Chapter 1
Satellite Earth Observations in Environmental Problem-Solving

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1.1 Introduction

Large-scale environmental problems have become prominent byproducts of the interactions between human activities and the biophysical settings in which they occur. Some of these problems, such as the destruction of tropical forests, arise in areas within the jurisdiction of individual states but have consequences (e.g., biodiversity loss, climate change) that are regional to global in scope. Other problems, including the seasonal thinning of the stratospheric ozone layer, occur in areas that lie beyond the jurisdiction of nation states. Still others, like marine dead zones, originate in areas within the jurisdiction of individual states but can spread and have impacts on areas outside these jurisdictional boundaries. In all these cases, efforts to come to terms with the relevant problems require international (often global) responses that call for transboundary cooperation and, more often than not, eventuate in the development of regulatory arrangements designed to limit or even prohibit the human actions that give rise to the problems.

In recent decades, international environmental regimes have arisen to address problems of this sort. These institutional arrangements provide governance systems designed to address a variety of issues ranging from atmospheric problems like acid rain or the seasonal thinning of the stratospheric ozone layer, marine problems like

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oil pollution from offshore platforms and tankers, to terrestrial problems like desertification in drought-stricken areas or tropical deforestation.[1] Regimes have met with varying degrees of success, attributable to many factors. But in all cases, a necessary condition for making progress is the acquisition of the data and information needed to grasp the fundamental character of the problems themselves and to support the activities of those responsible for administering the provisions of the resultant regimes.

One increasingly important source of data for addressing environmental problems is satellite Earth observation. In many cases (e.g., for monitoring global ozone depletion or tropical deforestation), there is simply no alternative for consistently tracking changes in environmental conditions at a global scale, frequent time interval, and fine spatial resolution. For example, while it is possible in principle to track deforestation in an area like the Amazon Basin from the ground, satellite Earth observation data provide a far more effective and efficient way to acquire an accurate picture of the scope of the problem.

Earth observations have shown great potential for generating global scientific information related to various environmental issues, but they have not yet been fully incorporated as a measurement tool in the monitoring processes of environmental regimes. Despite the call for more data and information for decision-making, a considerable disconnect remains between the policy needs and the data and information supply from satellite observations. To help close this gap, it will be important to identify the roles of satellite Earth observations and to consider how to manage the activities involved in acquiring and applying data, in order to enhance the contributions of these observations to solving problems.

The main goal of this book is to investigate methodologies for assessing the roles and impacts of satellite Earth observations in addressing environmental problems and, in the process, to contribute to thinking about broader questions relating to the interfaces among science, technology, policy, and society. We consider the development of Earth observation systems and the efforts being made to link societal needs and global policy demands to them in China, Europe, Japan, and the United States, as well as the prospects for cooperation among key agencies in each of these states (or consortia of states in the case of Europe). The book also attempts to identify generic models that might prompt governments and organizations to consider the connection of science and technology—in particular satellite Earth observation—to society and policy. We assess existing arrangements (e.g., the Group on Earth Observations, GEO) for coordinating the efforts of the producers of Earth observation data (e.g., national space or environmental agencies) and the users of the data (e.g., government agencies, researchers, NGOs, and businesses). In addition, we consider whether there is a need to create a more highly developed governance system covering satellite observations that would deal with interactions between producers and users of satellite observations, and to develop a system of rules and procedures applicable to the activities of all those active in this realm.

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[1] For a range of perspectives on international environmental regimes, see Young et al. (2008).

1.2 The Nature and Scope of Satellite Earth Observations[2]

Remote sensing is a relatively new term that arose in the 1950s–1960s in the U.S.[3] It refers to "the acquisition of information about an object without physical contact" (Colwell 1983). Humans employ remote sensing all the time, as our eyes detect the light reflected by objects beyond our reach. Earth observation by remote sensing involves the measurement of electromagnetic energy reflected from or emitted by the Earth's surface (or atmosphere), together with the establishment of relationships between the remotely sensed measurements and some phenomena of interest on the Earth's surface (or within the atmosphere) (Mather 1999). The terms *Earth observation* and *remote sensing* are used interchangeably in most parts of this book. While remote sensing encompasses the technical methods and the technology, the term Earth observation places emphasis on the purpose of the activity. The principal concern of the chapter is with the use of remote sensing, but we also include methods of global monitoring that employ technologies other than remote sensing, such as satellite navigations and communications (e.g., Automatic Identification Systems (AIS) of vessels).

The electromagnetic wavelengths typically utilized for remote sensing of the Earth's surface/atmosphere range from the ultraviolet to microwave regions of the spectrum (Fig. 1.1). Useful information can be extracted from remote-sensing data because different types of objects on the Earth's surface (or in the atmosphere) tend to have different electromagnetic reflectance/emittance properties. That is to say, they have different spectral characteristics. It is possible to identify many types of objects based on their spectral signature, i.e., their unique reflectance/emittance properties in some specific regions of the electromagnetic spectrum. In order to measure these signatures, satellites carry scanners and Charged Coupled Devices (CCDs) that collect digital data and transmit it by radio back to Earth. Because the data recorded by these sensors are digital, they can be manipulated in various ways to derive useful information from the spectral measurements.

Remote-sensing data from different parts of the electromagnetic spectrum convey different types of information about the Earth's land/water surface or atmosphere. Images acquired in the visible to intermediate, or shortwave, infrared wavelengths (typically called "optical" remote-sensing data) are often used for the monitoring of vegetation and other types of objects on the ground or atmosphere (e.g., clouds) that have distinctive colors. Multispectral optical sensors, which measure reflected solar radiation over a few (1 to approx. 30) relatively broad

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[2] For further technical introductions to remote sensing and Earth observation technology, see Short (2008), Colwell (1983), Mather (1999).

[3] Short (2008) indicates that the term "remote sensing" had been coined in the mid-1950s by Ms. Evelyn Pruitt, a geographer/oceanographer with the U.S. Office of Naval Research (ONR), to take into account the new views from space obtained by the early meteorological satellites that were obviously more "remote" from their targets than the airplanes that up until then provided mainly aerial photos as the medium for recording images of the Earth's surface.

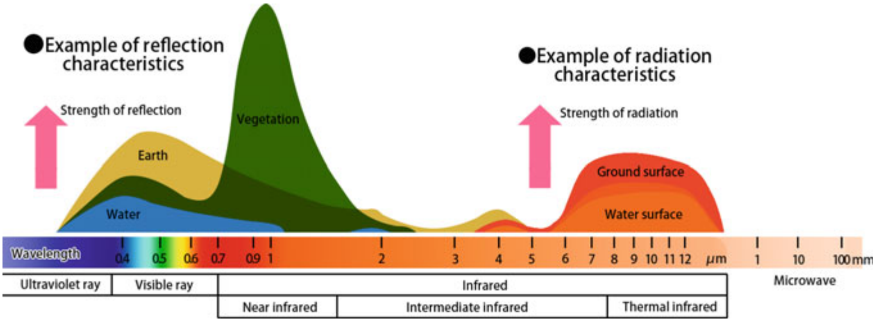

Fig. 1.1 Strength of reflection and radiation of electromagnetic waves from plants, earth, and water in each wavelength (JAXA 2016a, b, c, d)

portions of the optical spectrum, can differentiate between some types of objects on the surface/atmosphere. Hyperspectral optical sensors, which take measurements over many more (approx. 30 to several hundred) narrower portions of the spectrum, can discriminate between even more types of objects, but hyperspectral satellite imagery is still not yet widely available globally. Images acquired in the thermal infrared spectrum can provide information on the surface temperatures of objects and are often used to monitor the health of crops (e.g., leaf water content) or detect forest fires. Images acquired in different parts of the microwave spectrum can be used to monitor various vegetation/soil/water parameters. For example, short wavelength microwaves emitted from an active microwave satellite (e.g., a Synthetic Aperture Radar (SAR) satellite) are easily scattered by top surface materials (e.g., plant leaves in vegetated areas or the top of the soil layer in bare areas), providing useful information related to these materials (e.g., plant Leaf Area Index (LAI) or top soil moisture). Longer wavelength microwaves emitted by active microwave satellites can penetrate through these surfaces and provide other types of useful information (e.g., plant stem volume or subsurface soil moisture). Analysis of SAR images acquired at different time periods also allows for the measurement of surface deformations (e.g., land subsidence/uplift) or changes in water levels. Unlike visible and infrared satellite sensors, active microwave sensors are able to acquire information on the Earth’s surface regardless of cloud cover. Passive microwave sensors measure radiation emitted by the Earth’s surface at microwave wavelengths, and can be used to monitor soil moisture, snow melt, sea ice, sea surface temperatures, temperature profiles of the atmosphere, water vapor, ozone distribution, and precipitation. Finally, light detection and ranging (LIDAR) satellite data involve transmission of coherent laser light from the sensor and ranging to determine the height of objects on the Earth’s surface (e.g., ground elevation, water depth, vegetation/building heights) or the abundance of different particles in the atmosphere, depending on the wavelength of the emitted laser. Other types of remote-sensing data for Earth observation exist, but the contributions in this book focus mainly on the types of data described here.

Other specifications of satellite remote-sensing instruments that have important implications for their environmental monitoring capabilities are the spatial and temporal resolutions at which they image the Earth. As might be expected, the spatial resolution of remote-sensing data describes the level of spatial detail of the data. The spatial resolution of the imagery generally determines the minimum size of objects that can be detected by the sensor. For example, an object that is at least 1 m wide and 1 m long can be separated (resolved) theoretically from its surrounding objects in an image with a spatial resolution of 1 m or finer. Commercial satellites today can produce images with very high (i.e., fine) spatial resolutions, 0.5 m or better. The temporal resolution of remote-sensing data describes the time interval at which images are acquired over the same location. Some satellites, typically those that acquire lower spatial resolution images (approx. 250 m or coarser, e.g., Terra/Aqua MODIS, Himawari-8) can image the entire globe daily, while other satellites that acquire higher spatial resolution images (approx. 30 m or finer, e.g., Landsat 8, Sentinel-2A) may only collect images of the same location every few weeks.

In summary, Earth observation by satellite remote sensing provides a powerful tool for monitoring various features of the Earth's environment not only because of the wide range of measurements that can be performed, but also because of the high frequency and large area for which data can be acquired. The digital era has made it possible to perform, store, analyze, and share data globally in a way that no one could imagine half a century ago. Available technology allows Earth observation data to be disseminated widely, and the need is stronger than ever to devise ways to put the data to work in meeting societal challenges.

1.3 Applications of Satellite Earth Observations

As a point of entry into the analysis of the links between Earth observations and public policy, we provide some examples dealing with atmospheric CO_2 monitoring, marine observations, and forest observations. Later chapters include more detailed accounts of these cases and link them to specific policy issues.

1.3.1 Atmospheric CO_2

As world leaders and the climate community met in Paris, France, for the 21st session of the UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in December 2015, global whole-atmospheric monthly mean CO_2 concentration observed by analysis of Japan's Greenhouse gases Observing SATellite "IBUKI" (GOSAT) was passing 400 ppm for the first time since GOSAT's launch in 2009 (Fig. 1.2). If this upward trend continues, further analysis is expected to show that the trend line of global CO_2 (indicating the

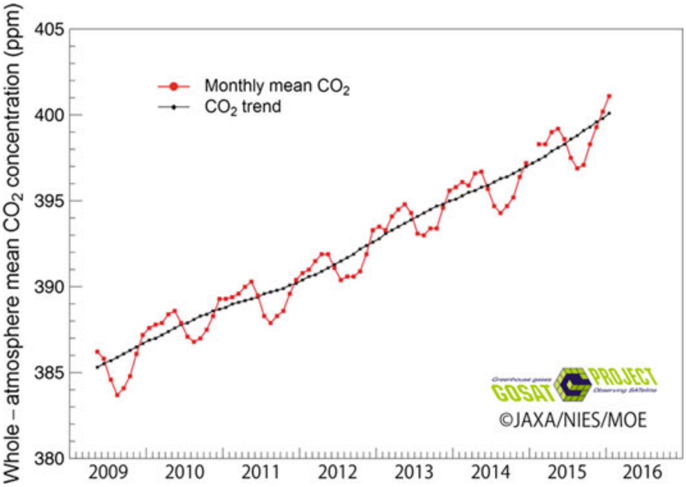

Fig. 1.2 Whole-atmosphere monthly mean CO_2 concentration derived from GOSAT observations. The CO_2 trend is calculated by removing averaged seasonal fluctuations from the monthly CO_2 time series (JAXA/NIES/MOE 2016)

trend after removing seasonal variations) exceeded 400 ppm around March 2016, which will mean that current global atmospheric CO_2 concentrations substantially exceed 400 ppm (JAXA/NIES/MOE 2016; JAXA 2016a, b, c, d).

Anticipating the policy needs of their governments, space agencies have been developing missions in recent years to provide detailed global measurements of various greenhouse gases. GOSAT, the first satellite designed specifically to monitor greenhouse gases from space, provides critical information on atmospheric CO_2 trends, as it is able to provide global, column-averaged CO_2 concentrations every three days, and has been monitoring long-term trends since its launch in 2009. In addition to GOSAT, NASA's Orbiting Carbon Observatory-2 (OCO-2) has been collecting data operationally since September 2014. OCO-2 is the first NASA mission designed to collect space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize the processes controlling its accumulation in the atmosphere. OCO-2 is able to generate a global product every 16-days showing column-averaged concentrations of CO_2 in the order of a few kilometers in resolution. In combination with chemical transport modeling and image compositing techniques, highly detailed global maps have been developed which clearly show periodic daily fluctuations of atmospheric CO_2 over key sources and sinks (Fig. 1.3). In the future, it is possible that near-real-time monitoring of CO_2 from space may be available to support all phases of environmental policy, including definition, monitoring, and enforcement.

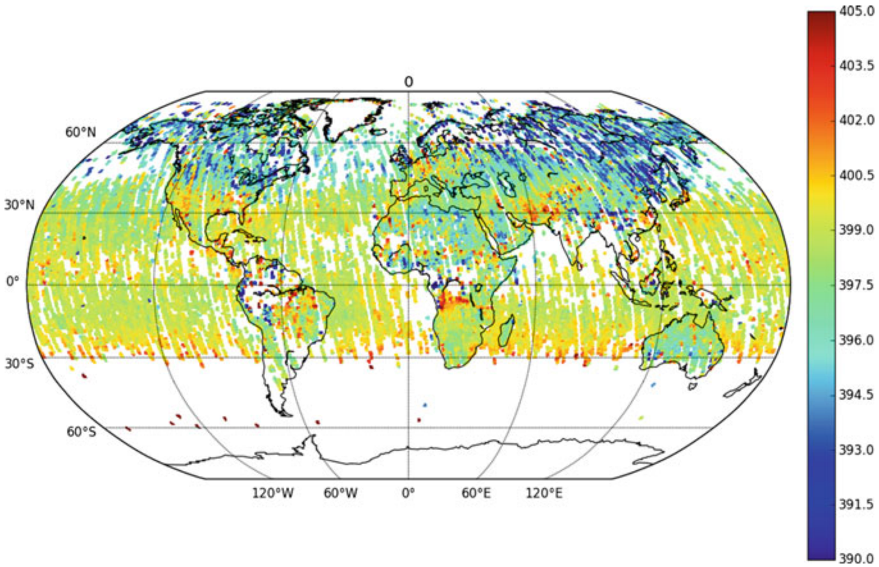

Fig. 1.3 OCO-2 Level 2 Lite product. One month CO_2 column-averaged dry air mole fraction (OCO-2 Science Team/Michael Gunson and Annmarie Eldering 2015)

1.3.2 Marine Pollution

1.3.2.1 Operational Oil Pollution Monitoring

The environmental impacts of large-scale industrial oil spills are quite well known. But smaller day-to-day leaks and discharges from passing ships also have a profound effect on marine ecosystems. Since 1998, Kongsberg Satellite Services (KSAT) in Tromsø, Norway, has operated a near-real-time oil monitoring system that relies primarily on SAR data, which is well suited to detecting surface slicks and can be used in all weather conditions. Missions such as Envisat (past), Sentinel-1, Radarsat-2, TerraSAR-X, and COSMO-SkyMed are used in combination with other sources of data, including optical satellite imagery and satellite-based AIS, to identify events and deduce responsibility. KSAT's system has been employed by customers all over the world, from national authorities to the offshore oil and gas industry, for self-monitoring, early spill detection, legal defence (in the case of false accusations), identification of polluters, regulatory compliance, and documentation of baseline conditions (KSAT 2016).

1.3.2.2 Gulf of Mexico Oil Spill

In 2010, the MODIS sensor on NASA's Terra/Aqua satellites provided a unique twice-daily perspective of the extent and movement of the oil slick originating from the Deepwater Horizon offshore oil platform (Fig. 1.4). Scientists and emergency response personnel used satellite imagery, in combination with ground observations and aerial photography, to plan and assess the progress of clean-up efforts. Satellite imagery was used to estimate the extent of ocean impacted by the disaster as 68,000 square miles (180,000 km^2). Such impact assessments are crucial inputs for legal proceedings and damage claims.

1.3.2.3 Red Tides

Red tides are algal blooms (phytoplankton) that occur naturally given certain combinations of environmental conditions. They are sometimes intensified by increased nutrient loading and temperature increases arising from human activities such as agricultural fertilization and coastal industrial activity. Harmful Algal Blooms (HABs) produce toxins that are dangerous to marine life and humans. Figure 1.5, captured by AVNIR-2 on the Japan Aerospace Exploration Agency's (JAXA) ALOS satellite, shows a red tide that occurred in Tokyo Bay from spring to summer of 2006. Satellite observations can be used to detect outbreaks before they become large in scale, facilitating management activities and identification of contributing factors.

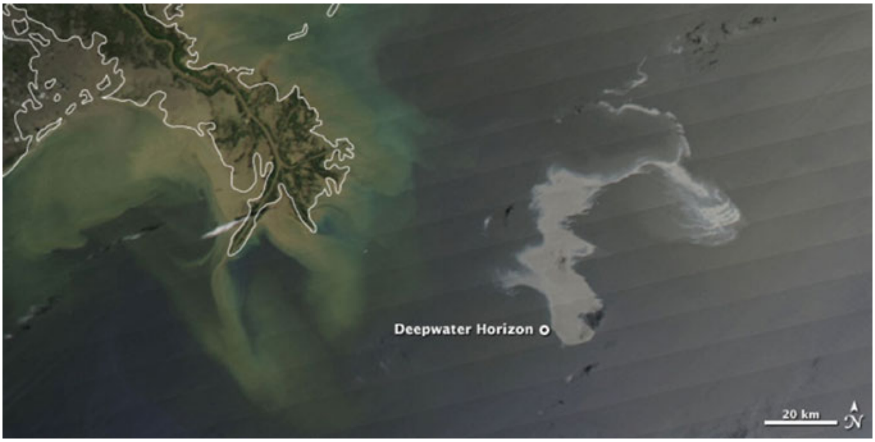

Fig. 1.4 Deepwater Horizon oil spill captured by MODIS (NASA MODIS Rapid Response Team 2010)

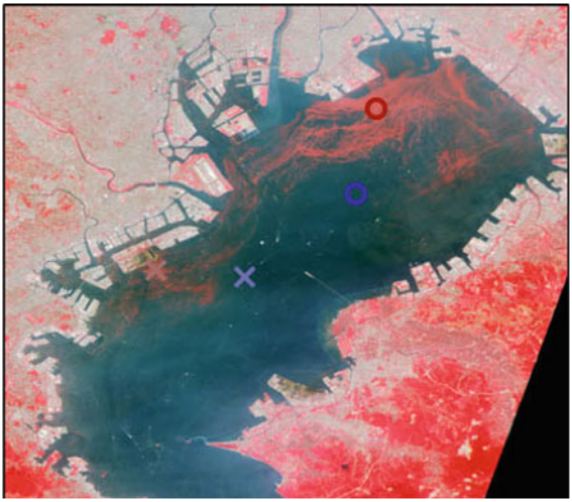

Fig. 1.5 JAXA ALOS (AVNIR-2) image showing a *red* tide that occurred in Tokyo Bay from spring to summer in 2006 (JAXA 2016a, b, c, d)

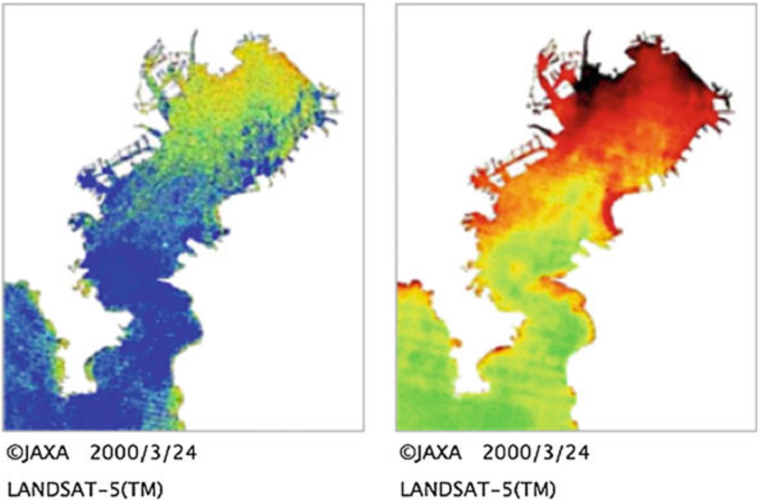

Fig. 1.6 Turbidity distribution (*left*) and clarity distribution (*right*) (JAXA 2016a, b, c, d)

Figure 1.6 shows some other useful products derived from satellite imagery—turbidity distribution (*left*) and clarity distribution (*right*). This information can be used to plot red tide distributions and inform decision-makers who must assess water quality and safety.

1.3.3 Deforestation

In response to Brazilian Amazon deforestation, the Japan International Cooperation Agency (JICA) established a technical cooperation project with the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) to combat illegal deforestation. Using data from JAXA's ALOS and ALOS-2 SAR instruments (e.g., Fig. 1.7), which have the ability to image in all weather conditions and regardless of the time of day, Brazilian authorities assess deforestation and work with local law enforcement agencies to control illegal activities. Over the 2010–2012 period, IBAMA reported a 40% decrease in deforestation, due in part to the collaboration with JICA and JAXA. These activities play a vital role in achieving Brazil's Nationally Determined Contribution (NDC) to combating climate change, which aims to reduce the rate of Brazilian Amazon deforestation 80% by 2020 (with respect to the 1996–2005 baseline of 19,500 km^2).

Figure 1.8 (from Landsat 4 TM in 1988) shows the drastic impact that politics and social forces can have on the environment. The image shows heavy agricultural development and thus forest clearing on the Mexican side of the border, which may have been due to the relative political stability in Mexico at the time, whereas Guatemala—in the midst of a civil war—experienced much less agricultural development and forest clearing. This image spurred bilateral discussions between the countries leading to increased conservation efforts, including the establishment of the Maya Biosphere Reserve in 1990 (Simmon and Gray 2012).

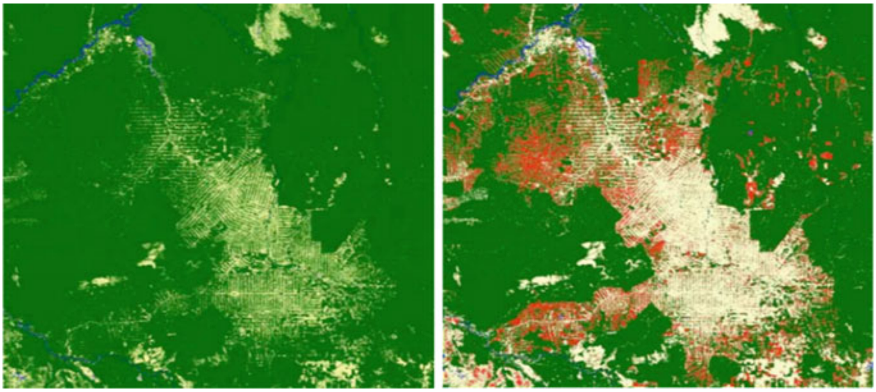

Fig. 1.7 Significant numbers of trees have been felled in Brazil, as evidenced by these two images acquired by Japan's JERS-1 (*left*) and ALOS (*right*) satellites in 1995 and 2007 respectively (Shimada 2016)

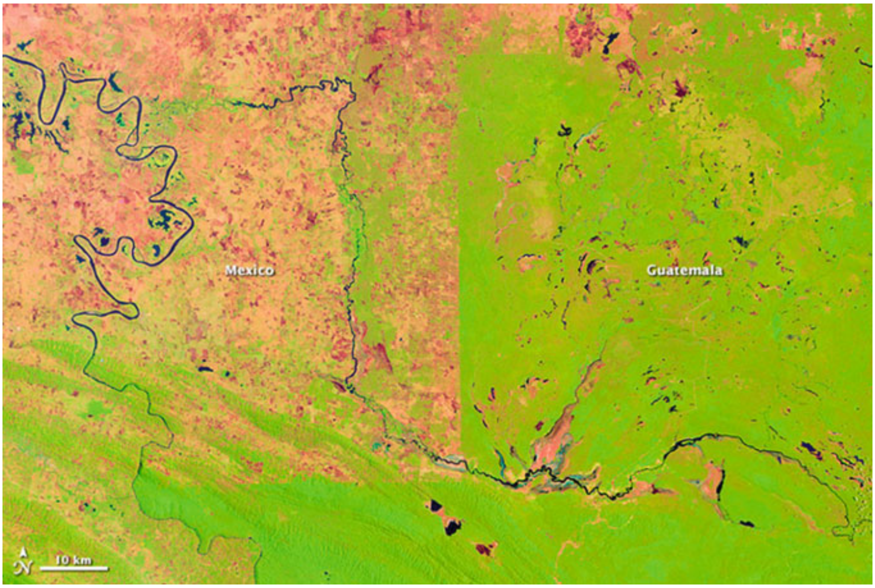

Fig. 1.8 Forest cover (*green*) at the border of Mexico and Guatemala (Simmon and Gray 2012)

1.4 A Taxonomy of Roles for Satellite Earth Observations

The examples highlighted in the preceding section make it clear that there is a place for satellite observations in efforts to solve a variety of environmental problems arising at the international level. However, they do not provide a more systematic account of the variety of roles that satellite observations can play in this realm. In this section, we tackle this challenge directly, presenting a simple taxonomy of the major roles that satellite observations can play in addressing environmental problems. This taxonomy offers an overview of the range and diversity of the contributions that satellite observations can make. It also provides a roadmap for those desiring to identify specific roles that can be subjected to more detailed analysis.

Table 1.1 provides a framework for thinking more systematically about roles for satellite observations. The table draws attention to environmental problems dealing with atmospheric, marine, and terrestrial systems. To some extent, these distinctions are artificial. Runoff of pesticides and fertilizers used in terrestrial farming operations, for example, is the principal source of marine dead zones. Tsunamis are marine phenomena, but they cause terrestrial environmental problems when the resultant tidal waves make landfall with destructive force. Nevertheless, it is helpful to begin with these distinctions in order to construct an overview of the roles of satellite Earth observations.

Table 1.1 Roles for satellite Earth observations in addressing environmental concerns

Function		Medium		
		Atmospheric	Marine	Terrestrial
Inform	Identify	Existence of the ozone hole	Occurrence of marine dead zones	Forest fires
	Monitor	Greenhouse gas concentration	Sea surface temperature	Pace of Amazon deforestation
	Assess	Recovery of the ozone layer	Rise of sea level Loss of sea ice	Loss of carbon stock
Assist		PM2.5 early warning	Provide early warning of tsunamis	Track pathways of tornadoes
Comply		Identify sources of greenhouse gas (CO_2 and CH_4) emissions	Track Illegal, Unreported, and Unregulated (IUU) fishing	Locate illegal loggers

Similarly, the table differentiates a number of distinct roles for satellite observations in coming to terms with environmental problems. The fundamental distinction separates roles that center on the supply of information, roles that involve the provision of emergency assistance, and roles that contribute to the achievement of compliance. Here, too, the boundaries are not watertight. Monitoring trends in concentrations of greenhouse gases in the Earth's atmosphere, for example, may prove helpful for those interested in the extent to which major countries are taking the steps needed to implement their NDCs under the terms of the 2015 Paris Agreement regarding climate change. Nevertheless, the categories included in the table do point to differences in purposes and in targets of observation that are important when it comes to the administration of Earth observation systems.

1.4.1 Identify

To begin with, satellite Earth observations can play critical roles in assembling the data needed to detect large-scale environmental problems, monitor shifts in the status or severity of these problems over time, and assess the success of concerted efforts to solve them. In some cases, the problems are largely unknown prior to observations from satellites. In the case of deforestation in the Amazon Basin, for instance, ground-based data were available to document local occurrences of destructive practices, but no one was able to grasp the extent of deforestation prior to the advent of remote-sensing images (National Research Council 1998). In other cases, satellite observations played a role in confirming the existence of a problem first identified by other means. The seasonal thinning of the stratospheric ozone layer, for example, was identified initially through ground-based observations made by British Antarctic Survey scientists located at Halley Bay, but satellite observations were able to verify these measurements and document the full scope and severity of the problem. In such cases, satellite observations can alter policy agendas by introducing and highlighting the significance of issues that did not exist previously as policy concerns, whether or not the problems had already come into existence in biophysical terms.[4]

1.4.2 Monitor

Once an environmental problem is identified, it becomes important to monitor the evolution of the problem over time. Satellite observations can play two distinct roles in this regard. One role involves monitoring trends in key variables without reference to policy interventions. The use of satellite observations to track shifts in seasonal maxima and minima in the extent of sea ice in the Arctic Basin or seasonal maxima and minima in the extent of dead zones in the Gulf of Mexico exemplifies this role. The other role centers on tracking progress toward fulfilling goals included in international treaties or agreements. This role is referred to as "systematic observations" in the ozone and climate change treaties (United Nations 1985a, b, 1992a, b). This is not a matter of measuring compliance on the part of individual actors. Rather, the critical concern is to contribute to determining whether the creation and implementation of an international regime is making a difference with regard to the status of the relevant problem. For example, are the so-called ozone holes over the polar regions becoming more or less severe over the course of time? Are glaciers retreating and, if so, is the rate of retreat increasing? Is the rate of desertification in sub-Saharan Africa or in northwestern China accelerating or slowing over time? In each case, the challenge is to explore links between the operation of a regime and observed trends in relevant biophysical phenomena.

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[4] Litfin (1995) stated that the discovery of the Antarctic ozone hole (published in the journal Nature by Josef Farman of the British Antarctic Survey in its paper about severe ozone depletion in the Antarctic and a strong correlation between CFC concentrations and ozone losses) was "officially ignored" in the international negotiations for the Montreal Protocol. However, "the ozone hole, signalling a dangerously high probability of ecological disaster, precipitated a sense of crisis conductive to the precautionary discourse eventually sanctioned in Montreal", and "once the hole's existence was confirmed by NASA satellite data, the race was on to explain it." However, the hole was unexplained until aircraft based measurements could link the hole to CFCs, and thus, the fact that the hole remained unexplained until after the Montreal Protocol was signed, indicates that "scientific ignorance, rather than scientific knowledge, set the stage for international cooperation".

1.4.3 Assess

Going a step further, satellite observations can play an important role in evaluating the effectiveness of international agreements at solving the problems leading to their negotiation. The goal of the 2015 Paris Agreement is framed in terms of temperature increases at the Earth's surface. But to achieve this goal, it will be essential to limit increases in concentrations of greenhouse gases in the atmosphere. Satellite observations will play an essential role in assessing trends in these concentrations. Similarly, the program known as Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) focuses on initiatives to provide developing countries with incentives to reduce emissions from forested lands or to increase areas devoted to forests. Satellite observations will play an important role in assessing the performance of this program over time. The point here is not to document (non-)compliance with rules or obligations on the part of individual members of international regimes. Rather, the emphasis is on evaluating the performance of the regime as a whole over time, with the objective of determining whether there is a need to adjust or reformulate the regime going forward in the interest of solving the relevant problem.

1.4.4 Assist

A different type of role for satellite observations involves provision of assistance regarding matters like early warning and search and rescue. This role encompasses a range of more practical contributions in situations involving natural or anthropogenic disasters. The International Charter on Space and Major Disasters aims at providing a unified system of space data acquisition and delivery to those affected by natural or man-made disasters through Authorized Users. Each member space agency has committed resources to support the provisions of the Charter and is thus helping to mitigate the effects of disasters on human life and property by responding to requests from afflicted countries for imagery. One of the latest applications involved the flood that occurred in Sri Lanka on May 17, 2016. Satellite observations can play major roles in providing early warning regarding the occurrence of tidal waves produced by tsunamis and the tracks of hurricanes and tornadoes. A well-developed space-based system would have been able to provide significant early warning in the case of the December 26, 2004 Indian Ocean earthquake and tsunami, an event that is estimated to have killed over 300,000 people. Similar comments are in order regarding search and rescue. AISs using low Earth orbit satellites sometimes in combination with observation imagery are capable of tracking ships at sea in real time and guiding rescuers to the site of maritime disasters on an efficient basis. On an operational basis, meteorological services provided by geostationary and other satellites around the world provide a successful model of internationally coordinated and shared information services using satellites for weather forecasting and management of extreme weather, as well as for climate monitoring services.

1.4.5 *Comply*

Taking the next step, satellite observations become more sensitive because they focus on the extent to which individual subjects (both states and non-state actors) comply with requirements and prohibitions rather than on systemic concerns, such as the size of ozone holes or rates of desertification. AISs, for example, can identify the precise location of ships at sea and access relevant databases to determine whether a given ship is in possession of an up-to-date certificate or license to operate in the relevant area (e.g., a Polar Certificate issued in accordance with the International Maritime Organization's new rules for ships operating in polar waters). Recent advances are likely to allow satellites to make an accurate determination of whether a ship is engaged in illegal, unreported, and unregulated (IUU) fishing, even in cases where the operators of a ship have turned off their transponder in an effort to avoid detection. Remote sensing may provide the only way to document the occurrence and the extent of illegal logging in remote areas such as the islands of Borneo and Kalimantan. Several countries have started to make regular use of satellite data for their national inventories of greenhouse gas emissions (by observing forest areas as carbon sinks); the information will be used for self-reporting according to the obligations included in the Paris Agreement (United Nations 1992a, b, 1997, 2015). Innovations in the technology underlying satellite observations are occurring regularly. If the proposition that such observations constitute a legitimate compliance mechanism is widely accepted, innovations that are targeted to this role of satellite observations are likely to be forthcoming.

1.5 Coordination Mechanisms

There have been several multilateral initiatives to coordinate the various national Earth observation programs and policies. Among these are intergovernmental programs, including the Global World Weather Watch (WWW) (World Meteorological Organization 2016) and Earthwatch (United Nations Environment Programme 2016),[5] informal voluntary groups or partnerships such as the Committee on Earth Observation Satellites (CEOS), the Global Earth Observation

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[5] The Global Resource Information Database (GRID) under the framework of Earthwatch integrates satellite remote sensing data and data collected by the Global Environment Monitoring System (GEMS).

System of Systems (GEOSS), and a number of other initiatives. The earliest efforts of multilateral coordination in remote sensing were with meteorological satellites. The WWW, the principal activity of the World Meteorological Organization (WMO), is a cooperative program for collecting, processing, and disseminating meteorological data from satellites and other sources, aiming to maximize the utilization of meteorological data from satellites. The Coordination Group for Meteorological Satellites (CGMS) meets annually to coordinate technical standards among satellite operators.

Intergovernmental agencies affiliated with the UN play a significant role in these initiatives for multilateral coordination of Earth observation and research for the protection of the environment. Among these are the World Climate Research Programme (WCRP), which studies physical aspects of climate change, and Future Earth, which operates under the auspices of the International Council for Science (ICSU). The Intergovernmental Oceanographic Commission (IOC), UN Environment Programme (UNEP), the UN Educational, Scientific, and Cultural Organization (UNESCO), and the WMO also help in planning these international research efforts. Funding agencies, such as the International Group of Funding Agencies for Global Change Research (IGFA) and what is now known as the Belmont Forum, also play an important role. To respond to the need for long-term climate monitoring, the Global Climate Observing System (GCOS) was established as a user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system; detecting and attributing climate change; assessing impacts of, and supporting adaptation to, climate variability and change; application to national economic development; and research to improve understanding, modeling, and prediction of the climate system (GCOS 2016).[6] The Global Ocean Observing System (GOOS) is a permanent global system for observations, modeling, and analysis of marine and ocean variables to support operational ocean services worldwide (GOOS 2016). A central purpose of these research programs is to inform and influence national policies and international agreements on environmental management.

In the first instance, coordination is a matter of avoiding unnecessary duplication of efforts and ensuring that there are no gaps in coverage regarding key roles played by satellite observations. At the same time, it is important to agree on rules and procedures (e.g., format standardization, data principles, and sometimes joint program planning), allowing for healthy competition among Earth-observing programs to encourage the flow of innovations that can expand the capacity of space agencies to play constructive roles in dealing with a variety of environmental problems.

Coordination is also a matter of linking the contributions of a variety of Earth observation instruments, including ocean buoys, meteorological stations and balloons, seismic and Global Positioning System (GPS) stations, remote-sensing satellites, computerized forecasting models, and early warning systems (Group on Earth Observations 2008). For most of the roles identified in the preceding section,

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[6] The GCOS is sponsored by: The WMO, UNESCO and its IOC, UNEP, and ICSU.

there is a need to integrate data coming from multiple sources to achieve the clearest and most detailed picture of the targets of Earth observations.

Many environmental agreements contain provisions for research and systematic observations, monitoring, or scientific research cooperation. The 1985 Vienna Convention for the Protection of the Ozone Layer expressly mentions satellite measurement (United Nations 1985a, b). The World Summit on Sustainable Development held in Johannesburg in 2002 adopted a Plan of Implementation, which includes several proposals on actions for satellite Earth observation, global mapping, and integrated global observations (United Nations 2002). At the same time, efforts to identify the adequacy of global observations for tracking climate change (GCOS 2003)[7] were carried out by GCOS and have been reported to the COP of the UNFCCC. The U.S. took the initiative to host the first ministerial Earth Observation Summit in Washington D.C. in 2003. In response to a call from the Group of Eight leading industrialized countries of June 2003 (G8 2003), the third Earth Observation Summit took place in Brussels in February 2005, initiating the formation of the GEOSS.

GEO is a voluntary partnership of governments and international organizations.[8] It provides a framework for these partners to develop new projects and coordinate their strategies and investments. GEO

> …links existing and planned Earth observation systems and supports the development of new ones in cases of perceived gaps in the supply of environment-related information. It aims to construct a global public infrastructure for Earth observations consisting in a flexible and distributed network of systems and content providers. (International Institute for Sustainable Development 2015)

GEO has taken a leading role in coordinating efforts to build GEOSS. At its 12th Plenary Session, held in Mexico City in November 2015, GEO entered its second decade and adopted a new Strategic Plan covering the decade from 2016 to 2025 (for more details see Chap. 11).

1.6 The Governance of Earth Observation Systems

As satellite observations have taken on expanded roles in responding to the provision of emergency assistance, the operation of compliance mechanisms, and the assessment of regime performance, the need to move beyond simple procedures to coordinate the activities of producers of Earth observation data has come into focus. Consider the following development in this context. In November 2014, Skytruth, Oceana, and Google announced the launch of Global Fishing Watch, a public tool utilizing SpaceQuest AIS data and algorithms developed by Analyze Corp to

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[7] Hereinafter: *GCOS Second Adequacy Report.*

[8] Some regard GEO as being technically an intergovernmental meeting but virtually a small-scale intergovernmental organization, see: Aoki (2006).

identify and display fishing activity worldwide.[9] Turning to hypothetical but entirely realistic scenarios, consider a case in which SpaceQuest, a private company, launches a satellite on a Russian rocket with the intention of deploying an AIS system to monitor compliance with the rules articulated in the IMO's Polar Code for ships operating in polar waters and to provide relevant data to governments in the countries where the ships are registered or where there are ports the ships are likely to enter. Or, to take another example, consider a partnership in which the European Space Agency (ESA) joins forces with Australia to track and ultimately apprehend a vessel registered in Panama that is thought to be harvesting Patagonian toothfish illegally in waters subject to the management regime established under the terms of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR).

As these examples suggest, we are moving into a realm regarding the role of satellite observations in addressing environmental problems that takes us beyond the efforts of consortia of producers like GEO. We are now dealing with a complex mix of private companies, public agencies, and public/private partnerships. The private companies are interested in selling their services to a variety of users that may include academic, commercial, governmental, and non-governmental customers. This is certainly reasonable in principle, though it may require focused and careful efforts to iron out differences among participants regarding the proper division of labor between private sector actors (e.g., SpaceQuest or Google Earth) and public sector players like NASA, ESA, or JAXA and many other existing and emerging space agencies around the world.

Note also that the relevant partnerships may involve representatives of intergovernmental organizations responsible for administering international regimes, such as the IMO and the secretariat of CCAMLR. While the IMO does not have the capacity to operate Earth-observing satellites of its own, it does have the authority to make and interpret international rules pertaining to various aspects of the design, construction, and operation of commercial vessels. As the toothfish example suggests, there may be cases in which it is important to coordinate the efforts of providers of Earth observations not only with the activities of states (e.g., Australia) keen on improving compliance with international rules but also the responses of states (e.g., Panama) that may be less enthusiastic about the application of the rules to actors operating under their jurisdiction (e.g., vessels registered in Panama).

Another important observation regarding the roles of satellite observations in addressing large-scale environmental problems is that these roles are normally instrumental. As our taxonomy of roles indicates, we are concerned with matters like the depletion of the stratospheric ozone layer, the growth of marine dead zones, and the destruction of tropical forests. Satellite observations cannot solve these problems. But they can play a variety of supporting roles that are helpful to those responsible for coming to terms with these problems.

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[9] http://globalfishingwatch.org/.

This makes it clear that there is a need for close cooperation between those seeking to implement or administer issue-specific regimes and those responsible for the operation of Earth-observing systems. It is possible, in principle, to launch satellites dedicated to the concerns of specific regimes and operated under the auspices of each regime. But arrangements of this sort are unlikely to become commonplace, for several reasons. Operating Earth-observing satellites requires material resources and trained personnel that are not available to most of those responsible for the administration of issue-specific regimes. There is no prospect that this will change in the foreseeable future. In addition, there are cases in which a satellite or a set of satellites can provide data responsive to the needs of two or more issue-specific regimes.

Under the circumstances, a key issue of governance will center on arrangements designed to ensure compatibility between the needs of the users of satellite observations and the activities of the providers of these data. Needed in this connection are what commentators on environmental governance call regime complexes (Oberthür and Stokke 2011). Such complexes are sets of institutional arrangements that deal with the same issues or with overlapping issues but that are not related to one another in a hierarchical manner. In such cases, it becomes important to work out, either formally or informally, a set of practices governing the interactions among the elements of the complexes.

There are examples of such arrangements that may offer insights to those concerned with the roles of Earth-observing systems. The Intergovernmental Panel on Climate Change (IPCC), for instance, is a body operating under the auspices of WMO and UNEP (Agrawala 1998). It provides scientific assessments that feed into the work of the UNFCCC, but it is not subject to the authority of the COP of the UNFCCC. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) operates under the auspices of UNEP, the UN Development Programme (UNDP), the UN Food and Agriculture Organization (FAO), and UNESCO (Díaz 2015). It provides scientific input in response to requests from decision-makers, especially those responsible for the administration of international governance systems like the Convention on Biological Diversity.

The situation regarding Earth-observing systems is more complex (see Chap. 16). But it is easy to identify some of the key issues arising in the relevant regime complexes. Consider the following examples.

At the center of these arrangements lie relationships between the providers and users of Earth observation data. It is therefore essential to consider the terms of trade between upstream providers and downstream users. Should Earth observations be supported by public funds and made available to all (or all certified) users on an open access basis? What is the role of private providers in such settings? Can users make contracts with providers to meet the needs of users on an ongoing basis under terms agreed upon for varying lengths of time? What are the incentives for providers to develop technological innovations that can improve the services they are able to supply to users of satellite observations?

Are there issues regarding the protection of privacy or proprietary information that need to be addressed in the production and dissemination of satellite observations that can help to solve environmental problems? With current satellite technology, it is possible to obtain images of activities occurring on the Earth's surface with a very high resolution. Using Google Earth, for instance, it is possible to obtain detailed views of individual houses located on a particular street within a specific community. Additional technological advances will make it possible to reveal even more details regarding the activities of various actors. This is good news in some respects. For example, providers or disseminators of satellite images now say that they can identify fishing vessels even when they have their transponders turned off and determine whether they have nets in the water in violation of the rules governing specific areas or seasons.[10] But it may be feasible to place certain restrictions on the acquisition of satellite images in order to protect privacy, without diminishing the usefulness of the relevant data for the implementation of specific regimes. To take a concrete example, it is possible to determine whether a commercial vessel operating in polar waters has a certificate that is valid under the terms of the Polar Code without tracking the movements of the vessel continuously in real time and seeking to determine its cargo.

Should we be concerned about dangers relating to the misuse of Earth observation data for purposes that are unrelated to solving environmental problems? The same data, especially in the case of very high resolution data, can be used to address environmental problems and for military purposes. Today, not only do many countries have space programs, but very high resolution data are also openly available through the expanding global market. Many countries operating Earth observation satellites or that have private businesses operating satellites are aware of the risk of these data being used against their security interests. Therefore, in many cases, regulations are adopted to control the acquisition of very high-resolution satellite data. As experience in the realm of arms control makes clear, the danger that satellite observations will be misused for purposes that threaten national security is a real concern in all cases. Although this problem seems less serious when it comes to addressing large-scale environmental problems, it would be a mistake to assume that there is no reason to be alert to concerns of this sort.

Such issues concerning data rights, security, and privacy have been dealt with for decades through what is commonly called Earth observation data policy. As difficult as it is to tackle these problems effectively, the overall message of this section is that we need to consider a transition from a continuing concern with coordination to a new awareness of the need for governance in the use of satellite observations to help in solving environmental problems. The activities of groups like GEO and CEOS, which focus on coordination among producers of Earth observation data, will continue to be important; they may well become increasingly important. But it will be necessary to supplement these efforts with an appropriate set of rules and practices addressing issues that arise in interactions between

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[10] See Howard (2015) for a report on the development of a collaboration involving SkyTruth, Oceana, and Google.

producers and users and, more specifically, in the contributions of satellite observations to the work of a range of issue-specific regimes addressing atmospheric, marine, and terrestrial problems. As a preliminary response to this need, efforts are taking place around the world to demonstrate the socioeconomic benefits of Earth observations. Space agencies and governments are faced with increasing pressure to plan space programs on evidence-based studies of anticipated societal benefits from investments in Earth observation systems. Such efforts should have in view the transition they want to achieve, which is to reach a world where satellite observations provide the data and information that meet the needs of policymakers through a set of rules and institutions that allow this to happen. The key to moving from technology driven R&D to societal benefits depends on whether or not this transition happens.

1.7 Architecture of the Book

The three substantive sections of this book contain a series of chapters that explore methodological issues relating to the development of policy-relevant satellite observations in a number of issue areas, the organization of agencies engaged in this work in both national and international settings, and the coordination and governance of Earth-observing systems to maximize their contributions to solving a range of environmental problems.

Part II on A Study on Methods for Assessing the Impact of Satellite Observations on Environmental Policy (Japan) describes the work of the Japanese Policy and Earth Observation Innovation Cycle (PEOIC) project. It includes a case study of the roles that satellite observations have played in supporting efforts to protect the stratospheric ozone layer. Part III turns to national and regional experiences in the U.S., Europe, and Asia. In addition to the experiences of NASA, ESA, and JAXA, it includes assessments of the UK Earth Observation Policy, the French Earth Observation Strategy, the Chinese Earth Observation Programme, and a specific case on greenhouse gas observation from space. Part IV deals with international initiatives and efforts to use satellite observations in coming to terms with issues of international significance. Specific topics include the experience and plans of the Organisation for Economic Co-operation and Development (OECD), Space Forum and GEOSS. Applications considered relate to the uses of satellite observations in dealing with matters of public health, the implementation of REDD +, and other global initiatives relating to the protection of forests and wetlands.

Part V on Prospects and Conclusions includes chapters that are more forward-looking regarding the roles of satellite observations in solving large-scale environmental problems. Chapter 16 focuses on future directions in institutional and organizational arrangements. It includes an analysis of whether there is a need to move toward the development of an arrangement that can be characterized as an “Earth observation regime complex” or an Earth observation component in various regime complexes dealing with large-scale atmospheric, marine, and terrestrial problems.

Chapter 17 is devoted to conclusions and recommendations. It addresses the principal conclusions emerging from a workshop of the PEOIC Advisory Board held in Tokyo, November 9–10, 2015, and seeks to draw on the cases discussed in the previous parts to extract lessons, and to articulate and refine a set of recommendations regarding ways to maximize the contributions of Earth observation systems both to policymaking in various issue areas and to addressing societal needs for environmental protection more generally.

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