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a0010

# Remote Sensing for Ecosystem Sustainability

**J Qi**, Michigan State University, East Lansing, MI, United States; Zhejiang University, Zhejiang, Republic of China
**J Chen**, Michigan State University, East Lansing, MI, United States
**R Lafortezza**, University of Bari “A. Moro”, Bari, Italy; Michigan State University, East Lansing, MI, United States
**Z Li**, Michigan State University, East Lansing, MI, United States

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## s0010 Introduction

### s0015 Ecosystem—Definition

p0010 From an ecological perspective, an ecosystem is a dynamic system formed by the interaction of plant, animal, and a community of organisms with their nonliving environment within a geographic unit or region. From a broad perspective, an ecosystem is any system formed by interconnecting and interacting biological, physical, and social components within a geographic unit or region, and involving humans.

p0015 Ecosystem services refer to the benefits human can derive from ecosystems, which are often categorized by provisional services such as water and food, regulating services such as floods and drought, supporting services such as soil and nutrient cycling, and socio-cultural services such as recreation, religion, and other nonmaterial benefits. These services are the fundamental benefits that humans rely on to survive, evolve, progress, sustain, and flourish. Changes in any of these ecosystem services, resulting from either climate change or unsustainable human activities such as deforestation and overgrazing, may negatively affect human well-being and even human survivorship (e.g., Dymond, 2005). Au1

p0020 The state of an ecosystem can be characterized by a set of ecosystem indicators such as environmental, biophysical, ecological, and social attributes. These attributes such as climate, vegetation type, water, nutrient, soil, and human population are fundamental characteristics of an ecosystem and they are critical in providing ecosystem services that human rely on for development and sustainability.

p0025 These ecosystem attributes are spatially heterogenic and may vary with time. While the spatial heterogeneity is largely perceived to be related to physical environmental conditions of geographic locations, variations with time is largely related to human activities, sometime termed human disturbances. Many of these ecosystem attributes, if not all, can be measured, assessed, and monitored by remote sensing and their states and trajectories can be quantified, analyzed, and even projected for sustainable planning, development, and intervention, if needed.

http://dx.doi.org/10.1016/B978-0-12-409548-9.10428-2

## s0020 Ecosystem Sustainability and Sustainability Science

### s0025 *Sustainability and sustainable development*

p0030 *Sustainability* can be defined as a socio-ecological process characterized by the pursuit of a common ideal (e.g., Brown et al., 1987; Gatto, 1995; Marshall and Toffel, 2005; Santillo, 2007; Wandemberg, 2015). However, *ecosystem sustainability* reflects an ecosystem's capacity to endure and maintain its functions and services indefinitely. In other words, ecosystem sustainability is a system's ability to maintain its functions and services after disturbances by either human or nature and very often by both. Temporary variation in functions and services is deemed to be a part of the system but the variabilities should be within a range that does not permanently transition the system into a different state that need human interventions to restore it.

p0035 Sustainable development is a development process with a goal of improving the quality of life while maintaining the ability of ecosystems to continue and provide ecosystem services that human depends on. Earlier sustainable development (e.g., Brundtland Commission, 1987; Gladwin et al., 1995; Pearce, 1993) definition seemed to be more human-centric, focusing on "Development Au2 that meets the needs of the present generation, without compromising the ability of future generations to meet their own needs." This guiding principle focuses on the ability of future generations but has neglected the natural assets of an ecosystem or Earth system. Griggs et al. (2013) stated that sustainable development is the "development that meets the needs of the present while Au3 safeguarding the Earth's life-support system on which the welfare of current and future generations depends." This view of sustainable development recognizes the fact that natural resources are limited and that human needs should be placed in the context of finite ecosystem services provided by the nature or the Earth.

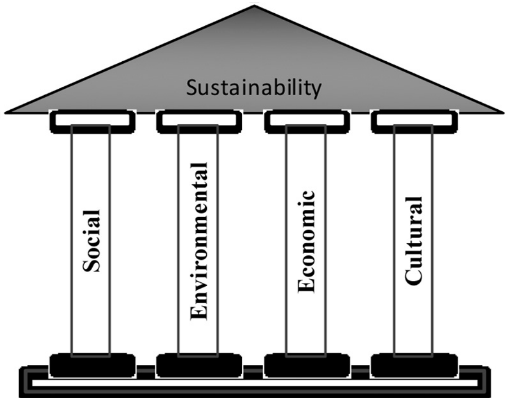
### s0030 *Four pillars of sustainability science*

p0040 Before discussing ecosystem sustainability, it is necessary to review sustainability science, because maintaining a sustainable ecosystem requires a full understanding of what drives an ecosystem to change, the core of sustainability science, and ways to prevent the changes from reaching tipping points. Sustainability science focuses on the essential elements of a system that are in balance to maintain a stable state. Four essential elements have been termed four pillars of sustainability science (**Fig. 1**): environmental, economic, social, and cultural, according to traditional social science literature (e.g., Basiago, 1998; Haimes, 1992; Jon, 2001; Roberts et al., 2005; Roseland, 2000). Au5 Au4

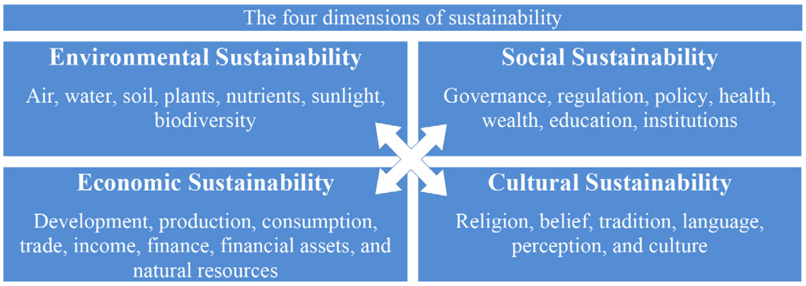
p0045 It should be noted that all four pillars are constantly changing and evolving but they must maintain a dynamic balance in order to support a stable and sustainable system. All four pillars are also interconnected and affect one another, yet each remains a unique dimension that can tip the balance when subjected to disturbances (**Fig. 2**). A key issue of sustainable development is how to maintain a balance among all of these dimensions while improving the quality of life.

#### s0035 The environmental dimension of sustainability

p0050 The environmental dimension of sustainability is the ability of the ecosystem to support a defined level of environmental quality and natural resource extraction rates indefinitely that meet the needs of human society within which these resources exist. This dimension has recently been discussed extensively due to rapid human exploitation of limited natural resources and increasing climate variability that have caused concerns and imposed threats to human systems. It highlights the functions and services provided by an ecosystem that benefit human society, including water, air, food, soil, plants, and minerals etc. to support sustainable development. While the environment itself can be characterized by a set of quantitative and qualitative ecosystem variables, the perceived values are related to human desires for quality of life, as stated in 9 of 17 United Nations' sustainable development goals or SDGs (https://sustainabledevelopment.un.org/sdgs). It is recognized that there is a disparity in quality of life among societies and perceived ecosystem values may vary with time, geography, culture, and society. Nevertheless, the environmental dimension of ecosystem sustainability has been the primary driver to push for sustainability research as humans realize that resources are limited and their over-exploitation will eventually result in an environment that is no longer suitable or desirable for humans.



f0010 **Fig. 1** Sustainability framework that maintains a balance among the four pillars of sustainability—social, environmental, economic, and cultural dimensions—to ensure a sustainable system.



f0015 **Fig. 2** The four dimensions of sustainability—environmental, economic, social, and cultural dimensions of sustainability—that are interconnected through direct interactions and/or tele-coupling across space and time.

### s0040 The economic dimension of sustainability

p0055 The economic dimension of sustainability is the ability of an economy to support a defined level of economic production indefinitely to meet the needs of a society within which they exist. This dimension has been a human pursuit for improved quality of live, wealth, and standard of living condition. It is also an essential component of sustainable development to ensure a system's (society, community, or nation) financial capability to purchase goods and other natural resources such as food. However, in many countries economic development relies heavily on extraction and often the over-exploitation of natural resources, thus drastically and frequently changing the environment to the point that "environmental" pillar of sustainability is threatened. This raises questions like "What is sustainable development?"

### s0045 The social dimension of sustainability

p0060 The social dimension of sustainability is the ability of a social system, such as a country, family, or organization, to function at a defined level of social well-being and harmony indefinitely. This dimension includes governance structure, regulations, policy, education, wealth, health, and resource management, where the society as a whole follows institutional policies for a perceived standard of living and quality of life.

### s0050 The cultural dimension of sustainability

p0065 The cultural dimension of sustainability is the ability of a society to experience cultural harmony by sharing and respecting differences in religion, beliefs, culture, language, age, gender, and ethnicity. Without these consensuses and cultural harmony, a system is in an unstable dynamic and sustainable state that eventually leads to a tipping point of changing from one state to another.

p0070 It should be recognized that with emerging research in sustainability science and a new understanding of the requirements for a sustainable ecosystem state, however, other pillars such as climate change were added to reflect the global environment beyond a single ecosystem or community and the nature of increasing global connectivity through tele-coupling processes. The literature suggests that the sustainability of an ecosystem cannot be fully assessed as a stand-alone system; rather, it should be considered with tele-coupled systems that have impacts through energy, information, and material flows. Therefore, when assessing remote sensing capability for ecosystem sustainability, it is important to include the geospatial dimension of these four pillars and their corresponding attributes that are physically, socially, and culturally connected or tele-coupled.

p0075 All four dimensions of sustainability can be characterized by a set of indicators or biophysical, ecological, social, cultural, and economic variables, some of which are qualitative and abstract while others are quantitative. It is important to recognize that these variables dynamically interact with each other to collectively form a system. Further, variations from the mean in these variables are a norm, but should be within a range that does not exceed the tipping point that results in an imbalance among the four pillars of sustainability.

p0080 Remote sensing can be an effective tool and approach to assess ecosystem sustainability by providing quantitative information about historical patterns and concurrent states of key ecosystem indicators or variables that are critical in maintaining a balance of the four pillars of sustainability science (e.g., Berry et al., 2003; Kates et al., 2001; Lake and Tim, 2012; Naidoo et al., 2008; Rapport, 1995; Renetzeder et al., 2010; Rose et al., 2015; Sample, 1994; Wulder et al., 2004). In conjunction with process-based models such as hydrological or biogeochemical or agent-based models, remotely sensed information can be effectively ingested into these models to infer key social, economic, and cultural information for sustainability assessment. The following sections provide some examples of how remotely sensed data and information are used in supporting quantitative analyses of the four pillars of sustainability, with an emphasis on the environmental sustainability of an ecosystem. Au6

## s0055 Indicators of Ecosystem Sustainability

p0085 The key of ecosystem sustainability is its ability to maintain a balance among the four supporting pillars: environment, economy, society, and culture. While these pillars are broad with qualitative terms, they can be characterized by a set of quantitative measures or indicators to represent their state and trajectory. What remote sensing technologies can provide is the spatio-temporal dynamics of some of these key indicators, such as scale, magnitude, and trajectory of critical biophysical, ecological, and socioeconomic attributes as well as their geographic locations in relation to other systems. While it is challenging to directly observe socioeconomic variables through remote sensing, it is possible to derive some clues of economic and social activities such as urban development, basic infrastructures, mining, and land uses in general that are important in sustainability assessment (e.g., Buyantuyev and Wu, 2010; Gatrell and Jensen, 2008; Gong et al., 2013; Long et al., 2007).

p0090 This article focuses on those ecosystem attributes that can be directly observed or inferred from remotely sensed data. **Table 1** is a summary of critical variables of the four pillars that can be either observed directly or inferred through modeling analysis, with emphasis on the biophysical and ecological attributes of an ecosystem.

### s0060 *Remote sensing challenges of ecosystem sustainability*

p0095 Sustainability assessment requires multidisciplinary expertise and sustainability indicators that are multidimensional encompassing both qualitative and quantitative variables. Some of these variables can be either directly measured by or inferred from remote sensing, while some cannot (**Table 1**). Challenges exist in the capability of remote sensing to provide the information needed for sustainability studies due to the fact that remote sensing is still limited in observational technologies or in theories to retrieve targeted signal information. For example, there are still no sensing technologies capable of directly measuring the biodiversity of organisms or the social cultures of environmental perceptions. Similarly, there is little advance in effective inverse theory to disentangle signals from a target of mixed pixels. Some important social and economic indicators, such as gender and household annual incomes, are impossible to obtain from remote sensing means, although they are critical in sustainability research.

p0100 The inability to remotely sense some important attributes of sustainability indicators presents challenges to the quantitative assessment of sustainability. This requires collective effort among different disciplines to synergistically use remotely sensed information along with socioeconomic and cultural information to assess ecosystem sustainability. For example, the human Au7 sustainable development index, an index often used for sustainability assessment, included growth domestic product, health (as indicated by life expectancy), education (number of years in school), and the environment (by total carbon dioxide emissions).

p0105 However, remote sensing technologies have been widely used to provide required information for environmental sustainability assessment. This article focuses on remote sensing capability for environmental sustainability studies. Other social, economic, and cultural variables can be obtained through surveys, statistics, and the literature.

t0010 **Table 1** List of ecosystem indicators or variables along with remote sensing capabilities to directly measure (D), be inferred through modeling (I), or be unable to obtain with existing technologies and methods

| *Pillars* | *Description* | *Indicator* | *Remote sensing capability* |
|---|---|---|---|
| Social | Governance, regulation, policy, health, wealth, education, and institutions | Wealth | I |
| | | Health | I |
| | | Education | I, U |
| | | Living condition | D, I |
| | | Gender | U |
| | | Population | I |
| | | Consumption | I |
| | | Employment | U |
| | | Food security | D, I |
| | | Energy security | D, I |
| | | Water security | D, I |
| | | Equity | U. |
| | | Others | ? |
| Economic | Development, production, consumption, and household incomes | GDP | U |
| | | Trade | I |
| | | Incomes | U |
| | | Consumption | U |
| | | Basic infrastructure | D, I |
| Environmental | Quality and quantity of natural resources, and biodiversity | Sunlight | D |
| | | Water | D |
| | | Soil | D, I |
| | | Plant | D, I |
| | | Biodiversity | D, I |
| | | Nutrients | I, U |
| Cultural | Perception, culture, language, and tradition | Traditions | I or U |
| | | Religion | U |
| | | Language | U |
| | | Beliefs | U |

## s0065 Remote Sensing Key Ecosystem Sustainability Indicators

p0110 Although the essential elements of ecosystem sustainability are the four supporting pillars—environment, economy, society, and culture—this article focuses on the discussions primarily related to the environmental dimension of sustainability, where remote sensing has the ability to directly or indirectly infer its biophysical and ecological attributes as listed in **Table 1**. For most attributes related to the economic, social, and cultural dimensions, remote sensing approaches to quantify them are still limited but whenever possible, discussions will be included in this article.

### s0070 Environmental Sustainability Indicators

p0115 Environmental sustainability indicators are primarily related to the quality and quantity of the environment and natural resources that support functions and services indefinitely. These indicators may include the quality and quantity of primary natural resources such as air, sunlight, water, soil, plants, and nutrients among many others, some of which can be measured by or inferred from remote sensing. Discussions in the other articles covered some of these attributes and therefore this article focuses on sunlight, water, soil, plants, nutrients, biodiversity, and landscapes that are found to be critical for all these biophysical attributes.

#### s0075 *Remote sensing sunlight use efficiency*

p0120 Sunlight is probably the most essential condition for life and other organic forms on Earth. It is a source of energy that is not only inexhaustible, but also totally nonpolluting (Omer, 2008). Different ecosystems utilize sunlight differently and some are more efficient in converting sunlight to other forms of energy that can be used directly for human benefit, such as photosynthesis, and solar renewable energy for electricity or heating and cooling. Au8

p0125 Remote sensing has been used to estimate the amount of solar radiation reaching the canopy (Frouin and Pinker, 1995; Propastin et al., 2012; Seaquist and Olsson, 1999) and a portion of the solar radiation can be effectively converted into biomass through photosynthesis. Imagery from satellite sensors have been used to effectively measure total photosynthetic active radiation (PAR), intercepted PAR by the canopy, and absorbed PAR (APAR) accounting for soil effect and fraction PAR (FPAR) converted by living plants (e.g., Asrar et al., 1984; Huete et al., 2002; Xiao et al., 2004). Previous and ongoing research has confirmed the capacity of remote sensing methods to estimate plant photosynthesis-related phenomena, particularly at a global scale (e.g., Goward and Huemmrich, 1992; Goward et al., 1994; Prince and Goward, 1995; Ruimy et al., 1994, 1999; Sellers, 1987; Tucker and Sellers, 1986) that relies on the established spectral vegetation indices (VIs) such as the normalized difference vegetation index (NDVI). However, relying on spectral VIs to estimate photosynthesis may result in some significant uncertainties for different ecosystems. For example, Roujean and Breon (1995) stated that some uncertainties exist when using NDVI–fAPAR relationship and brought up feasible suggestions, for example, establishing a new vegetation ratio renormalized difference vegetation index, to help lessen dispersions on abovementioned correlations.

p0130 A widely employed Moderate Resolution Imaging Spectroradiometer (MODIS) FPAR/LAI product is one of the most well-known and easily accessible remotely sensed information collections designed for vegetation studies (Myneni et al., 2002); it has been evaluated and verified in many case studies (Fensholt et al., 2004; Hill et al., 2006; Wang et al., 2001, 2004; Yang et al., 2006). This remote sensing product was often used to help determine the proportion of plant cover in different parts around the world. An example is the continuous field of vegetation products produced derived from MODIS imagery (e.g., DeFries et al., 1999, 2000). These remote sensing products have also been used to generate a robust terrestrial drought severity index globally (e.g., Mu et al., 2013; Zhao and Running, 2010).

p0135 The global terrestrial net primary production (NPP) is another important biophysical attribute that is critical in assessing an ecosystem's ability to utilize sunlight energy. A proxy of the NPP is commonly associated with an ecosystem's leaf area index (LAI) that represents the total amount of biomass of an ecosystem, such as agricultural crops and rangeland forage. This indicator has been widely studied and estimated from remote sensing imagery such as MODIS (e.g., Myneni et al., 2002). Some large-scale but at a coarser spatial resolution LAI products have been produced using GIMMS data (e.g., Zhu et al., 2013). Subsequent uses of these products are very broad and an example is to fuse the information with site-level observations to evaluate the performance of climate models such as the Community Land Model by injecting FPAR dynamic changes and spatial patterns into the model based on the solar radiance partition scheme aspect (Wang et al., 2013).

p0140 It should be noted that there are other environmental and biological factors that affect light use efficiency, such as plant types (e.g., C3 vs. C4 plants) as well as the availability of water in plants and ambient temperature that can affect light use efficiency. In general, remote sensing capabilities for such applications are quite effective and accurate products such as those produced by MODIS sensors.

#### s0080 *Remote sensing water resources*

p0145 Water resource is of immeasurable importance to both natural ecosystem dynamics and human eco-society development all over the world. It is one of the key drivers to life and resource cycling on the planet and, thus, to ecosystem sustainability. Due to climate change and increasing human uses, water storage, uses, and spatial and temporal distribution are changing and have significantly impacted the water availability for a variety of ecosystem services including agricultural food production, fisheries, and basic human consumptions (e.g., Vörösmarty et al., 2000, 2010). In addition to water scarcity, excessive water such as flood is a major natural disaster that has affected millions of people worldwide (e.g., Jonkman and Vrijling, 2008; Messner and Meyer, 2006).

p0150 Water quality has also long been a major concern due to increasing pollution from climate change and human activities (e.g., Hall and Ellis, 1985; Lindholm et al., 1989a,b). Thus, a need to monitor water quantity and quality, as well as its effective Au9 management, has become a primary prerequisite of sustainable development. Solutions to these needs rely on efficient information collection, and remote sensing has been a primary source of information for water quantity and quality assessment.

p0155 Remote sensing of water quantity has been studied for quite sometime already (see, e.g., Gitelson et al., 1993, 2008; Sawaya et al., 2003) using the spectral reflectance feature of water bodies. Simple methods, such as the normalized difference water index (NDWI), have been developed to delineate open water features (McFeeters, 1996). However, obtaining the total volume of water through optical remote sensing remains a challenge, as it requires information of, for example, lake depth and river hydrology in order to obtain an accurate estimate of total water volumes. The recent development of the GRACE satellite, jointly implemented by NASA and DLR, has proved to be feasible to obtain total volume using the Earth's gravitational system, which could provide more Au10 water quantity information at large scales (Richey et al., 2015), although accuracy could remain an issue.

p0160 Remotely sensed data combined with Geographic Information System (GIS) techniques have been widely applied in the quality assessment of freshwater resources (e.g., Han and Jordan, 2005; Olmanson et al., 2008; Torbick et al., 2008; Wang and Shi, 2008). Reliable spatial coverage and cost-efficient remote monitoring techniques for inland lakes and coastal waters have been developed and used by numerous researchers to address eutrophication issues (Bukata, 2005; Gege, 1998; Gitelson et al., 2008; Miller et al., 2006; Ruddick et al., 2001; Schofield et al., 1999; Simis et al., 2005, 2007; Stumpf and Tomlinson, 2005).

p0165 Water quality indicators that can be inferred from remotely sensed data include colored dissolved organic matter, chlorophyll concentrations, sediments, and algal concentrations. Landsat, for example, has a long history in water quality detection of the Great Lakes, from the observation of colors in Lake Erie (Strong, 1974), calcium carbonate precipitation in Lake Michigan and Lake Ontario (Strong, 1978), chlorophyll detection in central Lake Michigan and Green Bay (Lathrop and Lillesand, 1986), total suspended solids or Secchi depth in Green Bay (Lathrop et al., 1991), or phycocyanin detection in western Lake Erie (Vincent et al., 2004). While some Landsat studies have looked back at water quality over time (Olmanson et al., 2008), none have created algorithms for the purpose of assessing chlorophyll trends over the lifetime of the Landsat program.

p0170 Although these studies proved that remote sensing is effective in water quality assessment, it should be noted that remote sensing remains a challenge to operationalize water quality retrieval algorithms across large geographic areas. Examples are the methods developed for the Midwest region of the United States. Using Landsat proved to be quite accurate in inland lakes in Minnesota, but much uncertainty exists when applied to deep-water lakes in Michigan (e.g., Novitski et al., 2016).

### s0085 *Remote sensing soil resources*

p0175 Soil is another basic element of all ecosystems and natural communities. Soil health refers to the capacity of soil to maintain equilibrium within a living system in different ecological aspects. Considering the fact that the assessment of soil health is of crucial relevance to agricultural production and sustainability, scientists from different disciplines have been involved in soil quality research for years. Some proposed indicators of soil quality for land management and crop monitoring could be measured using satellite-retrieved information, for example, spatial–temporal changes in organic matter levels, crop characteristics such as yield and plant vigor, and pest distribution and movement (Doran and Zeiss, 2000).

p0180 One of the most severe problems in the sustainable development of soil management is the widespread phenomenon of soil erosion. Consequently, many models for estimating and predicting soil erosion risks have been developed using empirical data and algorithms; remote sensing and GIS were implied to provide promising informative and analytical evidence for improvements in this field. For example, a case study was carried out in Rondonia, Brazilian Amazonia, a region that had experienced high rates of deforestation during the past 20 years and thus suffered a significant soil erosion and soil loss (Lu et al., 2004). The study combined the Revised Universal Soil Loss Equation, topographic factor (LS) generated from a digital elevation model (DEM), cover-management factor (C) retrieved from spectral mixture analysis of Landsat ETM+ images, and the soil erodibility factor (K) from survey data, to generate a soil distribution map and calculate soil erosions. Similar studies were carried to assess soil degradation in pasture and agroforestry lands, as demonstrated by a case study in the Upper Nam Wa Watershed, in Thailand (Bahadur, 2009), where researchers examined the impacts of cultivation shifts on soil erosion.

p0185 In addition to soil erosion, salinization is the most common and has been studied by many researchers. A summarized review for keynote publications of remotely sensed data potentiality related to soil salinity was discussed to draw conclusions on the constraints and advantages of airborne remote sensing capabilities for such applications (e.g., Farifteh et al., 2006). Attempts were also made to use spatial landscape characteristics to depict spatio-temporal changes in soil salinity in irrigated croplands. For example, Abbas et al. (2013) used Indian Remote Sensing Linear Imaging Self Scanning (IRS-1B LISS-II) digital data, supplemented by ground truth data of soil samples and SAR analysis, for monitoring the occurrence of salt-affected lands. They discovered that the improper reuse of low quality groundwater for irrigation would most likely increase the risk of soil salinization in the basin. Such exploration of causes for soil degradation is of great importance to formulate sustainability strategy in precision agriculture.

### s0090 *Remote sensing plants and vegetation*

p0190 The photosynthesis process of plants and biomass, including the above- and below-ground sections, as well as of some organisms, can convert radiant solar energy into the chemicals required by living creatures. While remote sensing of photosynthesis was discussed earlier, here the focus is on crops, grasslands, and forests. In general, the sustainable development of plant management is a key element to secure and maintain crop and foliage production for food security. Since the last century, remote sensing techniques have become prevalent for understanding vegetation phenology. It was affirmed that remote sensing had performed quite well when modeling, defining, and mapping the biophysical, spatial, and temporal patterns in crops, grasslands, and forests (e.g., Idso et al., 1977; Pinter et al., 2003; Prince, 1991; Treitz and Howarth, 1999; Tucker and Sellers, 1986). These studies included Au11 crop yields, grassland primary production, and forest biomass.

p0195 Many of these biophysical variables or vegetation indicators can be remotely sensed, directly or indirectly, using simple VIs. One of the most commonly used indices is the NDVI, which is a significant indicator for evaluating bioproperties using the visible and near-infrared (NIR) bands of the electromagnetic spectrum. Several well-known sensors, namely, NOAA advanced very-high-resolution radiometer and Terra/Aqua MODIS have the required spectral bands that produce even global scale NDVI products for large-scale analyses of vegetation dynamics across the globe. For example, these products were used to explore spatial correlation features and clustering patterns of vegetation productivity in the pastures of Inner Mongolia, China, together with climate information (Wang et al., 2015) to assess ecosystem vegetation dynamics. Another case study was conducted in the Dengei pahad microwatershed, Khurda District, Odisha, involving a 16-year series of IRS satellite data to calculate land cover change using NDVI as a principle index, especially for vegetation land cover type (Rout et al., 2015). These are just examples of the many studies that utilize remote sensing imagery to examine vegetation dynamics at multiple spatio-temporal scales.

p0200 Plant diversity can also be inferred from remotely sensed data by examining the spectral patterns of mixed pixels. For example, John et al. (2008) used the MODIS enhanced vegetation index (EVI) time series to predict plant diversity in arid grasslands.

p0205 Plant disease is a major threat to food production and plant diversity, which requires monitoring mechanisms to take the appropriate measures for ensuring food production, an important sustainable management strategy. Physiological stress to plants typically causes a rise in temperature and change in leaf color, which can be sensed remotely. A recent paper providing an overview of insights in the application of noninvasive optical sensors for plant disease detection, identification, and quantification at different levels (Mahlein et al., 2012) has concluded that: (1) the most promising sensor types are thermography, chlorophyll fluorescence, and hyperspectral sensors, (2) imaging systems are preferable to nonimaging systems, and (3) a multidisciplinary approach is urgently needed.

### s0095 *Remote sensing nutrients*

p0210 The topic of sustainable nutrient management is often intermixed as a subtitle within other research interests. Nutrients are dynamically exchanged within different ecosystems, as in the aforementioned water-, soil-, and plant-related systems. Sustainable nutrient management is also a hotspot for interdisciplinary research.

p0215 Given the complex conditions of a wide range of pasture ages, soil types, management strategies, and climates, only remote sensing techniques could offer a feasible solution to help assess local pasture biogeochemistry and nutrient cycling spatially over the vast study area. For example, a case study was designed to understand the biogeochemical dynamics in cattle pasture receded from forests in two study sites located in the central Amazon Basin (Asner et al., 2004). The study used a Landsat TM collection for pasture age evaluation as well as live photosynthetic vegetation, senescent, nonphotosynthetic vegetation, and bare soil coverage extraction. The results confirmed the potential of remote sensing to be applied for reliable estimations of pasture land use change in three aspects: pasture area, pasture condition, and nutrient cycling.

p0220 In another study, DEM and airborne visible and infrared imaging spectrometer data were introduced to assist in designing a bottom-up illustration map of predicted nutrient availability across the landscape in Kauai, Hawaii (Porder et al., 2005). Approximately 17% of the landscape was identified as nutrient-poor; higher clusters of nutrient availability were evident on valley slopes and floors.

p0225 A recent review of the long-term experiments for sustainable nutrient management in China pointed out that China had turned into a net carbon sink. Satellite remote sensing data combined with other information can be used to confirm or validate carbon budget at national level. For example, a recent review of the long-term experiments for sustainable nutrient management in China Au12 confirmed that China had turned into a net carbon sink (Miao et al., 2010).

p0230 For sustainable crop management, reasonable control of nitrogen (N) plays a key role and significantly affects the final yield. The accurate assessment of castor bean nitrogen and pigment is a demanding requirement for crop development. In a recent study, a remote sensing algorithm was developed for such studies (Reddy and Matcha, 2010), where the researchers used a portal spectroradiometer to measure leaf reflectance with a higher spatial resolution and identified two reflectance ratios of 455/605 and 505/605 nm that were highly correlated to leaf nitrogen content. This plot level finding with hand-held remote sensing device provides an opportunity to scale up for large-scale analysis.

### s0100 *Biodiversity*

p0235 Biodiversity, which represents the variety and variability of life in all forms (i.e., species richness), is a key element of an ecosystem and its definition, as well as its relationship with human well-being is discussed elsewhere in this book. Here the biodiversity term is placed in the context of ecosystem sustainability, as it is an important indicator of an ecosystem health and therefore its environmental sustainability.

p0240 Remote sensing may offer the potential to infer biodiversity information, such as landscape metrics derived from remotely sensed data that is strongly correlated with biodiversity indicators. For example, Petrosyan (2010) developed a model using remote sensing data to observe sustainable ecosystem based on the concept of biodiversity, while Duro et al. (2007) measured sustainable development from the perspective of biodiversity using four key indicators derived from remote sensing data, including productivity, disturbance, topography, and land cover. These attributes were found to be well correlated with the richness of biodiversity.

p0245 It should be noted that remote sensing data continuity, data affordability, and access to high-quality data are still a problem in many parts of the world that prevents researchers from linking satellite data to biological information for biodiversity studies (e.g., Turner et al., 2015).

### s0105 *Landscape and land uses*

p0250 Landscape ecology is an important dimension of environmental attributes that are critical for maintaining an ecosystem health and biodiversity and is filling the knowledge gap in sustainable development (e.g., Termorshuizen and Opdam, 2009). Landscape ecology pertains to the generation and dynamics of ecosystem patterns, as well as the implications of population-, community-, and ecosystem-level process patterns (Urban, 2006). Thus, landscape metrics has been widely used as a crucial indicator in studying sustainable planning and development. Landscape metrics quantify the composition and configuration of ecosystems across a landscape (e.g., patch size, shape, nearest-neighbor distance, proximity index, etc.) thus allowing quantitative comparison between different landscapes or within the same landscape at different times. Once spatial information on landscapes has been derived from remotely sensed data, pattern analysis can take place considering each landscape unit (e.g., land use/cover type) as part of a discrete patch mosaic.

p0255 Some frameworks have been proposed to use the landscape approach to advance the integrated research of sustainable development, such as the principles of defining terms and concepts (e.g., Axelsson et al., 2011). The notions of using landscape ecology have been suggested for studying the sustainability of landscape (e.g., Leitão and Ahern, 2002). In these studies, numerical landscape metrics derived from land cover maps was made available for analyzing landscape planning as well as ecosystem management. Landscape metrics quantify the composition and configuration of ecosystems across a landscape (e.g., patch size, shape, nearest-neighbor distance, proximity index, etc.) thus allowing quantitative comparison between different landscapes or within the same landscape at different times. Once spatial information on landscapes has been derived from remotely sensed data, pattern analysis can take place considering each landscape unit (e.g., land use/cover type) as part of a discrete patch mosaic.

p0260 Landscape classification for ecological purposes requires that broadly-described land use/cover types be reclassified as, for example, habitat quality or units of landscape for some target guild or species (Lafortezza et al., 2010). Even small changes in management, such as changes in farm tillage from conventional to minimum tillage, have implications for ecological outcomes such as carbon sequestration, runoff, soil loss, and habitat. Further, land use/cover is essential to the landscape, indirectly influencing the sustainability of ecosystems. For example, land cover information derived from remotely sensed data, combined with other qualitative assessment data, can serve as a useful tool to evaluate human impacts on the landscape and, hence, on ecosystem sustainability (Burkhard et al., 2009). Moreover, land cover itself can also be used as a critical environmental indicator. Chen (2002) found significant impacts of land cover change on regional sustainable development using remote sensing and GIS techniques.

## s0110 Remote Sensing of Typical Ecosystems Sustainability

### s0115 Remote Sensing Forest Ecosystem Sustainability

p0265 Over the last decades, remotely sensed data have played a key role in quantifying, mapping, and monitoring forest ecosystems across different regions (e.g., Boyd and Danson, 2005; Dubayah et al., 2010). Numerous studies used optical sensors to primarily establish the extent and floristic composition of forest areas and track the progress of deforestation and/or other disturbances, such as forest fires or insect outbreaks, through changes in spectral indices.

p0270 VIs are usually used in the assessment of forest health indicators such as concentration of nitrogen, carbon, and leaf pigments, important indicators of forest ecosystem sustainability (e.g., Daughtry, 2001; Fourty et al., 1996; Gitelson et al., 2002). These indices were based on spectral properties of vegetation at or near red edge (Red) and in the NIR spectral regions, which are primarily related to forest physiology determined by a combination of foliage chlorophyll concentration, canopy area, and canopy structure. Healthy forests have strong reflectance peak in the NIR but low reflectance in the Red wavelength, where chlorophyll absorption is strongest (see, e.g., Tuominen et al., 2009).

p0275 Among many spectral VIs, the NDVI is the most frequently used and most well-known as a good forest health indicator. Another commonly used vegetation index is the EVI as an operational remote sensing product of MODIS (e.g., Huete et al., 1999), which has been used to study forest ecosystems. Variants of these spectral VIs include the red edge normalized difference vegetation index, which can only be calculated from hyperspectral data to study subtle changes in tree canopy chlorophyll content (Sims and Gamon, 2002), the water band index, the NDWI, and the moisture stress index to study changes in canopy water content (Ceccato et al., 2001; Gao, 1996; PeÑUelas et al., 1993).

p0280 Spectral VIs were also used to estimate the amount of stress-related pigments in vegetation. For example, carotenoids and anthocyanins are pigments that are present in higher concentrations in stressed vegetation. Particularly, anthocyanin pigment concentration is typically high in senescence and in new leaves. The anthocyanin reflectance index 700 was developed and used to estimate the total amount of anthocyanin in vegetation (Gitelson et al., 2001).

p0285 It should be recognized that these spectral indices derived from optical remote sensing sensors are extensively used in forest studies they are incapable to infer vertical distribution of woody material of a forest. Forest biomass, total amount of carbon, and forest volume can be retrieved with greater confidence using SAR and LiDAR data that is primarily sensitive to such forest biophysical properties like tree height, biomass, and vertical structure (Giannico et al., 2016; Lucas et al., 2008; Mitchard et al., 2012; Ranson et al., 1997; Sun et al., 2011). These aspects of forest dynamics have been further extended to estimate forest fuel loads and fires (e.g., Erdody and Moskal, 2010; Lavrov et al., 2006), carbon stocks (e.g., García et al., 2010; Le Toan et al., 2007), structures (e.g., Chambers et al., 2007), and nutrient cycling (e.g., DeFries, 2008; Treuhaft et al., 2010).

p0290 Radar remote sensing has the advantages of cloud-free capabilities, which is important when one considers studying forests in tropical or subtropical environment where frequent cloud cover prevents quality optical remote sensing acquisitions.

## s0120 Remote Sensing Wetland Ecosystem Sustainability

p0295 Wetland is an important ecosystem playing a vital role in environmental functions such as biodiversity, regulating services (e.g., Adam et al., 2010; Kadykalo and Findlay, 2016; Mitsch and Gosselink, 2007). In many remote sensing analyses, wetland is treated as one type of land cover but their ecological characteristics are complex and critical to ecosystem resilience to disturbances. Wetland sizes and shapes vary greatly, as do the diversity of plant species and vegetation structures and types that make remote sensing of plant species challenging (e.g., Adam et al., 2010). Water levels fluctuate daily and seasonally, which can confound spectral classification, and many wetland plant species are spectrally similar to one another making the separation of unique signatures difficult, particularly when only a few broad spectral bands are available for classification (Bourgeau-Chavez et al., 2009; Ozesmi and Bauer, 2002; Wickham et al., 2004). The presence of water interspersed with the vegetation dampens the overall spectral reflectance of the vegetation and further diminishes the separability of individual species (Adam et al., 2010; Silva et al., 2008). Periphyton and algae can form large floating masses around wetland vegetation and may further complicate wetland vegetation classification.

p0300 Despite these limitations, the remotely sensed multispectral imagery from Landsat, SPOT, and other major data sources (Adam et al., 2010; Ozesmi and Bauer, 2002; Silva et al., 2008), as well as synthetic aperture radar images (Hess et al., 1995; Kasischke and Bourgeau-Chavez, 1997; Kushwaha et al., 2000; Townsend and Walsh, 1998), have a long history of use in wetland mapping applications. The multispectral imagery of high-resolution satellite systems is of particular interest for wetland mapping because, in addition to the typical spectral bands (i.e., visible blue, green, red, and NIR) the red edge band facilitates the identification of vegetative conditions and has been shown to reveal differences between healthy trees and those impacted by disease or pollution. This feature could be useful in identifying wetland features affected by hydrologic stress. The NIR band that is partially less affected by the atmosphere enables a broader vegetation analysis and biomass studies (Asmaryan et al., 2013). Incorporating spectral VIs such as NDVI and texture measures resulted in greater accuracy in wetland mapping and, therefore, these indices will continue to improve our understanding of wetland landscape environments (Lane et al., 2014).

p0305 A quantifiable relationship exists between hydrological characteristics (frequency and duration) and plant species composition in the seasonal floodplains for wetland biodiversity studies. This relationship can be used to predict the occurrence of indicator species at a site of known flood duration or frequency. By combining independent remote sensing dry–wet interpretation and vegetation survey techniques it is possible to identify relationships between the state of vegetation and hydroperiod in floodplains to quantify wetland seasonality and phenology. The high-temporal resolution MODIS imagery for generating near-real time maps of flood extent in this wetland system is considered excellent (Townsend and Walsh, 2001).

p0310 Mangrove wetlands are unique in many aspects such as biodiversity and flood regulation. However, due to sea level rises and human disturbances mangrove forested wetlands are changing at a much rapid rate (e.g., Gilman et al., 2008). Mangroves grow at the land–sea interface and, therefore, remotely sensed pixels often consists of signals from mangroves, soil, water, and other substrate vegetation (Kuenzer et al., 2011). Textural and spectral characteristics of the canopy and leaves are the main features used to distinguish mangrove communities (Díaz and Blackburn, 2003). Spectral variations of the mangrove canopy reflectance can be depicted as a function of several optical properties, such as LAI, background reflectance, and leaf inclination (Díaz and Blackburn, 2003). The spectral signature of a single species is defined by age, vitality, and phenological and physiological characteristics (Blasco et al., 1998). The spectral-response signal also depends on the internal leaf structure, mainly composed of palisade parenchyma and spongy mesophyll, as well as the number of cell layers, intercell spaces, air–water interfaces, and cell size (Jones et al., 2004). These leaf components include salt, sugar, water, protein, oil, lignin, starch, and cellulose, as well as the leaf structure. Additionally, intertidal effects and soil type influence the spectral signal of plant communities (Blasco et al., 1998). Mangroves with lower-stand density are significantly influenced by intertidal effects; the sparser the vegetation canopies, the greater the influence of the ground surface (Gao, 1998).

p0315 In the past, aerial images were an indispensable technique particularly for the local mapping of mangroves, local change detection, and habitat-management support (Kuenzer et al., 2011). Conventional space-borne satellite sensors have played an important role in mapping mangroves over large geographical regions. The data most commonly used stem from Landsat-5 TM and SPOT. Data from other sensors such as Landsat MSS, Landsat-7 ETM+, IRS 1C/1D LISS III, and the Advanced Space-borne Thermal Emission and Reflection Radiometer were also used by investigators to map mangroves.

## s0125 Remote Sensing Grassland Ecosystem Sustainability

p0320 Remote sensing plays an increasing role in grassland ecosystem sustainability research, especially regarding large spatial and/or long-term temporal scales. Numerous studies have applied remote sensing technologies to examine grassland ecosystem productivity, including NPP, biomass, biodiversity, and even fire ecology (Chiesi et al., 2005; Kuenzer and Knauer, 2013; Smith et al., 2008; Sun and Zhu, 2001; Wang et al., 2010; Wulder et al., 2004). For example, empirical relationship between grassland biomass and spectral VIs from remote sensing such as NDVI has been well established and applied over large scales to estimate NPP and grassland biomass (Anyamba and Tucker, 2005; Gu et al., 2013; Tucker, 1979; Tucker et al., 1985).

p0325 For remote sensing in grassland research, significant effort was made to improve vegetation sensitivity while suppressing noises related to soil substrate variability and atmospheric effects. For example, because NDVI is subject to external factor impacts such as soil and atmosphere, particularly in sparsely vegetated regions, improved spectral VIs were developed including, the soil-adjusted vegetation index and modified soil-adjusted vegetation indices (MSAVI), for more accurate estimates of grassland biomass and foliage that are critical for livestock grazing, soil erosion protection, and water cycles (e.g., Huete, 1988; Kaufman and Tanre, 1992; Qi et al., 1994). These indices were further developed into a global optimized, EVI that is a line of MODIS product (e.g., Huete et al., 1999, 2002). The EVI combined with FPAR significantly improved the performance of above-ground biomass estimation (e.g., Wu, 2012).

p0330 In addition to grassland biomass and NPP estimation, remotely sensed imagery and spectral indices were also applied to assess land degradations such as desertification and degradation (Bastin et al., 1995; Collado et al., 2002; Sternberg et al., 2011). For example, by combining vegetation fraction images, NDVI images with auxiliary field information and rainfall information, grassland desertification could be assessed, quantified, and monitored (e.g., Holm et al., 2003; Wang et al., 2009). Grassland biomass has been related to the green vegetation index, brightness index, and wetness index, and subsequently used to assess impacts of grazing practices on total biomass production of shortgrass steppe (Todd et al., 1998).

p0335 Remote sensing can enhance the assessment of soil properties of grasslands, an important indicator of long-term sustainability of an ecosystem. For example, combination of high-resolution remotely sensed images and LiDAR data with plant community information can quite effectively predict the soil organic carbon content in alpine grasslands, and effectively reduce the amount of field work required by soil surveys (Ballabio et al., 2012).

p0340 Nitrogen in plant canopies is central to a number of important grassland ecosystem processes. Partial least squares regression models have been employed for predicting the mass-based canopy percentage of nitrogen across management types using input from airborne and field-based imaging spectrometers (Pellissier et al., 2015).

## s0130 Remote Sensing Urban Ecosystem Sustainability

p0345 Urbanization has caused a number of significant environmental concerns that are relevant to urban sustainability and sustainable development. The most obvious impact of urbanization is the urban sprawl and large-scale creation of impervious surfaces that have considerable hydrological consequences such as increasing surface runoff, delivering pollutants to rivers, and causing erosion (e.g., Jat et al., 2008; Seto et al., 2010; Weng, 2001). Au13

p0350 Remote sensing is increasingly used for the analysis of urban ecosystems and for developing pathways that support management decisions and investment for sustainable urban development. For example, by using time series remote sensing images researches can monitor urban sprawl across time and space and assess its effects on the four dimensions of sustainability. Knowing the rate and geographic regions of urban sprawl allows a holistic assessment of urban planning and development strategies (e.g., Bhatta et al., 2010; Seto et al., 2010; Sutton, 2003). Au14

p0355 Impervious areas are generally considered an indicator of urban sprawl (Epsteln et al., 2002) and they constitute the key feature of urban sprawl. Impervious surfaces can be determined through remotely acquired data (Jat et al., 2008; Yang and Liu, 2005). The most time consuming and costly, yet most accurate method to measure impervious areas and urban sprawl is the manual extraction of impervious surface features from remote sensing images through heads up digitizing. Remote sensing pattern recognition approaches, such as supervised, unsupervised, and knowledge-based expert system approaches, have recently been used to measure impervious areas and urban sprawl (Lu and Weng, 2005; Mundia and Aniya, 2005; Taubenbock et al., 2012). With ancillary soil data of urban planning and development, urban sprawl can be fully assessed, monitored, and hopefully, regulated to ensure a sustainable environmental condition.

p0360 Urban heating and the formation of the urban heat island (UHI) is another attribute of urbanization and land use transformation that is a vital parameter for urban sustainability. This urban indicator is not only a key environmental sustainability measure but also a social sustainability indicator as it is directly related to human health, ecosystem function, local weather, and possibly climate (Imhoff et al., 2010; Roth et al., 1989; Schwarz and Manceur, 2014; Schwarz et al., 2011; Zhang et al., 2013). The UHI phenomenon is generally seen as being caused by a reduction in latent heat flux and an increase in sensible heat in urban areas as vegetated and evaporating soil surfaces are replaced by relatively impervious low albedo paving and building materials. This creates a difference in temperature between urban and surrounding nonurban areas (e.g., Mariani et al., 2016; Schwarz et al., 2011).

p0365 Remotely sensed data of land surface temperature (LST), urban green cover, and other surface characteristics have been widely used to describe the UHI phenomenon (Gallo and Owen, 1999; Weng et al., 2004). The urban–rural differences in air temperature were linearly related to urban–rural differences in the vegetative cover (derived from NDVI) and surface radiant temperature (e.g., Gallo and Owen, 1999). Use of satellite-derived data may contribute to a globally consistent method for analyzing the UHI phenomena and its impacts on human health. The LST data have been combined with impervious surface area, as well as vegetative cover, to characterize temperature differences across space and time (Xian and Crane, 2005; Yuan and Bauer, 2007). The latest MODIS LST data were also widely used to evaluate the surface temperature differences between urban and surrounding suburban areas (Cao et al., 2016; Zhou et al., 2014) to assess UHI severity, duration, and geographic areas, an important sustainability information for potential human intervention and mitigation.

## s0135 Concluding Remarks

p0370 The environmental pillar of the ecosystem sustainability is changing, driven by escalated climate variability and human activities, thus demanding human interventions to mitigate further changes or adapt some irreversible changes that have already happened. There are important indicators of environmental sustainability that can be monitored, analyzed, and even predicted, through remote sensing technologies. Knowledge of the nature, extent, spatial distribution, potential, and limitations of key environmental indicators such as those discussed in this article provides an important clue to develop pathways toward a sustainable ecosystem. Advances in remote sensing technologies and the reduced cost of sensors have provided multispectral, multiresolution, and multitemporal data to quantify quantity and quality of these key ecosystem indicators.

p0375 Despite the tremendous advances in sensor technology, data processing, analysis and interpretation techniques, however, there are numerous ecosystem sustainability indicators that remote sensing is still unable to retrieve. Therefore, continued research is needed to develop new sensing technologies and innovative information retrieval methods.

p0380 It should be noted that a sustainable ecosystem is supported by well-balanced four pillars of sustainability: environmental, economic, social, and cultural. Remote sensing is capable of monitoring and assessing most environment-related variables, but often it is incapable of inferring information in the social, culture, and economic dimensions of ecosystem sustainability. Therefore, a multidisciplinary collaboration is critical for ecosystem sustainability research.

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## Relevant Websites

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http://www.dlr.de—DLR: German Aerospace Center.
http://www.nasa.gov/—NASA: National Aeronautics and Space Administration.
https://sustainabledevelopment.un.org/sdgs—SDG: United Nations' Sustainable Development Goals.
PAR: Photosynthetically Active Radiation. Au33
NDVI: Normalized Difference Vegetation Index.

# Non-Print Items

**Abstract:**

An ecosystem is a system formed by the interaction of a community of organisms with their environment within a geographic unit or region, and *ecosystem sustainability* is an ecosystem's capacity to endure and maintain its functions and services indefinitely. Although some literature is emerging on the development of sustainability science frameworks, there is little information available on framing ecosystem sustainability. Part of the challenge is that it requires the full integration of natural and human systems with a quantitative nexus among all fundamental elements of an ecosystem. In this article, we first review key elements of ecosystem sustainability, and then provide a review of remote sensing capabilities to provide spatio-temporal dynamics of key indicators of an ecosystem that are critical to its sustainability. While traditional sustainability science tends to focus on four pillars of sustainability—social, environmental, economic, and cultural—ecosystem sustainability will need to be placed in the global context. This article focuses on the environmental dimension of sustainability science with a review of remote sensing capabilities for such applications.

**Keywords:** Coupled nature and human systems; Ecosystems; Geospatial information; Landscape ecology; Remote sensing; Sustainability; Sustainability indicators