Chapter 21: Remote Sensing in Environmental Management

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1. Abstract

Environmental management decisions depend on measurements: without measurement it is not known if some environmental parameter of interest is changing importantly, or how. For many environmental issues, it is important to have information that is spatially distributed, i.e., mapped. Remote sensing from space, the air, or on the ground can provide maps of many important environmental parameters – information that is not available in any other way. This chapter illustrates how remote sensing can be used to further our understanding of environmental problems and aid decision-making. The science and art of remote sensing are described with special attention paid to the issues of temporal and spatial scales as these determine applications of these geospatial technologies in environmental management. The chapter provides a set of concrete examples of the use of remote sensing in a diverse set of environmental applications, before concluding with suggested readings and a sample syllabus.
2. Introduction

In the business world there is a well-known adage regarding management: “you cannot manage what you do not measure”. Measurement is also paramount in environmental management: without measurement we do not know if some environmental parameter of interest is changing importantly – but what to measure, how, and how often are key questions. Many environmental management issues – for example, the effects of industrial activities on air and water quality in adjacent areas, or point source pollution events such as dilbit leaks from pipelines – cover relatively small scales in space and time and may best be measured *in situ* by going to the field and taking measurements, or collecting physical samples to bring back to the laboratory for subsequent analysis. In many cases, these methods are the only, or the best option. However, for many of the environmental challenges that face us today, Yogi Berra’s famous saying “you can learn a lot just by looking” rings true – especially if we “look” using technologically-advanced sensors flying on aircraft or Earth-orbiting satellites that view over much larger areas than those we can sample on the ground. This is “remote sensing”.

There are many environmental parameters that cannot be inferred using remote sensing, either because they occur below the surface (e.g., groundwater contamination), or because they cannot be observed at the necessary spatial or temporal scales, or with sufficient precision; however, there are many important issues that can *only* be addressed using remote sensing. For example, understanding phenomena that occur at regional to global scales often requires multiple, linked data sets at commensurate spatial scales and at seasonal or inter-annual intervals, for applications (drivers) as diverse as mapping and monitoring crop yields (climate, management); carbon sequestration in forest biomass (deforestation, degradation, management); algal blooms and ocean “dead zones” (agricultural nutrient and effluent run-
off); and sea level rise (ice sheet and glacier melting, thermal expansion of the oceans).

It has been said that remote sensing began with people climbing hills to get a better view of the landscape – and the location of opposing military forces. It remains true that many developments in remote sensing have been spurred by military and intelligence considerations: the field expanded rapidly during both World War II (using high altitude aerial photography) and the Cold War (using Earth-orbiting satellites for the first time) but has seen major advances more recently with the advent of digital imaging, powerful small computers, and the Internet. These three developments have allowed many more people to use this technology, or at least become aware of it (for example, through the Google Earth™ high resolution image browser).

This chapter will describe how remote sensing is used by environmental management practitioners and scientists to inform and aid in decision making; it is thus essential that the reader have a good understanding of remote sensing fundamentals and how these systems are constrained by physics, practicality, and cost, as well as the available sensing and computing technologies. The chapter therefore begins with a brief primer, then proceeds to examine the critical issue of scale and how this relates to our understanding of “environmental management”. It includes several case studies that illustrate the application of the technology and how it is used at a wide range of scales – from local to global – often together with other geospatial technologies: Geographical Information Systems and Global Positioning Systems. The chapter concludes with suggestions for further reading so that interested readers may easily locate more in-depth information. Key terms and concepts needed by anyone learning the basics of environmental remote sensing are italicized.
3. What is Remote Sensing?

3.1 Remote Sensing in a Nutshell

Remote sensing is the science and art of inferring information about surfaces or features that are distant from the observer, usually using measurements of reflected or emitted electromagnetic radiation (EMR). In the visible wavelengths – approximately 0.4 to 0.7 µm – our eyes can detect this radiation and we call it “light”. Remote sensing instruments are not limited to this narrow range and are capable of detecting EMR at both shorter (e.g., ultraviolet) and longer (e.g., near-infrared, thermal infrared, microwave, and radio) wavelengths. If the source of the detected EMR is natural – i.e., sunlight or the longer wavelength radiation emitted from the Earth’s surfaces or atmospheric elements – the remote sensing method is termed passive. If, on the other hand, the target surface is illuminated artificially through generation of EMR pulses as either radio waves (radar: radio detection and ranging) or laser light (lidar: light detection and ranging), then the method is termed active. Both active remote sensing methods work at night – no sunlight required – but only radar can penetrate clouds (the radio receiver in your iPod will still receive your favorite station, even if you are indoors: radio wavelength EMR can easily penetrate the walls of buildings; this is why ground-penetrating radar techniques can be used by police to locate buried cadavers).

Instruments (“sensors”) that sense reflected sunlight in a few regions of the EM spectrum (“bands”) are termed multispectral, while those that sense in a hundred or more narrow bands – thus allowing imaging spectroscopy – are termed hyperspectral. Images produced using light across the visible to near-infrared range are called panchromatic
(meaning “all colors”). Observations are usually made from above, with the remote sensing instrument located on a platform – balloon, helicopter, fixed-wing aircraft, or satellite – although ground-based methods with sensors located on towers or sometimes just a meter or two above the surface are also used, e.g., for the collection of ground reference data. The phrase “ground truth” should be avoided since it is impossible to collect data on the ground with zero error. Flying sensors on satellites provides the benefits in greater stability, regular repeat viewing, and global coverage.

All remote sensing systems sample the observed surfaces: these samples may be contiguous or overlap (in which case a 2-D image may be constructed from them), or they may be isolated (in which case linear profiles or grids of the point samples may be constructed; a 2-D image may only be built using interpolation between the grid points). Thus, while most remote sensing devices generate data that can be interpreted as an image, not all do – and it must never be assumed that the sampling is complete, or regular, or uniform, or consistent over time. Some imaging sensors scan surface-leaving EMR using rotating mirrors to sample a scan-line perpendicular to the platform’s track direction, while others sample in continuous strips using arrays of multiple detectors (e.g., CCD arrays; Fig. 21-1). Scanning systems usually have a lower signal-to-noise ratio because the dwell time (the period during which light falls on the detectors) is much shorter. Both types may observe the surface far away from nadir (straight down).

[Figure 21-1 here]

Remote sensing systems are characterized by an instantaneous field-of-view (IFOV, unit: degrees or radians): they measure target-leaving EMR from an area on the surface that is termed the ground-projected instantaneous field-of-view (GIFOV; the projection of the
instrument’s IFOV onto the surface). If the GIFOV of an imaging system is approximately 1 m $\pm$ 3 m, the system is termed “high resolution”; if it is between 5 m and 50 m it is termed “medium resolution”; and if it is larger than 50 m it is called “moderate resolution”. Panchromatic images can have higher spatial resolution because the light incident on the detector is not divided by into bands. We must also note that the surface under the GIFOV that is sampled – often called a pixel, (i.e., “picture element”) – is rarely composed of one kind of material and even a 1 m pixel may contain contributions from concrete, tarmac, grass, and painted metal (e.g., for a divided highway). Thus our samples might more accurately be called mixels, though – unfortunately – the term pixel has remained in common usage.

To compound matters, surfaces scatter light in different directions with respect to the source of illumination (usually the Sun). Very few natural surfaces exhibit specular reflection, where incident light scatters as if from a mirror; most scatter light in different directions, anisotropically. Anisotropy is the quality of exhibiting properties with different values when measured along axes in different directions (derived from the Greek $isos$ (equal) and $tropos$ (way), with the prefix $an$ indicating an exception). The function that describes this reflectance anisotropy is called the Bidirectional Reflectance Distribution Function (BRDF). Reflectance anisotropy arises from the 3-D structure of the surface and is partly owing to shadowing effects, though structures do not have to be large: even short grasses and bare soil surfaces demonstrate considerable anisotropy. This can be tested if the Sun is not close to zenith (overhead) by comparing digital photographs of a uniform lawn target taken in the solar and anti-solar directions. Even with auto-exposure, it will evident that the shadows cast by grass leaves darken the picture taken looking towards the Sun; with the Sun behind the viewer, shadows are hidden by the objects casting them. Even soil elements can contribute to strong BRDF effects (Fig. 21-2).
Both the sensor design and the platform on which the sensing device is mounted determine the eventual spatial and temporal sampling characteristics of the remote sensing system. For example, consider the case of an imaging Earth-observing satellite in a polar orbit around the Earth (orbital inclination of approximately 98° to the Equator) at an altitude of 705 km (438 mile) equipped with a sensor with a 185 km (115 mile) swath. This satellite will circle the globe every 98.9 minutes, imaging the entire globe every 16 days, except for the highest polar latitudes, with approximately 14.5 orbits per day, (Fig. 21-3). These parameters describe the joint National Aeronautics and Space Administration (NASA) / United States Geological Survey (USGS) Landsat 8 mission launched on February 11, 2013 (Irons et al., 2012), the latest in the Landsat series that has imaged the Earth’s land surfaces since 1972. As with all remote sensing systems, Landsat 8 has some limitations: from the revisit period it might seem feasible to construct a global 16-day image series; however, in the wavelengths in which the sensor observes, none are capable of penetrating the turbulent collections of water droplets that we call clouds. This importantly reduces the frequency with which comprehensive, wall-to-wall image series can be constructed.

In contrast to this imaging system, NASA’s Geoscience Laser Altimeter System (GLAS) operated on the ICESat satellite from January 2003 - October 2009. ICESat was in a near-circular, near-polar orbit (94° inclination) with an altitude of approximately 600 km (373 miles): not very different from the current Landsat 8 orbit. However, unlike Landsat, GLAS was neither imaging, nor passive. Instead of measuring reflected sunlight, GLAS fired green and near-infrared wavelength laser pulses towards the surface at regular intervals and sensed
the reflections, resulting in a linear sampling in the satellite’s along-track direction with a gap of about 170 m between each 70 m diameter shot (Fig. 21-4). The repeat period was eight days. This profiling, “remote-sensing-with-gaps” approach may seem odd to those used to imagery – but the ICESat/GLAS eight-day, 170 m sampling was more than sufficient to address the primary objective of the mission: to measure the elevation of Earth’s great ice sheets (Greenland, Antarctica) and thus track rates of change in ice sheet mass balance (Zwally et al., 2002). ICESat-2 is slated for launch in 2016; NASA is filling the six-year gap using aerial mapping with *Operation IceBridge*, a series of aircraft campaigns.

### 3.2 What Can Remote Sensing Data Tell Us?

There are a limited number of information domains that can be exploited in environmental remote sensing, viz.:

- **Spatial**: texture, pattern, hue, brightness, context, and range (distance)
- **Spectral**: variation with respect to wavelength
- **Directional**: variation with respect to viewing and illumination directions
- **Polarization**: variation with respect to horizontal or vertical polarization
- **Gravity**: variation with respect to gravity anomalies
- **Magnetism**: variation with respect to magnetic field strength and direction
- **Temporal**: variation in any other remotely-sensed quantity over time

Space precludes an in-depth discussion of all of these sources of information but note that the most common methods involve exploiting spectral, spatial, and temporal variations, while gravity has been successfully used only recently – and magnetism is rarely used. It is often
possible to exploit more than one of these sources of information simultaneously; for example, examining changes in ice sheet surface roughness (derived from analysis of surface BRDF) would exploit information in the directional and temporal domains.

Before examining other uses of remote sensing in environmental management it is worth noting that almost no environmental parameters are accessed directly but are inferred from measurements; and that these measurements are subject to error from sensor noise, orbital drift, attenuation by the atmosphere (aerosols, water vapor, ozone, clouds, rain); the inherent difficulty of extracting information at the appropriate spatial and temporal scales and combining it with other geospatial information – such as elevation data – in order to address the environmental problem at hand.

[Figure 21-4 here]

This is even true of high resolution imagery such as that seen in Google Earth™: although quite small features such as automobiles, houses, and trees may be resolved, it remains difficult to derive useful information from such images. For example, how to identify, count, and measure these objects? It is too time-consuming to perform these operations manually, object-by-object, except for very small study areas: an automated – or at least semi-automated – method is required. Fortunately, computer hardware, software, and inter-connectivity have improved rapidly over the last few decades, so that it is now possible to employ a diverse set of strategies for interpreting remote sensing imagery. Our marvelous brains can be used to obtain information on the target of interest by visually assessing hue, texture, context, shape, size, pattern, and shading – but can be supported by the use computers to implement methods that require many millions of calculations, often required when studying large areas. Clearly, it is not feasible to perform such calculations manually – if we hope to make it home for the holidays. It is now possible to transfer gigantic, multi-gigabyte
files around the world with ease and store a terabyte of imagery on a hard drive the size of a smartphone. Moreover, software developments in compression mean that vast swathes of highly detailed imagery can be navigated seamlessly: the interpretation toolset has never been so advanced. However, these technological advances are not a panacea: it is still up to the remote sensing expert to use her/his knowledge to analyze (take apart) and/or synthesize (put together) appropriate data sets for each application and to use her/his expertise, discretion, and intelligence in obtaining valid and useful results.

The impact of inexpensive yet powerful computing has had another important effect: it has enabled new and better uses of data from the historical archive. Although it might seem less exciting to work with older data, observing changes through time often yields much greater understanding than a snapshot. Many activities are driven by cost and remote sensing is no exception. This is why for regional and continental scale land cover and vegetation mapping, moderate resolution (1.1 km) imagery from the NOAA Advanced Very High Resolution Radiometer (AVHRR) and NASA’s MODIS was preferred over medium resolution (about 30 m) Landsat imagery: not only were Landsat images expensive at around $600 per 180 x 180 km scene but they required what was considered at the time to be hefty data storage and processing capabilities. Now, the entire Landsat record has been made freely available and new software has made it possible to process imagery consistently (e.g., the Landsat Ecosystem Disturbance Adaptive Processing System software, Masek et al., 2012). This has led to something of a resurgence in Landsat applications, especially for regional to continental scale studies that previously would have been too data-heavy and plagued by inconsistencies; the value of the lengthy Landsat archive is finally being realized (Kluger and Walsh 2013).
3.3 Environmental Management at Diverse Spatial and Temporal Scales

The remote sensing systems we have at our disposal are highly diverse – using reflected and emitted EMR; passive or active sources; perform imaging or profiling; cover the ultraviolet to microwave wavelengths, and may even exploit gravity (Song et al., 2013) – and observe at a wide range of spatial and time scales. To see how useful a particular remote sensing system is in addressing a specific environmental management issue it is useful to consider the following five characteristics:

1. Geographic coverage (site, local, regional, global)
2. Spatial resolution (grain)
3. Duration of the record (period of operation)
4. Frequency of observation (revisit time); and
5. The nature of the measurement (i.e., can the required information be inferred?).

Four of these five characteristics are related to scale. Even if the measurement type is completely able to supply the required information, to be useful it must also be available for a long enough period of time, at a suitable frequency, over a sufficiently large area, and with sufficient spatial detail for the area of interest.

The question of scale has implications for the way we regard environmental management itself. Dictionary.com defines “environmental management” quite broadly as “an attempt to control human impact on and interaction with the environment in order to preserve natural resources”. Some practitioners consider most “environmental management” issues to be local-, city-, or at most hinterland-scale problems, perhaps because of an implicit assumption that only problems occurring at these scales can be “managed”. However, we
should by now be painfully aware that mankind’s reach extends much further in both space and time: our collective environmental impact is global and has long-term consequences. For many of the truly momentous environmental problems of the 21st century – including the increase in net solar energy retained on Earth as a result of enhanced greenhouse and aerosol forcings and their proximate and indirect impacts (i.e., “global warming”) – it is imperative to observe at the global scale as well as locally. For example, it is now understood that important reductions in Arctic sea ice extent at the end of the northern hemisphere summer and the resulting increased heating of the Arctic Ocean and lower atmosphere are responsible for reductions in the thermal gradient from low to high latitudes and some important changes to atmospheric circulation patterns, including sudden stratospheric warmings, a weakened polar jet stream, and unusually strong and persistent high pressure blocking patterns, resulting in extreme weather patterns e.g., the 2011 Texas drought and the severe winter of 2012 in the United Kingdom. In short, unlike Las Vegas, what happens in the Arctic, does not stay in the Arctic (Francis et al., 2012). Although we have only been able to monitor sea ice extent using satellite remote sensing from 1979 (NASA, 2012a), this is long enough to allow us to appreciate the unexpected rapidity of the changes and see how far the minimum area has decreased from those of the preceding decades – and from the expectations of glaciologists and modelers (Fig. 21-5).

You have probably heard the saying “all politics is local” but is the same true for environmental management? Is it reasonable to contend that management of global environmental issues is just not feasible? After all, many years after the gravity of the problem was recognized we have failed spectacularly in attempts to negotiate a single international treaty to reduce the emissions and particulates that are causing rapid climate change. So, is it even possible to “manage” environmental problems at global scales? The pervading political climates of many of the major developed nations (including the USA, Canada, Australia, the
United Kingdom, and Japan) do not currently seem to be conducive to such an agreement and no binding environmental treaties have been established. However, it is not so very long ago that the Montreal Protocol on Substances that Deplete the Ozone Layer of the Vienna Convention for the Protection of the Ozone Layer entered into force (1 January 1989); and since then two ozone treaties have been ratified by 197 states and the European Union. International environmental management agreements have thus been shown to be possible and effective and others are in the pipeline (see REDD+ below). With respect to the relationship between global environmental treaties and remote sensing, it is worth noting that high quality, robust measurements are required, especially where there is the potential for large economic impacts of regulation (John R. Townshend, Keynote talk at the 4th Global Vegetation Workshop at the University of Montana, Missoula, June 16-19 2009). In the case of stratospheric ozone, measurements from NASA’s Total Ozone Mapping Spectrometer (TOMS) instrument on the Nimbus 7 satellite did record the loss of stratospheric ozone over Antarctica in 1985, but the values were so low that a screening algorithm flagged them as “bad values”, so they were ignored. This flagging was reasonable because atmospheric scientists did not think that such low values were possible; when it became clear that the ozone layer had in fact been severely depleted, the TOMS data were reanalyzed and found to confirm the losses seen in sun photometer readings. Three TOMS instruments were subsequently used to monitor the extent of the “hole” in the ozone layer, until 2005 when they were replaced by the Ozone Monitoring Instrument (OMI) on the Aqua satellite and the Ozone Mapping and Profiler Suite (OMPS) on the Suomi NPP satellite.

[Figure 21-5 here]
3.4 Google Earth: A Remote Sensing Panacea?

As an everyday example of the importance of scale, consider *Google Earth*. While appearing to non-specialists as a flexible and user-friendly tool for mapping the Earth’s diverse environments, it quickly becomes obvious that there are numerous environmental problems that it is unable to address, for two majors reasons. First, the imagery presented is mostly *pan-sharpened true color* imagery from commercial imaging satellites such as Digital Globe Inc.’s *QuickBird* series. It is called “true color” because the sensor red, green, and blue multispectral bands are used to produce an image in which natural colors are approximated. It is “pan-sharpened” because an algorithm is employed that uses higher spatial resolution (0.6 m) panchromatic imagery to increase the spatial variation of the 2.4 m resolution multispectral imagery. To understand this, imagine a 2.4 m true color image printed on a semi-transparent plastic sheet that is placed on top of a print of a 0.6 m grayscale image. The detail of the finer grayscale imagery is superimposed on the color imagery. Pan-sharpening achieves the same thing but using software. This provides a detailed and quite realistic pictorial representation of the landscape, so that when Google Earth was first released in 2005 there were suggestions that it would obviate the need for other remote sensing methods: anyone could now simply navigate to almost any location and determine the nature of the surface and its features. However, a moment’s thought reveals the fallacy of this thinking. First, we cannot easily measure many important environmental parameters – soil moisture, atmospheric pollution, aquifer levels, ice sheet surface melt, ice sheet mass balance, sea surface temperature, sea level, ocean salinity, amongst others – cannot be measured using pictorial representations, no matter how detailed. Second and perhaps more importantly, the temporal sampling provided is inadequate, owing to sparse data collection and the presence of clouds that obscure the surface. Google Earth imagery contains marked discontinuities at the boundaries of adjacent images (Fig. 21-6). These are owing to differing dates of acquisition, snow/no-snow
conditions, differing vegetation conditions (depending on whether the imagery was acquired at the beginning, peak, or end of the growing season); and to differing atmospheric conditions (haziness, variable aerosol optical depth, high thin cirrus clouds). Large discontinuities can also be caused by differences in sun elevation that occur with changes in season and latitude: the 3-D structure of the surface – soil, grass, shrubs, trees – results in scattering and shadowing effects that change the amount of light reflected to the sensor. Imagine the Sun is nearly overhead (zenith), as in summer time or at low latitudes: shadows will fall underneath the objects that cast them; contrast this with the situation where the Sun is near the horizon, as in winter or at high latitudes: shadows will then fall far from the objects casting them, effectively darkening imagery. These perturbing factors not only reduce consistency in the Google Earth database – they also affect lower resolution remote sensing – but can be addressed only partly by empirical corrections or modeling (e.g., of atmospheric scattering and absorption).

[Figure 21-6 here]

This does not mean that high spatial resolution imagery is not useful: clearly, there are many applications that can only be addressed using this kind of imagery, especially if interpretation or feature recognition can be partly automated. For example, the shadowing problem can be turned into an opportunity: although imagery is a 2-D representation of the surface, we can obtain information about 3-D structures (e.g., the locations, crown radii, and tree heights) through analysis of the patterns of sunlit and shaded features apparent in the imagery (e.g., the sunlit and shaded parts of tree or shrub crowns and the shadows cast by them). Provided the canopy is not too dense, tree number density, crown radii distributions, tree heights, and aboveground biomass estimates can be rapidly obtained using algorithms
such as *CANopy Analysis using Panchromatic Imagery* (CANAPI; Chopping, 2011, Fig. 21-7). This reminds us yet again that one person’s noise can be another’s signal.

[Figure 21-7 here]