global (per city)	GHS-BUILT; GHS-POP; GHS-SMOD	[97]
	47	SDG Voluntary Local Reviews: Using GHSL layers	SDG indicator reviews for European cities	European (per city)	GHS-BUILT; GHS-POP; GHS-SMOD; ESM	[98]
E.13 Policy indicators	48	Green growth indicators	Natural capital indicators	Global (per country)	GHS-BUILT	[99]
	49	Economic surveys in India	Urbanisation in India	India	GHS-SMOD; GHS-BUILT	[100]
	50	The future of cities	Socio-economic trends in cities	European/Global	GHS-SMOD; GHS-POP; GHS-UCDB	[101]
	51	Adapt now: A global call for leadership on adaptation	Population in low elevated coastal zones	Global	GHS-SMOD	[102]

3.1. Human Presence

Outlining settlements to partition urban and rural areas is a practice implemented to guide policies. Most countries have developed urban/rural criteria that best suit their country needs and their societal development. That diversity of criteria makes a comparison of urbanisation figures across countries of the world difficult. In addition, settlement growth may occur at such a rate that countries do not have the resources to measure the updates. Satellite-based earth observation is increasingly considered to make up for the shortage or even for missing data if the methods are not yet consolidated. This review shows that a number of researchers and policymakers continue to address the task of

(1) sizing cities and settlements; (2) analysing the built-environment within settlements (Table 1).

3.1.1. Sizing Cities and Settlements

Balk et al. [53] analysed the relationship between built-up areas mapped in GHSL layers with urban areas defined by the US Census Bureau for the conterminous USA. The study shows a positive relationship between the two figures and suggests that GHS-BUILT estimates could be considered to estimate the extent of urban areas in the USA. The authors find that 30% of the areas defined as urban by the census are considered non-urban when using GHS-BUILT estimates that consider as urban the cells with more than 50% built-up. The paper calls for improving the analysis towards a better understanding of the spatial patterns of built-up.

Galdo et al. [54] and Balk et al. [55] analysed urbanisation in India to address the conflicting urbanisation statistics generated from different sources. Balk et al. [55] use gridded estimates of population at a resolution of 1 km along with two spatial renderings of urban areas—one based on the official tabulations of population and settlement types (i.e., statutory towns, outgrowths, and census towns) and the other on remotely-sensed measures of built-up land derived from the Global Human Settlement Layer. The work of Galdo et al. [54] combines GHS-BUILT and Nightlight imagery to generate settlement outlines that are then partitioned into urban and rural settlements. The work aimed to provide an independent overview of urbanisation from that provided by national statistics and the many claims that India is more urbanised than official figures indicate. Outlining settlements and providing a categorisation of settlements based on size and/or density continues to be tested using national and international set criteria and satellite images of different types to evaluate the best methodologies to use that often relate to the type of urbanisation.

Baragwanath et al. [56] use different built-up layers, including GHS-BUILT and nightlights, to assess the number of Indian markets. The study tests methodologies for further subdividing the geographic unit of analysis—the metropolitan area—into smaller ones nested within metropolitan area units. The authors use a combination of GHS-BUILT and nightlights and test other sources for built-up. The ultimate objective of the analysis is to evaluate the potentially highly spatially heterogeneous economic impacts of investments in infrastructure.

Urbanisation studies also address the outlining of metropolitan areas that include cities and the lower density settlements that are economically connected to cities. Moreno-Monroy et al. [57] used the Urban Centres (UC) and GHS-POP to generate functional urban areas (or metropolitan areas) in the world based on estimated surrounding commuting zones. Functional Urban Areas (FUAs) are metropolitan areas that are defined based on objective characteristics (i.e., travel time to Urban Centres, area of the UC, local population and country GDP per capita).

3.1.2. Assessing Settlements within Their Perimeter

The spatial arrangement of the built-up area and that of other land uses within the settlement perimeter is the outcome of the settlement development history and may be influenced by urban planning and management. The spatial patterns within a city influence the quality of life of its populations, the need for energy, the disaster risk and urban sustainability.

The provision of open and green spaces is a major issue addressed by city planners and transport specialists and is a measure related to the quality of life of its citizens. Corbane et al. [58] use satellite-based measures of greenness as a measure of vegetation within Urban Centres. The greenness measure is generated as complementary to that of the built-up area within the HDC. This is the first global assessment of greenness for more than 10,000 cities worldwide. The estimation of green open spaces contributes to measuring “open space for public use for all” in urban centres as described in the SDG indicator 11.7.1.

Stokes and Seto [59] test a conceptual framework with settlements in India to understand the trajectories of built-up spatial patterns. The key inputs to completing this study are independent datasets on population change and electric infrastructure change. The study is multi-temporal and uses the GHS-BUILT spatial grid to quantify urban land change. The work provides a new indicator that, when measured over time, can be used in addressing the sustainability of settlements.

The International Organisation for Migration [60] reports on the location of internally displaced people for Nigeria and Ethiopia using the GHS-SMOD classes. Understanding IDP (Internally Displaced Persons) location—whether in urban or rural settings—is critical to understand the access to services of IDPs and the need for humanitarian intervention to overcome that lack of access to services. The report shows that despite different degrees of urbanisation (Nigeria is more urbanised than Ethiopia), IDPs concentrate more in rural areas in both countries.

3.2. Settlement Spatial Growth and Impact

In well-run settlements, urban planners and city managers typically monitor and manage built-up spatial growth. Built-up spatial growth encroaches on natural land and increases the environmental challenges of supplying clean air and water and recycling waste. In order to satisfy the needs of a growing economy and a growing population, urban growth can follow different trajectories, including densification and urban spatial growth. Both trajectories pose their own sustainability challenges. The review covers global, regional and local built-up studies that address spatial settlement growth (Table 2) and the impact of urban spatial growth (Table 3).

Melchiorri et al. [10] applied the lineage of GHS products to provide a picture of the demographic and spatial traits of urbanisation between 1990 and 2015. The research quantified the spatial expansion and demographic growth of urban areas identifying that these areas were responsible for 90% of the global demographic change and 72% of the spatial expansions of built-up areas. The statistics provide the first global insights into the cumulative effect of urbanisation and the unequivocal fact that urbanisation is one of the most measurable signs of the Anthropocene. The study highlights the increase in built-up area from 2.21×10^5 in 1990 to 5.68×10^5 km² in 2015. That trend is expected to continue in the decades to come making sustainable urban spatial growth one of the key priorities for sustainable development.

Hoole et al. [61] provide a focused analysis of the built-up area increase for megacities of the world (settlements that exceed 10 million inhabitants). It is a comparative study across megacities using GHS-POP data. There are a number of particularly striking findings from the analysis. The 2015 total population of 30 megacities has doubled when compared to that of 1975, accounting for 6.4% of the world population in 2015. Some cities like Jakarta added 10 million people to their population of 1975. This rate of urbanisation is often neither sustainable nor desirable, yet it is the lived reality for residents and policymakers in many large cities across the Global South. Third, from the analysis of individual densities, especially high maximum density figures of more than 100,000 people/km² were found in Cairo, Kolkata, Guangzhou-Shenzhen, Manila and Shanghai in 2014.

Dunque et al. [62] address the temporal spatial dynamics of urban growth in Latin American cities based on temporal growth provided by GHS-BUILT. The datasets also provide an understanding of the form and the fragmentation of the perimeter of cities. More specifically, the built-up is used to measure the “fullness” index, which is the ratio between the actual built-up area within the city spatial boundary and the area defined by its spatial boundary. Latin American cities are rather compact, with a relatively regular texture and regular perimeter. The variations of these parameters over time impact protected areas, livelihoods and quality of life. This is a preliminary analysis for use in the generation of scenarios of future city growth. It also uses GHS-POP to measure the “Sprawl index”, a measure of the density within the urban extent.

Fan et al. [63] address the interrelationship between urbanisation and sustainability for seven cities in Siberia. Sustainability is broken up into three components—economic, social and environmental—and urbanisation measures the urban spatial dynamics using GHS-BUILT. The authors find that economic development appeared to be an important driver of urbanisation (built-up spatial growth), as well as social development, and of environmental degradation in Asian Russia.

Bhanjee and Zhang [64] use GHSL-POP and GHS-BUILT to understand spatial settlement growth for the metropolis of Dar es Salaam (Tanzania). The city has not only swelled dramatically during the period from 1990 to 2014, but has also followed a sprawling path of urban expansion, which is characterised by significantly lower population density than the old urban areas and includes informal settlement as the dominant form of residential construction in the urban fringe area.

Balk et al. [65] compare the results from built-up spatial and volumetric estimation from GHS-BUILT and Quick-SCAT satellite observation for the Greater Saigon region. The analysis shows that volumetric change is more concentrated in the central district of Saigon, and it relates to the provision of amenities, such as parking lots or facilities that improve the wellbeing of its inhabitants, while the horizontal growth is more related to migration influxes in the city.

Nautiyal et al. [66] assess built-up growth in Uttarakhand, the Himalayas state of India. The three important findings of the study include the built-up growth in foothills, while the mountain settlements stagnate, the relevance of GHS settlement information layers for India (for which data are relatively scarce), and that of the faster built-up growth after the Uttarakhand state was established in 2000.

Randolph and Deuskar [67] address population growth in urban settlements of different sizes and compare trends across the globe using income groupings of countries. The authors use GHS-SMOD and GHS-POP over time to show that urban growth in the Global South occurs largely in small cities and towns with fewer resources for urban planning. Comparatively, urban growth in the Global North occurs more in larger cities. The paper also highlights that megacities account for a fraction of the urban growth, while receiving most of the attention, and that small size cities and towns should receive more attention from planners and economists.

Built-up spatial growth has a direct and indirect impact on the natural environment. The direct impact is an encroachment on other land covers, typically forest and agricultural land, as listed in the reviewed literature (Table 3). The indirect effect relates to the land use changes, due to increased societal demands for resources. That increased demand is often due to a growing population and more often to both a growing and more affluent population. Current sustainability challenges include the increasing demand for food and agricultural areas (often at the expense of forests), and the increasing extraction of resources from managed ecosystems through intensification. Intensification is often associated with an increase of chemical input in the form of fertilisers and pesticides that are not completely absorbed by plants in managed ecosystems, and become waste that impact waterways and coastal seas. Societal impact is also associated with the discharge of waste within settlements, including hazardous chemical waste—hazardous elements and emissions from fossil fuel use that affect societies within settlements as pollution, and beyond settlements by changing the atmosphere composition, and thus, modifying its climate. Cities and settlements remain the largest emitters as most resources are used within settlements [5], and understanding city and settlement functions are the key to addressing sustainability issues.

The most pressing challenge regarding global environmental change—at the core of The Paris Agreement—is the accumulation of greenhouse gases in the atmosphere that induce climate warming. Greenhouse gas emissions originate in cities and accumulate with emissions originating from natural or managed ecosystems. In fact, ecosystem compression reduces the ability to store CO₂ from the atmosphere. The extensive deforestation in the tropics [103] and the extensive fires at all latitudes are eroding ecosystems and depriving

human societies of their services [104]. The review shows examples of carbon emissions at the local scale, aggregated at the global scale, as well as deforestation at the local scale, and a number of studies also address the loss of agricultural land. Carbon emissions, the input of nitrogen and phosphorus are three thematic areas addressed by planetary boundaries [105].

Liu et al. [68] combine GHS-BUILT with other analogous satellite-derived global built-up datasets available over time to generate built-up change statistics. The authors claim that these are more accurate than using single global built-up layers. The authors provide evidence that most of the built-up spatial growth occurs at the expense of agricultural land. That varies within regions of the world. The authors also analyse built-up spatial growth in a regional context with emphasis on the developing and fast growing economies compared to the high income economies. The findings show that the built-up growth rate is higher than the population growth rate in high income countries, which confirms what was reported by Melchiorri et al. [10]; and Schiavina et al. [97].

Two papers analyse the encroachment of built-up on agricultural land in two selected provinces in China. Wang et al. [69] use a land use model to anticipate land consumption in Jiangsu province to accommodate the increasing urban population (urbanisation understood as built-up spatial growth). This work uses land use models to evaluate different scenarios that include cropland protection policies. The study uses the GHS-POP densities in combination with cropland and crop yield, as well as the demands for new built-up areas generated by an increasing population, to estimate future crop production scenarios based on different urban change trajectories. Luo et al. [70] provide an insight into the rapid expansion of the built-up area in the Yangtze River delta and the potential reduction of agricultural land. The authors also provide a correlation between the increase of built-up and GDP per capita, indicating a larger built-up for higher Gross Domestic Product (GDP). The two papers compare the increase in built-up aggregated at the district level against population increase for the same district available from national sources.

From a conservation and ecological viewpoint, built-up encroachment on natural land decreases the bio-capacity of natural ecosystems and negatively alters the ability to generate biomass and maintain biodiversity and ecosystem integrity. Kennedy et al. [71] use 13 societal variables—referred to as anthropogenic stressors—to quantify the degree of land modification across all ecoregions and biomes of the world. The GHS-BUILT is used in combination with other variables as one of the anthropogenic stressors. The motivation of the authors is to quantify the status of natural and semi natural land to conserve and protect it from the pressure of future land use changes. The authors find that fewer unmodified lands remain than previously reported and that most of the world is in a state of intermediate modification, with 52% of ecoregions classified as moderately modified.

Hojas-Gascon et al. [72] analyse the built-up growth and population growth in Dar es Salaam city and relate it to deforestation around the city. The authors claim that the city dwellers rely almost entirely on fuelwood for domestic use and that fuelwood is collected in the woodlands surrounding the cities. The study finds that the remaining accessible timber supplies lie at distances of over 60 km from the city. The authors anticipate that the future urban population growth of Dar Es Salaam will deplete the woodlands even further. This is a case study for unsustainable forest resource use that could be reversed if the city dwellers provided alternative energy sources to fuelwood.

Fuente et al. [73] assess the amount of built-up within and around nature protected areas worldwide. They find that the built-up share of surface within protected areas is only 0.12%, but that in the surrounding areas, it is over 2.7%, which is higher than the global average. The work aims to raise attention to the rising pressure of human presence and activities on biodiversity and ecosystems.

3.3. Settlement Societal Impact

The size and perimeter [106] of cities and settlements, as well as the spatial arrangement of built-up versus green areas, can impact local climate, the consumption patterns and emissions of its inhabitants (Table 4). The increase in buildings and built infrastructure at the expense of vegetated land changes the absorption and limits evapotranspiration, and thus, the cooling effect from vegetation, whereas the size and volume of buildings can generate their own climate.

The impact of cities on the local climate is addressed by a group of research institutions that collaborate and have established the World Urban Database and Access Portal Tools (WUDAPT) [74]. WUDAPT focuses on classifying built-up areas based on the spatial arrangement of buildings, as well as their spatial and vertical size for climate modelling. The GHS-BUILT spatial grids are used as a generalised measure of spatial settlement patterns available for all cities of the world, which complements the fine scale spatial settlement patterns generated from local and more precise surveys. The “local climate zones” at the city level are typically used as input to climate models. Demuzere et al. [75] provide a detailed mapping of European cities into urban climate zones based on the WUDAPT framework.

Watts et al. [76] use the spatial delineation of 486 urban centres (UC) larger than one million people in 2019, derived from GHSL-SMOD, and vegetation indices derived from MODIS to quantify urban green spaces. The authors argue that the urban green space indicator is an important measure to reduce population exposure to heat. The authors found that 9% of such urban centres had a very high or exceptionally high degree of greenness, while more than 156 million people were living in urban centres with concerning low levels of urban green space.

Cities are significant emitters of pollutants, and air pollution is a major issue for health, as well as for contributing to greenhouse gases at the national and global level. The IPCC calls for regular measures of emissions. Moran et al. [77] estimate the carbon footprint for over 13,000 cities providing a first rough assessment for carbon footprints. The work reports that the 100 highest emitting urban areas (defined as contiguous population clusters) account for 18% of the global carbon footprint.

Chowdhury et al. [78] model NO₂ emission globally to assess the incidence of asthma in children and adolescent population. Authors rely on two global datasets: Community Emission Data Centre and the Global Fire Assimilation system, that they processed to obtain emission from societal sectors. They use two GHS-SMOD classes, rural ‘low density’ and ‘very low density’, to define the background areas to estimate emission at a continental level. The authors also used the GHS-POP at 1 km and combined the Global Burden of Disease database to obtain a share of children and adolescents to estimate the exposed population. The exposure datasets were then aggregated at 5 × 5 km grid cells. The analysis focuses on assessing the relevant shares of emission per sectors, including transport, biomass burning, domestic and shipping and in different continents. The research posits that transport is not an important emission sector in high income countries, while countries like Pakistan, India, China have a large share of domestic emissions.

Anenberg et al. [79] estimate fine particulate matter (PM_{2.5}) mortality in the 250 most populous cities worldwide. The study used PM_{2.5} concentrations, population, disease rates and concentration-response relationships, and showed that city-level PM_{2.5}-attributable mortality rates ranged from 13 to 125 deaths per 100,000 people. The results provide only a cross-sectional snapshot of cities worldwide: They point to opportunities for cities to realise climate, air quality, and health co-benefits through low-carbon development. Guttikunda et al. [80] combine analysis from emitting sources with that of the built-up over time to estimate the pollution of twenty Indian cities. Satellite observations coupled with global model simulations provide a useful baseline to monitor progress and validation of data towards emission targets.

Qiang et al. [81] estimate emission from vehicles in Chinese cities based on GHS-BUILT. The focus of the research is to estimate PM_{2.5} emission from vehicles and compare

to total emissions. The GHS-BUILT is used as a spatial reference to emission in the model that includes spatial autocorrelation techniques. The authors claim that vehicle emission accounts for only a fraction of the emissions of Chinese cities.

Societal access and use of energy resources is a typical trait of affluence. Large areas of low income countries still have no access to a continuous supply of electricity with all the services that are connected to that supply. The supply of green energy is also one of the cornerstones towards a carbon-free society, one of the main goals of the Green Deal for Europe. Three papers address energy access, need and potential for the supply of green energy.

Ehrlich et al. [82] combine GHS-POP, GHS-BUILT and satellite nightlight imagery to identify the relative abundance or scarcity of the three variables for data averaged over 2015. It is a visual analysis based on a colour composite map of the world, which uses the colour green to locate population, blue to locate night light and red to locate built-up. The global composite shows a clear distinction between affluence and scarcity of the three variables across the globe. It also identifies conflict areas characterised by electrical blackouts. This is a preliminary global qualitative comparison, intended to provide complementary information to more traditional methods for inequality mapping.

Two studies, from Tröndle et al. [83] and from Bódis et al. [84] use the European Settlement Map (ESM) [107]—the continental fine scale built-up spatial grid available for 39 European countries—to estimate the area of rooftops that can be used to install photovoltaic panels. Tröndle et al. [83] show that most of Europe could be self-sufficient in producing electricity. Only a small set of the larger cities, where consumption is higher, are among the few areas that would require additional electricity inputs.

Built-up or population density or a combination of the two variables can be used as a baseline spatial information infrastructure and can be combined with socio-economic variables. The GHS-POP is a baseline spatial grid used to develop socio-economic scenarios. Kummur et al. [85] generate a fine scale gridded Gross Domestic Product (GDP) and Human Development Index (HDI), a gap-filled multiannual dataset for the 1990–2015 timeframe. The downscaling occurred at two spatial resolutions, first at 5 degrees using the HYDE population database and then at finer 30 arc-second based on GHS-POP. The finer scale disaggregation provides the resolution that allows for more local within-country comparisons.

Wang et al. [86] estimate GDP based on VIIRS night-time imagery at $1 \times 1 \text{ km}^2$ resolution using GHS-SMOD urban clusters as spatial aggregation units. The authors estimate urban GDP based on VIIRS data and rural GDP based on GHS-POP data. The results are validated based on regional GDP estimates available from the Organisation for Economic Co-operation and Development (OECD) Regional Statistics and Indicators, the Gini coefficient data from The World Bank databank, and the 20:20 Ratios from United Nations Development Programme (UNDP) and The World Bank datasets. The method aims to generate accurate subnational GDP data products used in mapping and monitoring human development uniformly across the globe.

Weiss et al. [87] and Nelson et al. [88] both generate travel time to cities based on such settlements defined in GHS-SMOD. The indicator measures the travel time from grid cell to the closest settlement. Weiss et al. [87] measure the travel time to HDC only. Nelson et al. [88] include cities, as well as eight other settlement classes ranging from five thousand to five million people. This finer scale analysis provides insights into the types of services provided to populations—such as access to a larger city will provide more services than that of a smaller city.

Cattaneo et al. [89] build on Nelson et al. early analysis and use GHS-POP and GHS-SMOD urban centres and towns to generate urban-rural catchment areas. The authors' grouped urban centres based on classes of settlement size and measure 1, 2 and 3 h travel time from urban centres. Towns with a population of 20,000 to 50,000 thousand are also included. Authors also relate rural pixel to a hierarchy of urban centres where proximity to a large centre dominates over a smaller centre. All rural pixels are allocated to one of the

three-travel time classes and associated with one urban centre. That is used to generating urban-rural catchments areas defined by travel time. Rural pixels outside the 3 h travel time are considered not gravitating to any urban centre. Authors find that less than 1% of the world population lives more than 3 h away from an urban centre and that a large share of people lives in peri-urban areas not only of large centres, but also smaller urban centres. The research also provides insights on diverse patterns based on country income. For example, the research shows that in high income countries, 8% of the rural population live in high density rural areas, while in middle income countries, the rate is 26%, and in low income countries, it is 55%.

Verbavatz and Barthelemy [90] use GHS-POP to measure access to mass transport within Functional Urban Areas (FUA). The authors define the Population Near Transit Index—a measure of people access to public transport access points—and compute distances from public transport for 85 cities in OECD countries. The 250-m GHS-POP is used to measure the population within a given distance from access points. The analysis provides comparative insights among cities and calls for testing the indicator for cities on other continents.

3.4. Hazard Impact

Operational crisis management tools and disaster risk assessment use GHS-BUILT and GHS-POP spatial grids to assess the exposure of the variables in the risk equation (Table 5). Risk ensues from hazardous natural or manufactured processes, whose destructive energy may affect the built-infrastructure and cause injuries and casualties (Yellow arrows in Figure 1). The issue is central to “understanding risk”, the first priority of the Sendai framework for Disaster Risk Reduction; it is also central to understanding adaptation and mitigation addressed by The Paris Agreement.

The international crisis management community was the first to require global datasets on population density and built-up. In fact, Bono and Chatenoux [91] used an earlier vision of the GHS-BUILT spatial grid, referred to as GHS-REFERENCE, to generate a global exposure layer used to assess risk for the Global Assessment Report 2015 [108]. Ehrlich et al. [92] expanded that early work to estimate the current and past exposure for the five fast onset hazards that trigger disaster events to which the international crisis management community responds. That work also provided built-up and population estimates aggregated at the country level to generate indicators used for future humanitarian aid. The multi-temporal analysis of that work highlighted the importance of the increase of built-up and population in hazard hotspots that lead to the accumulation of disaster risk.

Freire et al. [93] used GHS-POP to estimate the amount of population potentially exposed to volcanic eruptions for all Holocene volcanoes of the world. The analysis focused on estimating population totals and change over time as a function of distance from volcanoes. The analysis showed that a higher concentration of population is to be found between 10–20 km from volcanoes. Moreover, in Southeast Asia, the highest population growth rates over 40 years occurred within 10 km from volcanoes, while in Central America in zones beyond 50 km.

A number of authors generate risk assessments based on GHS information products. Alfieri et al. [94] analysed different scenarios of flooding risk based on climate warming estimates. The GHS-POP is used as the exposure layer to estimate the impact on societies of future flooding. The work identifies the regions of the world that are likely to be affected by river floods in the future, including China and Europe. Ceccherini et al. [95] investigated drought magnitude in Africa using the daily Heat Wave Magnitude index. They found that heatwaves have increased during 2006–2015, and using the GHSL-POP, found that heatwaves occur in highly populated areas.

3.5. Development and International Framework Indicators

A number of reviewed papers address policies issues by generating spatial indicators that aggregate built-up and/or population density into spatial units relevant to policies.

The section identifies indicators for the 2030 Agenda for Sustainable Development that use national administrative spatial aggregation units, and for SDG 11 uses the city outlines.

Two references address SDG 11 reporting. Melchiorri et al. [96] provide discussion and evidence on the use of the essential variables to generate SDG indicator 11.3.1 and the three characteristics: First, the definition of a city, which is provided from the GHS-SMOD; second, the information about the change in built-up area over time provided by GHS-BUILT, and third, changes in population provided by GHS-POP. The authors compute land use efficiency—indicator SDG 11.3.1—for all of the thirteen thousand urban centres with populations of fifty thousand or larger, in 2015. This work leverages the GHSL principles of global geographical coverage, multi-temporal (diachronic) information, demographic and spatial (built-up areas) information, open and free data. The work also identifies that the built-up area per capita change is very diverse across urban areas that have similar land use efficiency values calculated with the SDG 11.3.1 methodology.

Schiavina et al. [97] build on the above earlier work and provide assessments of SDG 11.3.1 by using a spatial unit of aggregation, including the over ten thousand Urban Centres, and other selected settlement typologies arising from the Degree of urbanisation for major regions of the world. While SDG 11.3.1 is requested to be reported at the city level, the multi-scale analysis provides a fresh outlook on the land use trajectories of countries and regions. Schiavina et al. also suggest spatially explicit metric to assist in interpreting the land use efficiency value according to the UNDESA methodology.

Siragusa et al. [98] extend the SDG framework to geographical units smaller than nation states. The aim is to provide additional insights by generating complementary indicators other than the official ones used in SDG reporting. The proposed indicators are grouped as ‘Harmonised official’ (following the SDG official guidelines), ‘not harmonised official’, ‘Experimental harmonised’, ‘Experimental not harmonised’. The volunteer SDG commitments indicate an interest in developing subnational and local sustainable development indicators that are in line with those at the country level used for International framework reporting.

Policy documents typically report based on administrative spatial units at the national or second order national level. The OECD [99] assesses a number of natural capital indicators, including the one using the GHS-BUILT spatial grid over time to measure the change in built-up for every country and region of the world. The findings provide the staggering figure that the 2014 global built-up figures are 30% higher than those in 1990. This impacts a number of natural capital indicators, including biodiversity loss, agricultural land loss, soil sealing and the consequences. Most importantly, the report finds that in high income countries, the built-up area increases faster than the population.

The 2016–2017 economic survey of India [100] includes urbanisation statistics also generated using the GHS-BUILT spatial grid. In the section “How Urban is India” the report highlights the inconsistencies arising in urbanisation figures, due to the inevitable differences in definition and reporting. The work does stress that GHS-BUILT generated figures also based on the urban centres are higher than those reported in official statistics. The work calls for the use of standardised datasets similar to those that GHS-BUILT provides, which can be used for more objective reporting.

The Future of Cities report [101] provides an overview of key challenges and issues for cities, focusing on European cities. The report provides context to the degree of urbanisation and its conceptual development that is used to generate standardised urbanisation statistics in Europe with key summaries that use GHS-BUILT, GHS-POP and GHS-SMOD. The work also aims to be the first of a series of reports available as a ‘living’ platform, which will host future updates, including additional analyses, discussions, case studies, comments and interactive maps that go beyond the scope of the current version of the report.

The Global Commission on Adaptation [102] provides insight into the issues and challenges involved in adaption to a changing climate. Some of the challenges are illustrated by identifying the urban centres and urban clusters in the coastal areas below 10 m in elevation that may be affected by a possible sea level rise with all the associated consequences.

4. Discussion

This review shows that: (1) a GHS dataset or a combination of GHS products, often in combination with other datasets, are used to address 13 thematic areas related to human presence (Table 1), spatial settlement growth (Tables 2 and 3), societal impact (Table 4), and hazard impact (Table 5). (2) The 13 thematic areas are linked to a simplified Earth system diagram to show the relevance of this initial body of research to address societal impacts on the environment at local, regional and global scale. The study also reviews documents that focus on spatially aggregating societal variables at the national jurisdictional scale [109] used for reporting on Framework agreements or to address policy demands (Table 6).

The review indicates that sizing settlements focuses on identifying perimeter, area and settlement components, such as green areas. The sizing is of relevance to partition the built-environment into urban and rural settlements: a key policy demand. The review shows that for large countries (e.g., India), the availability of consistent built-up data provided by GHSL is useful for reconciling differences in measurements taken with different protocols and to test new definitions. Understanding the built-environment within settlements is important for urban management and key to the NUA. Green areas, as measured from satellite imagery, are spatially complementary to the built-up. Green areas are also related to city climate and city air quality, and thus, relates to the urban quality of life. Corbane et al. [58] show that green spaces in cities can be related to open spaces, and thus, can be used as complementary to measure open spaces in estimating SDG 11.7.1. Factoring building height and the vertical property of the built-environment has not yet been addressed by researchers at the global level. Building height is expected to become a new component of the essential societal variables as it is used to characterise the built-up and of use to locate and size slums or informal settlements. That characterisation is of utility to compute SDG 11.1.1: “Proportion of urban population living in slums, informal settlements or inadequate housing”.

Estimating the physical size of settlements is also closely associated with assessing the spatial settlement growth over time (Table 2), a key issue in urban and regional planning, key to the NUA and addressed within SDGs: Directly in SDG 11 and indirectly in a number of other SDGs. For example, the ratio of land consumption rate over population growth rate (SDG 11.3.1) provides insights into land use efficiency indicators. The impact of built-up growth as factor eroding other land cover is of relevance to SDG 2 related to food security, as most of the expansion occurs on agricultural land, which is a major concern in densely populated countries like China as reviewed herein (Table 3). The built-up spatial growth in time is also associated with the degradation of natural or managed land and considered as one component of SDG 15.3.1 related to land degradation.

Table 4 lists the research areas addressing the generation of societal variables or of analysing societal processes (that relate to the flow of energy and materials) and their impact within and beyond settlements. This review shows that built-up, population and settlement typologies in combination with other thematic information are used as proximate variables to address the demand for resources (e.g., electricity, timber) and associated changes in land use [110], as well as generation of waste (e.g., emissions, heat). The reviewed papers discuss the use of building stock rooftops to generate renewable energy, and thus, independence from traditional energy sources. The demand and supply of electricity also address in reporting for SDG 7 and specifically that of SDG 7.1.1, which calls for assessing the proportion of the population with access to electricity. Most importantly, the review shows that spatially explicit societal variables are used to build socio-economic pathways indicating trajectories towards sustainability. Spatially explicit gridded access to cities and settlement indicators are potential to be used in the future to assess access to services, health facilities and education, as well as to estimate the cost of providing transport infrastructure in remote mountainous areas.

Natural hazards impact settlements by damaging building stock and the population within, and GHS Layers are used to map potential or actual exposure to hazard risk (Table 5). Disaster outcomes are to be reported in a number of SDGs, including SDG 1, 2, 9

and 11. The reviewed paper shows that population and built-up are used to measure the increase of exposure to fast onset natural hazards, as well as for heat waves. Future work will combine the characteristics of the building stock with hazard probability to define the quality of the building stock and its vulnerability and the resilience of the community to hazard impact.

The reviewed papers address the use of essential societal variables to generate SDG indicators (Table 6). The work aims to provide examples to technologists within national institutions on how best to use the EO derived datasets for building indicators within their own countries and contributing to international reporting. The reviewed papers also prompt scientists and decision makers to adopt Earth Observation solutions within the SDG reporting system using the examples provided. These assessments inform policymakers and support the monitoring and implementation of policies.

The reviewed policy papers and reports generate aggregate assessments to inform policymakers beyond what is requested by international frameworks (Table 6). The indicators are often similar to those of international frameworks, but defined differently. Relevant indicators include that estimating green areas in cities within OECD countries. Others provide insights on the risk of inundation in low coastal areas, due to climate warming-induced sea level rise, an issue at the core of The Paris Agreement. The reviewed papers also provide insights for possible future indicators for use in the European Green Deal. For example, the European Green Deal requires monitoring progress towards the de-carbonisation of the economy, and both the gridded GDP and gridded emission datasets reviewed herein may be used for the task.

The reviewed papers address global processes, as well as a number of fine scale processes. These regional or local studies extract societal data corresponding to the area covering the country or the city of interest for comparison and validation purposes. For many areas of the world, global spatial grids generated with top-down approaches and with granularity ranging between 250×250 m and 1000×1000 m cell size may be an acceptable compromise for policymakers (e.g., countries in fast economic and demographic transition) lacking finer scale standardised data generated from finer scale input data. When available, continental, regional and local datasets should be used instead. For example, authors have used the open-source European settlement layers for mapping energy needs and the potential for solar panel installation instead of the equivalent global dataset.

This review also calls for a new generation of essential variables that have improved detail and thematic content, and part of this work is under way. The future release of GHS layers will use finer scale Sentinel satellite imagery as input to possibly improve the accuracy and precision of both built-up [111] and population density spatial grids to map even smaller settlements and dispersed housing across the whole urban-rural continuum. The expected work from the research community will be that of combining the finer scale global datasets with regional and local datasets and making them consistent across scales and suitable for pairing with socio-economic datasets to generate new societal insights. Understanding the trajectories of societal processes is key to understanding sustainability at the city, regional and global level.

5. Conclusions

Addressing the sustainability of planet Earth remains a formidable challenge that starts with measuring and understanding societal patterns and processes and the societal resource demands and use. This review shows an initial body of scientific literature addressing unresolved measurement and assessment issues, while the policy reports indicate the demand for such data for informing policy and for reporting in international frameworks.

This review calls for working within an integrated Earth system science framework that combines physical and societal processes. Human societies have been studied largely using linear projection from past to present, aiming to provide insights into the future. Humanity functions as a complex set of subsystems that will require non-linear types of

modelling to understand its growing metabolism and potential tipping points. Thematically improved datasets on energy and resources demands and use analyses the processes occurring at different scales, as local processes impact global processes and vice versa. For example, the cumulative effect of local land cover change impacts the Earth's climate and its biogeochemical cycles. Similarly, meteorological processes governed by global physical processes have an impact at the local scale. The reviewed papers have started to address the competing use of resources (i.e., agricultural land versus built-up land) through the many nexuses that govern societal needs that should be explored quantitatively [112].

Finally, international framework reporting utilises variables combined into indicators to monitor progress towards the 2030 Development Agenda. Some variables—identified in this review—may be considered for reporting on SDGs, as direct measures or as a component that contributes to measuring the targets. For example, GHS-BUILT, POP and SMOD together satisfy all requirements to measure SDG 11.3.1 directly. In SDG 11, the two variables reviewed to fit the needs of measuring the increasing “human presence” change in built-up areas and change in population within city boundaries. Had the population density and built-up not been available at the fine scale, the assessment would probably be based on statistical estimates that do not allow for the same flexibility as the global gridded variables. Global gridded datasets may be best for international comparison, and societal processes should be analysed with variables suited to describe the processes at the operational scale at which they occur [113]. However, when data are not available at a national or subnational scale, countries may rely on estimates extracted from global datasets. The review of papers shows that GHSL data can be used directly or indirectly to address some SDG indicators.

Ultimately, the 2030 Agenda for Sustainable Development and contributing frameworks cover one or more aspects of sustainable development and of Earth system integrity, objectives that are mirrored by the European Green Deal and the EU Strategy on Adaptation to Climate Change [114]. The European Green Deal emphasises the importance of reducing energy use through an ambitious action plan that addresses improving energy efficiency in buildings and the transport sector, producing green energy for households, limiting forest degradation and promoting environmentally friendly agriculture from the farm to fork. At the same time, recognising that the climate will change, promotes adaptation. The reviewed articles all directly or indirectly addressed in part the priorities of the European Green Deal and EU Strategy on Adaptation to Climate Change [114] that will be addressed in a separate paper.

This research trend of continuous refinement of current societal variables and the generation of complementing new variables that can capture the more subtle aspects of human activities must be continued. That research will be most successful if conducted within international cooperation alliances, such as the Group on Earth Observations, that share open-source data and knowledge.

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