Remote Sensing and Mapping

6

INTRODUCTION

Access to coastal ecosystems such as mangroves, salt marshes, and seagrasses for field surveys can be very expensive, difficult, and/or hazardous. In addition, they do not lend themselves well to conventional manual sampling regimes, are so large they may not be able to be studied within project time constraints, or are in need of a change analysis with no previous on-site sampling having been conducted. Given these impediments, remote sensing can provide unique and valuable information on coastal vegetation structure and areal coverage that could not easily be obtained otherwise.

For the purposes of measuring blue carbon, remote sensing is vital for determining ecosystem extent, stratification and plot design, biomass measurements, and analyzing land use and carbon stock change over time for national carbon accounting. Remotely sensed measurements can be made at different spatial resolutions and, depending on the sensor, can identify various biophysical and structural characteristics of the coastal vegetation communities. Also, once in service, satellites are usually a continuous source of information for many years, providing decade long and large scale monitoring of natural and man-made changes in ecosystems.

Here we provided guidelines on the possibilities and limitations of different remote sensing approaches. This chapter is not intended to describe how to carry out remote sensing. We recommend that experts be brought into the project to aid with the actual data collection and analysis. Instead, the goal of this chapter is to provide information so that the reader is familiar enough with the procedures and options to communicate their needs more effectively to remote sensing experts.

BASICS OF REMOTE SENSING

Here we briefly describe the basic concepts of remote sensing; there are numerous books and reviews devoted to this topic that provide more detailed background information and possible applications (Green *et al*. 2000; Klemas 2010; Kuenzer *et al*. 2011; Giri 2012; Rees & Rees 2012).

Passive vs. Active Techniques

Remote sensing systems can be categorized as either passive or active, depending on the source of the energy being detected. Passive sensors record reflected sunlight (optical) and emitted temperature (thermal) from the Earth's surface. Optical and thermal imagery are currently the most commonly available datasets for monitoring coastal ecosystems. Optical imagery is easy to use and interpret but images can be hindered due to persistent cloud cover, common in tropical regions where many of these ecosystems are located. By contrast, active systems transmit their own energy pulses and measure the time of travel and intensity of the pulse that gets reflected from the surface back to the sensor. Active remote sensing can be more expensive but it can penetrate clouds and thick canopies thus providing more information.

Each sensor works in specific bands of the light spectrum (e.g., colors) to create images. Bands are a set of similar wavelengths or frequencies. For example, visible light is composed of blue, green, and red bands of the electromagnetic spectrum; other bands include radio, microwaves (radar), and infrared waves. Visible (blue, green, and red), near-infrared (NIR), and microwaves are primarily used in coastal vegetation studies.

Both active and passive techniques offer unique advantages and disadvantages (**Table 6.1**). Combining data from both techniques is a viable option and can often offer unique information that is not detectable through one method alone.

Table 6.1 Advantages and disadvantages of remote sensing techniques.

	ADVANTAGES	DISADVANTAGES
Passive	Data is usually easier to interpret as it produces images similar to a camera; the reflection from different spectral bands can be used to classify land cover types and vegetative species; vegetative health can be inferred using near-infrared and infrared reflections.	Requires sunlight for imaging; changes in season need to be considered (polar regions with large variation in length of day light by season, for example); cloud cover can limit imaging capabilities because clouds scatter and absorb light (equatorial regions that often have persistent cloud cover year round).
Active	Transmit their own energy pulses that are often weather- and daylight independent; possible to directly compare images done using the same parameters (mode, incidence angle, polarization and processing level).	Can be more expensive; image analysis is more difficult and can differ dramatically depending on the parameters used.

Resolution

In remote sensing, the fundamental unit of data collection is known as a pixel and is defined in terms of ground dimensions. It is usually presented as a single value that represents the length of one side of a square. For example, a spatial resolution of 30 meters means that one pixel represents an area 30 meters by 30 meters on the ground. The resolution of an image is an indication of its potential detail, where the smaller the pixel the finer the detail (**Fig. 6.1**). In other words, 30 meters resolution data could identify any earthly feature that is 30 meters by 30 meters (useful for mapping ecosystem extent). Anything smaller than 30 meters by 30 meters requires a coarser resolution (10-meter resolution can be used to monitor encroachment by agriculture). We recommend starting with higher-resolution satellite

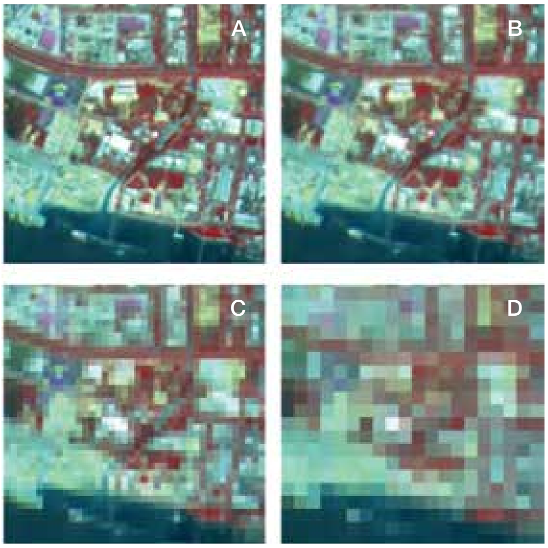

Figure 6.1 Effect of pixel size on the visual appearance of an area.
(A) 10 m pixel size,
(B) 20 m pixel size,
(C) 40 m pixel size,
(D) 80 m pixel size
(© Centre for Remote Imaging, Sensing & Processing)

imaging to obtain a general view of the ecosystem extent and overall health. Then follow with higher-resolution imaging just for areas of particular interest. In most cases, freely available 30 meter resolution imaging will be sufficient for blue carbon ecosystem mapping.

AVAILABLE DATA SETS

Satellites equipped with instruments for monitoring the earth's surface have been launched into orbit by a host of Nations since the 1970s creating a huge archive of data. However, this wealth of data can be overwhelming and not all data are freely available to the public. In addition to the satellite data, aerial photography has also been used for coastal monitoring, especially after natural or anthropogenic disasters (such as hurricanes or oil spills), but those data sets are very limited, research oriented, and not readily available. Currently Landsat, MODIS, SRTM, PALSAR and ICESat/GLAS datasets are appropriate and freely available for the operational purpose of coastal ecosystem studies at global scales. All are described in detail below.

Landsat

Description: Landsat is the most popular and longest running series of civilian Earth-observing satellites. The first Landsat was launched in 1972, and the latest satellite in the series, Landsat-8, launched in 2013. Landsat data is by far the most widely used dataset to map and monitor tidal wetlands. All missions carried multispectral sensors operating from the visible to the near infrared (NIR) portion of electromagnetic spectrum. Landsat 8 was augmented with a new band (true-blue) to facilitate measurements in coastal waters. It is a passive sensor and provides both optical (30 m pixel size) and thermal (60 m pixel size) imagery. Optical bands of this satellite record blue, green, red, near-infrared, and mid-infrared regions of the reflected sunlight. Different combinations of these bands are used to detect vegetation health, seasonal variability, leaf area index, land cover change, deforestation, and afforestation. Detailed information on Landsat is available on the following web site: http://landsat.usgs.gov/.

Figure 6.2 Example image from LANDSAT-8 data (© NASA)

Where to find the data: Landsat data can be viewed and downloaded from multiple places, but the most reliable place is the US Geological Survey (USGS) web portal. The Landsat Look Viewer site (http://landsatlook.usgs.gov/) is for viewing data availability and downloading a pseudo-color jpeg image. The GloVis site (http://glovis.usgs.gov/) is for browsing and downloading individual images. For searching and downloading multiple images of an area covering all available imagery, the EarthExplorer site (http://earthexplorer.usgs.gov/) is appropriate. All of these sites are intuitive, self-explanatory, and they make browsing and downloading data easy.

The EarthExplorer site allows a user to filter data based on different criteria, such as range of dates, percentage of cloud cover in an image, different Landsat satellites, etc.

Potential applications: For blue carbon purposes, Landsat images can be used to produce vegetation index (VI) products, which indicate the presence/absence and abundance of vegetation. A detailed review of different VIs and their usage is given in Bannari *et al*., (1995). Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are the two most robust and widely used Vis; however, each has its own limitations. NDVI values easily saturate at moderate to high vegetation density leading to underestimates in very dense ecosystems. EVI does not saturate, but the blue band reflectance can add significant noise due to the atmospheric scattering of blue light. Recent studies have shown that for coastal ecosystems, a modified EVI, called EVI2, is better suited to provide accurate estimates of vegetation intensity. Unlike NDVI, EVI2 does not saturate, and due to the lack of the blue band, it does not add significant noise.

The VI data calculated from Landsat imagery can estimate intensity of vegetation cover in coastal mangrove, tidal salt marsh, and in some seagrass ecosystems. Higher VI values indicate denser vegetation with higher leaf area index. Correlating the VI values to field-observed vegetation density produces spatially explicit maps of biomass at 30 meter pixel size for the entire area of study.

MODIS

Description: NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor aboard NASA's Terra and Aqua satellites. Terra was launched in 1999 and orbits around the Earth from north to south crossing the equator in the morning. Aqua was launched in 2002; it passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS view Earth's entire surface every 1 to 2 days, acquiring data in 36 spectral bands, at a spatial resolution of 250 m, 500 m, and 1 km. Detailed descriptions about MODIS can be found in NASA's http://modis.gsfc.nasa.gov/ website.

Where to find the data: MODIS data of different processing and product levels can be downloaded from NASA's MODIS websites (such as Land Processes Distributed Active Archive Center LPDAAC site: https://lpdaac.usgs.gov/products/modis_products_table). However, each MODIS data granule covers a vast area, which may cover too large an area compared to what is needed for blue carbon projects. A more suitable place to download areal subsets of MODIS data is NASA's Distributed Active Archive Center (DAAC) at Oak Ridge National Laboratory (ORNL) (http://daac.ornl.gov/MODIS/). This site is intuitive and it provides step-by-step instructions for downloading data. Another advantage of using this site is that the data can be downloaded as geo-tiff files in the latitude-longitude format, which can be easily opened by any image processing or geographic information system (GIS) software program.

Potential applications: Similar to the Landsat data, VI images from MODIS data can be used to identify vegetation density of coastal ecosystems, and when correlated with biomass of field plots, these data can be used to map large areas of biomass. Another important use of MODIS data is the change detection of coastal areas. MODIS sensors have collected data from global land and ocean surfaces since 2000, making daily time series data available for studying changes in the vegetation cover of coastal areas. Since the highest spatial resolution of MODIS is 250 m, EVI2 index images produced from these datasets are appropriate tools

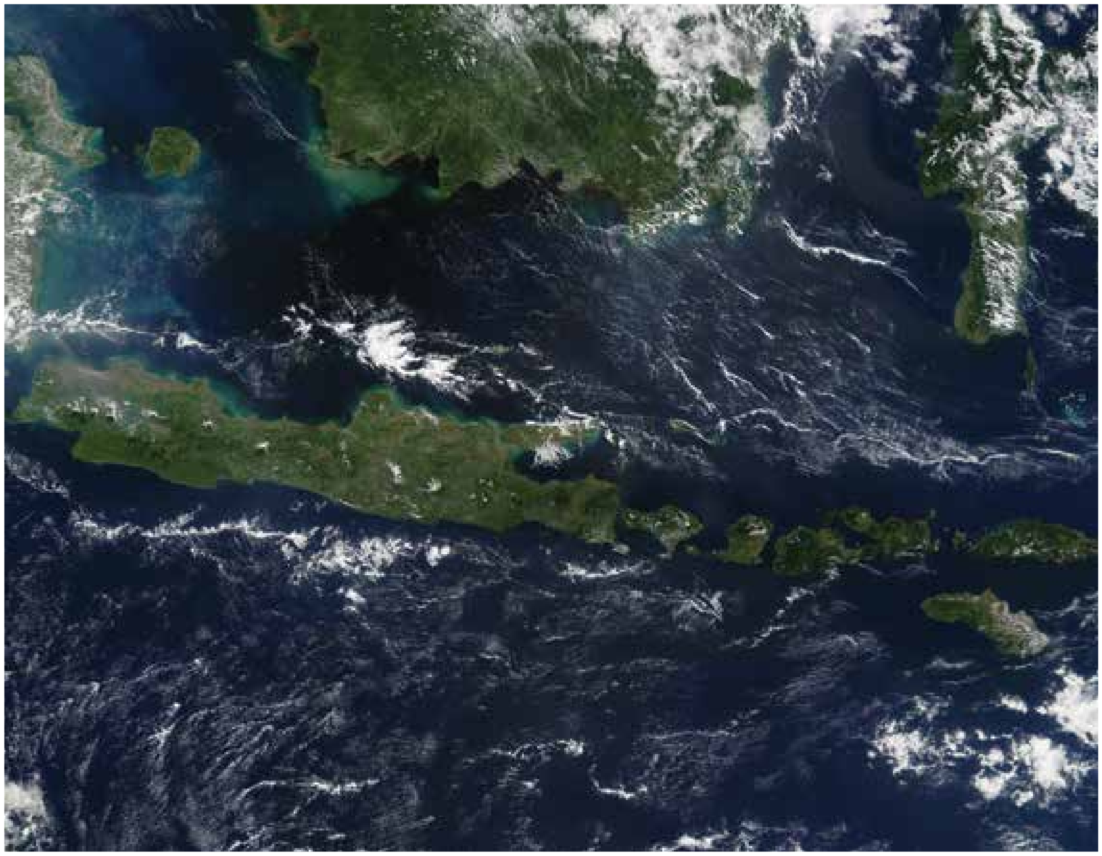

Figure 6.3 Example image from MODIS data (© NASA)

for studying temporal changes of coastal mangroves and salt marshes. A detailed method for using MODIS data to quantify mangrove destruction of a large area is given in Rahman *et al*. (2013).

SRTM

Description: The Shuttle Radar Topography Mission (SRTM) was flown aboard the space shuttle Endeavour February 11–22, 2000. Single-pass radar interferometry was used for these datasets, which acquired two signals at the same time by using two different radar antennas. An antenna located on board the space shuttle collected one dataset; the other was collected by an antenna located at the end of a 60 meter mast that extended from the shuttle. Differences between the two signals allowed for the calculation of surface elevation. The processed data are available in 1-arc-second (approximately 30 meter) resolution elevation only for the United States and 3-arc-second (approximately 90 meter) resolution elevation for global coverage.

Where to find the data: USGS EarthExplorer (http://earthexplorer.usgs.gov/) sites provide the SRTM data for the U.S. Global coverage of SRTM data can be downloaded from the Consultative Group on International Agricultural Research (CGIAR) Consortium for Spatial Information (http://srtm.csi.cgiar.org/) website. NASA has released version 3 of the SRTM data, which exhibits well-defined water bodies and coastlines. The version 2 directory also contains the vector coastline mask derived by National Geospatial Intelligence Agency, called the SRTM Water Body Data (SWBD), in ESRI Shapefile format. The data may be obtained through the http://dds.cr.usgs.gov/srtm/ website. All versions are distributed with

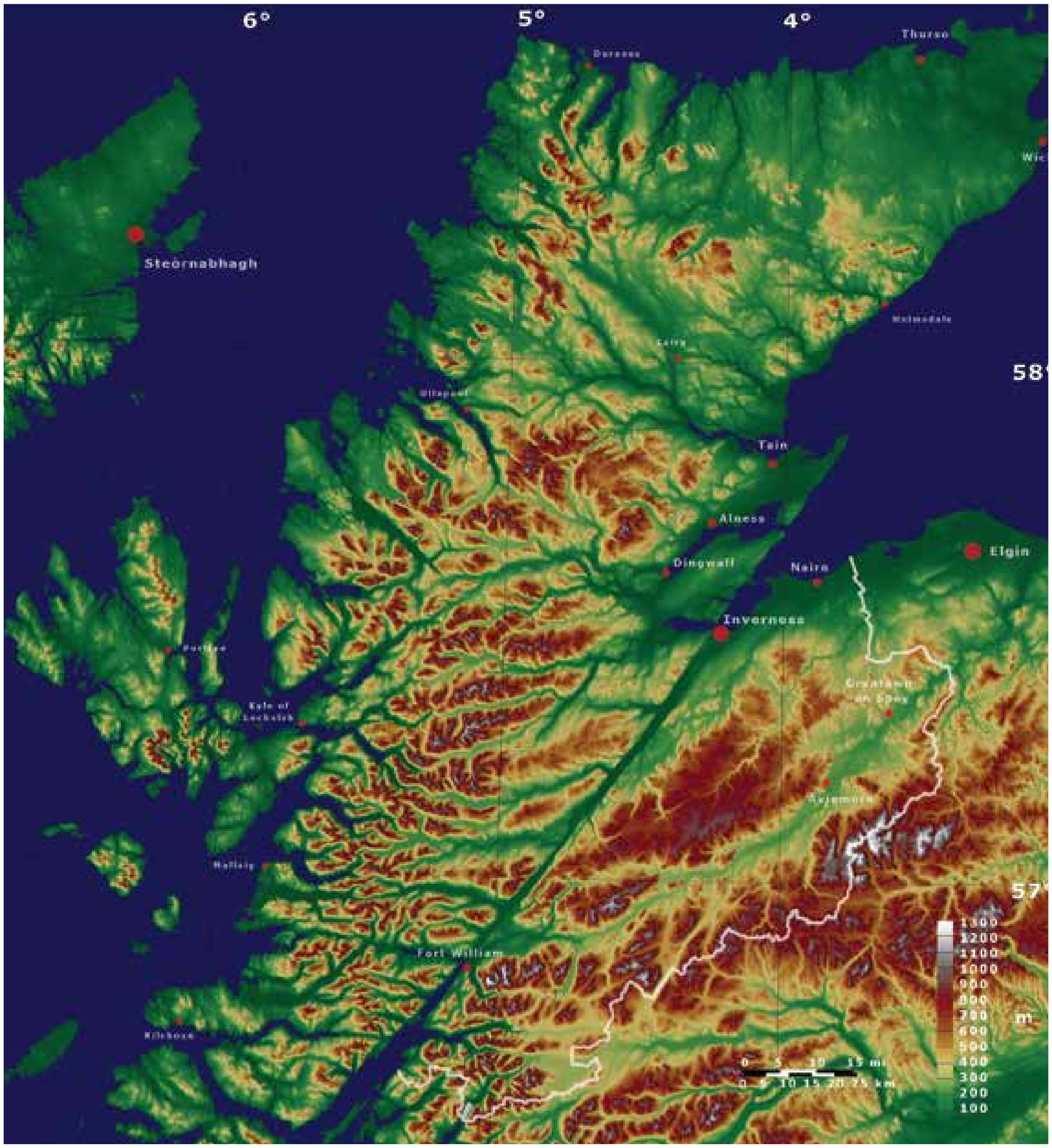

Figure 6.4 Example of a falsely colored image from SRTM elevation data (© PawelS Wikimedia Commons)

the appropriate metadata documentation.

Potential applications: The application of SRTM data for blue carbon estimation is mainly to map watersheds and mangrove environments. Since mangroves grow at sea level, the SRTM data can potentially provide vegetation heights of mangrove stands. Although the data are from 2000, mangroves grow very slowly and these data can still be utilized to assess the vegetation height of mangrove stands that have remained undisturbed. Using allometric equations that correlate aboveground biomass with canopy height and diameter-at-breast height (dbh) measurements, SRTM data can provide biomass of mangrove stands. Data from the areas that have been disturbed or deforested since 2000 can be used to estimate the loss of above ground biomass (Simard *et al*. 2006; Simard *et al.* 2008).

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PALSAR

Description: The Japan Aerospace Exploration Agency's (JAXA) Phased Array L-band Synthetic Aperture Radar (PALSAR) produced data from 2006-2011, and a new sensor was launched in 2014. PALSAR is an active microwave sensor used to achieve cloud-free and day-and-night land observation. It is a fully polarimetric instrument, meaning it measures the polarization of transverse electromagnetic waves. PALSAR can emit and receive horizontal (H) or vertical (V) transverse waves in various combinations, fine-beam mode with single polarization of HH (horizontal transmitting, horizontal receiving) or VV (vertical transmitting, vertical receiving), dual polarization (HH+HV or VV+VH), or full polarimetry (HH+HV+VH+VV). The scattering patterns measured from the different polarizations provide information to the structure of the vegetation. It also features wide-swath ScanSAR mode, with single polarization (HH or VV). Spatial resolution of the fine-beam mode HH or VV polarization is approximately 12 m, and that of the ScanSAR mode is 100 m.

Where to find the data: PALSAR data can be downloaded from the Alaska Satellite Facility (ASF) https://ursa.asfdaac.alaska.edu/cgi-bin/login/guest/ website. Data can be imported using ASF MapReady software to produce geo-tiff format images. Background noise that may lower the quality of the image can be removed using Lee filter, and the images can be mosaicked for each polarization (HH with HH, HV with HV).

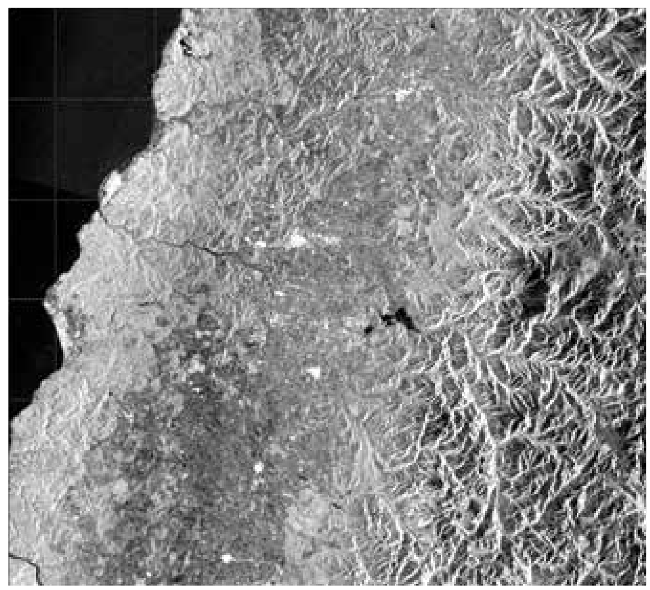

Figure 6.5 Example Image from PALSAR data (© JAXA)

Potential applications: Fine-beam PALSAR data can be used to make digital elevation maps (DEM), extract topography data, or estimate biomass of coastal ecosystems. In order to extract the coastal vegetation information, we suggest a Principal Component Analysis (PCA) be performed. The first step is to create a Radar Forest Degradation Index (RFDI) from the HH and VV images. The RFDI is able to assess the strength of double-bounce scattering, which is the scattering of radar waves off a horizontal (ground) and a vertical (grass, tree trunks, etc.) surface. This double-bounce scattering has the potential to differentiate between distinct types of vegetation. Next, the RFDI, HV, and HH layers are stacked to create a three-band image. Studies have shown that PCA-1 can clearly distinguish between water and vegetation, thus allowing mapping of coastal deforestation (mainly of mangroves). PCA-2 can potentially be used to estimate vegetation height at ~12 m resolution. This can be combined with field data to estimate biomass of coastal ecosystems.

A document explaining ALOS Palsar data from JAXA is available at www.eorc.jaxa.jp/ALOS/en/doc/fdata/ALOS_HB_RevC_EN.pdf. Section 7 of that document has detailed description of PALSAR data, including the steps required to process data at different levels according to the user requirement. JAXA has also released global mosaics of ALOS/PALSAR data that can be found at www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm and can be used to monitor land use changes as well as biomass.

ICESat/GLAS

Description: Launched on 12 January 2003, after seven years in orbit and 18 laser-operations campaigns, the Ice, Cloud, and land Elevation Satellite (ICESat)'s science mission ended due to the failure of its primary instrument. The main objective of the Geoscience Laser Altimeter System (GLAS) instrument was to measure ice sheet elevations and changes in elevation through time. Secondary objectives included measurement of cloud and aerosol height profiles, land elevation and vegetation cover, and sea ice thickness. Lidar datasets from ICEsat/GLAS (Geoscience altimeter system) contain global data points collected over a period of seven years (from 2003 to 2009).

Where to find the data: The National Snow and Ice Data Center (NSIDC) distributes 15 Level-1 and Level-2 data products from the GLAS instrument that was aboard the ICESat satellite. For information please consult the NSIDC website http://nsidc.org/data/icesat/data.html.

Potential application: GLAS data allows estimate of canopy height with accuracies of a few meters (Simard *et al*., 2011; Simard *et al*., 2008; Fatoyinbo & Simard 2012). The new ICESat-2 is set to launch in 2016, given favorable conditions the data produced may provide more dense spatial coverage.

It is important to note that there are many other data sets that are not highlighted here. Data from European satellites, such as SPOT, have also been used for coastal ecosystem studies, but these data are of limited access. Image data from commercially available satellites, such as IKONOS, GeoEye, and QuickBird have also been applied to study the coastal ecosystems, but these data are of limited spatial and temporal scopes, and not freely available. Sonar data are mainly useful in the mapping of seagrass meadows regardless of water clarity, but are very rarely available. The applications, limitations, and potentials of sonar data for blue carbon estimation are still in the active research phase and not yet operational on a global scale.

Developing clear goals and working with a trusted remote sensing expert to determine which sensor and method of data analysis is most appropriate and practical for your project will ensure that the end product meets the project goals (Chapter 2: Conceptualizing the Project and Developing a Field Measurement Plan).

DATA ACQUISITION AND PROCESSING

Once the data type, resolution, and scale needed for your project have been determined, the resulting images will need to be processed (**Fig. 6.6**). This should be done by a remote sensing specialist, but the extent of processing that has been done to an image should be documented in the image's metadata (Chapter 7: Data Management).

Remote sensing data sets are extensive, span decades, and most require expertise and professional software to download and analyze; therefore, it can take 10 to 32 weeks (realistically) to implement a project. This time frame largely depends on an organization's experience, if any additional images had to be requested beyond the freely available archives, and/or the number of steps that have been provided by others (e.g., data providers, software programs). The appeal of raw data, which may be faster to obtain, is the ability to apply one's own calibration/navigation formulae to it, in contrast to using standard algorithms from some data provider. The disadvantage of this approach is that the user must possess the hardware, software, and personnel resources to perform these steps before the data is usable.

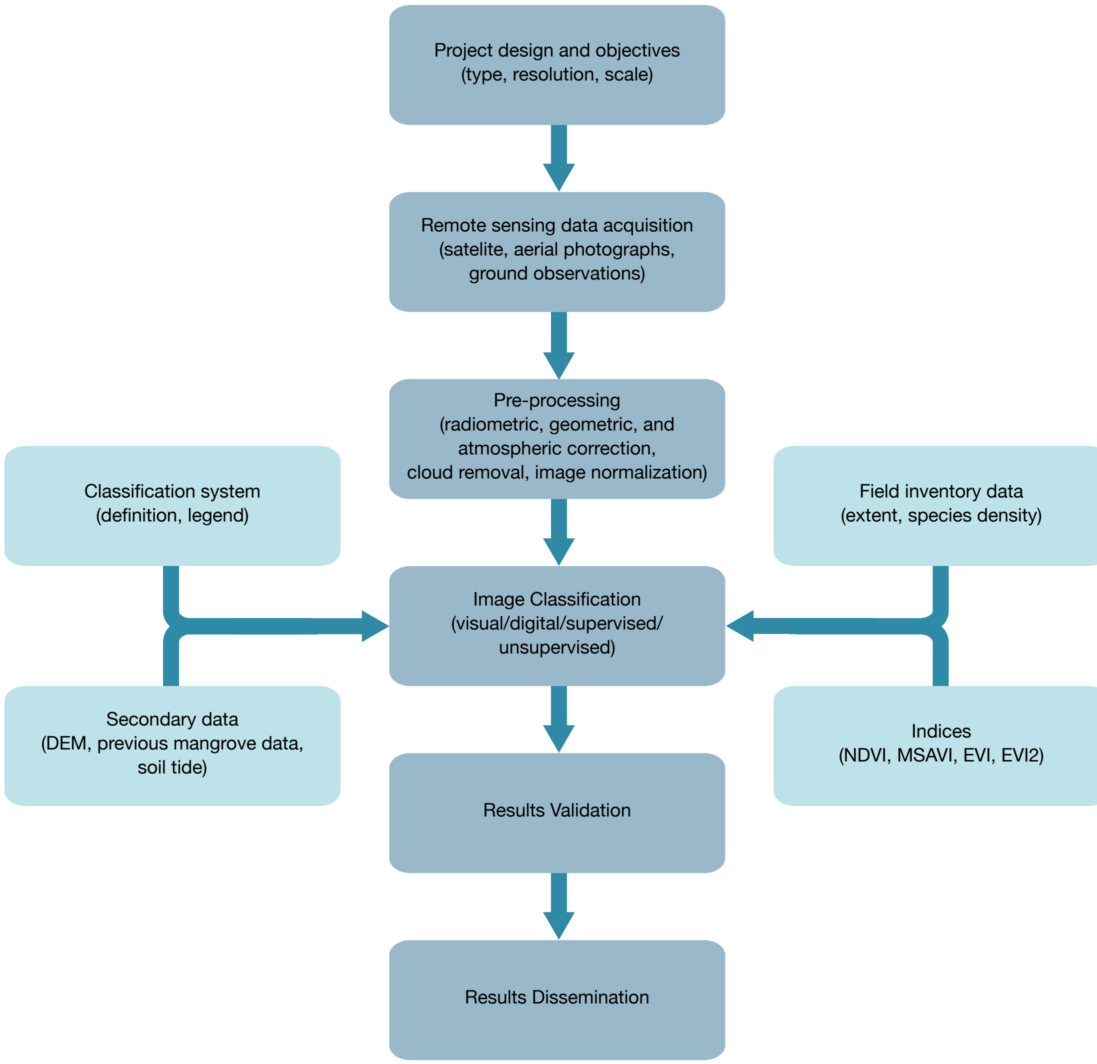

Figure 6.6 Steps for processing remotly sensed images

Pre-processing of remotely sensed data involves correction of distortion, degradation, and noise introduced during the imaging process and produces a corrected image removing these anomolies. Typically, images will need to be processed to correct radiometric (haze and atmospheric scattering) and geometric (Earth's rotation and satelite location) issues. Persistant cloud cover is a major issue in most of the tropical regions where blue carbon ecosystems exist. When Radar data is not available or is too expensive, cloud free pictures can be assembled using individual images collected over time. The time frame used depends on the rate of change. For example, if the ecosystem being mapped is relatively stable, then it might be possible to piece together images spanning serval years without loosing any infomration. However, if the ecosystem is being distroyed at a rate of 10% every 5 years you might want to limit your search to images produced in the last year to create a current map that is as accurate as possible. Image normalization is needed to analyzse multi-temporal data or data covering large areas.

Once the images are acquired and pre-processed to create a usable image, the image will need futher processing to extract the project relevant data. Processing involves classification of the image components (i.e., trees, shrubs, water, mud flats, etc.) and may also include data on vegetative species composition, density, and biomass. Any additional information, such as known vegetation cover, density, species composition, management history, and past disturbances will be useful during image classification. Secondary data such as tide information, elevation maps, published and unpublished ecosystem maps and reports are also highly beneficial. The United Nation's Land Cover Classificaiton System (LCCS) is the recommended standard for defining mapping classes (Di Gregorio & Jansen 2000; Di Gregorio 2005). Validation should be performed using higher resolution remote sensing data or ground truthed data.

POTENTIAL USES OF REMOTELY SENSED DATA

Mapping

Habitat mapping and classification by means of remote sensing are performed by correlating a cluster of numerical pixel values with verified features, such as vegetative cover, open water, tidal flats, inland marshes, forested wetlands, or bare soil type. Remote sensing techniques coupled with on the ground validation and modeling has led to the development of spectral signatures that can be used to map ecosystem extent, type, and in some cases provide information at the species level (see Appendix E for a general protocol for mapping mangroves and salt marshes). However, challenges such as distinguishing coastal wetland vegetation from the neighboring inland vegetation, accounting for areas where the vegetation is sparse, and routine detection of individual species remain difficult to overcome (Heumann 2011).

There are many techniques for creating coastal ecosystem maps. For example, mangroves and marshes are found within the intertidal range (up to two meters above sea level); thus it is possible to use ground elevation and tidal range data to determine the potential location of these systems. However, accurate DEM data at large scales are rare, so your area of interest may require additional local knowledge to design the proper limits. Another technique that can be employed is to map tidal extent using a time-series of images that coincide with high and low tide (Murray *et al*. 2012). Synthetic aperture radar (SAR) data have been increasingly used for mapping, and monitoring at local and regional scales. SAR is particularly useful as it can penetrate the forest canopy and interact with larger vegetative components (branches, trunks and above ground roots) (Lucas *et al*. 2007a; Souza-Filho *et al*. 2011; Nascimento Jr *et al*. 2013). SAR data has also been used to identify mangrove forest structural parameters such tree density, basal area, height, biomass, age distribution, and forest structure (Aschbacher *et al*. 1995; Mougin *et al*. 1999; Held *et al*. 2003). Most recently, UNEP-WCMC updated the "World Atlas of Mangroves" in 2010 (Spalding *et al*. 2010), and Giri *et al*. (2011) generated an updated global mangrove baseline map primarily using Landsat data (**Fig. 6.7**). UNEP-WCMC has also accumulated global observations of salt marsh distribution and extent; that map should be available fall of 2014.

Seagrasses is particularly difficult to map using remote sensing. The water turbidity and color, sun glint, and the epiphytes that cover the blades of grass may dilute the spectral reflectance signal of sea grasses and hinder the instruments ability to “see” through the water. They are also found to grow in a wide range of densities which can affect the return signal to the sensors. Under clear water conditions, remote sensing images have been able to detect a wide variety of seagrass densities ranging from < 25% to 100% cover (Roelfsema *et al*. 2009; Pu *et al*. 2012) and, when combined with local knowledge, aerial photography, and observations in the field, rough outlines of seagrass extent can be successfully mapped.

Figure 6.7 Global distribution of mangroves prepared using Landsat satellite data at 30 m spatial resolution of year 2000 (Giri *et al*. 2011)

Canopy Height and Biomass

Besides mapping ecosystem extent, remote sensing can be used to map biomass that can later be used to estimate the amount of carbon in the aboveground vegetative pool. Biomass is mapped based on the species composition and height, and several datasets are available and serve this purpose. GLAS data allows estimate of canopy height with accuracies of a few meters (Simard *et al*. 2008; Simard *et al*. 2011; Fatoyinbo & Simard 2013). The new spaceborne interferometric system launched by the German Space Agency: TanDEM-X could potentially be used to measure height and biomass within salt marshes and canopy height in mangrove forests. In February 2000, STS-109 successfully fulfilled its SRTM mission (Shuttle Radar Topography Mission) and gathered topographic data over 80% of the land surfaces of the Earth as well as radar backscatter (HH, VV polarization) and interferometric coherence. SRTM elevation measurements can be used to estimate canopy height with an accuracy of 2–4 meters but unfortunately this makes it insufficient for mapping the height of salt marshes (Simard *et al*. 2012). Space Shuttle Endeavour was equipped with two radar antennas used interference patterns between the two radar signals to derive terrain height.

Baseline maps of mangrove height and biomass have been generated for several regions, including Africa (Fatoyinbo *et al*. 2008; Fatoyinbo & Simard 2013), Florida (Simard *et al*. 2006) and Colombia (Simard *et al*., 2009). A global map should be published in 2015. When used in combination with SAR data, the height maps not only improve the accuracy of biomass estimates, but also can be used to map mangrove species (Held *et al*. 2003; Lucas *et al*. 2007b). For example, Held and Ticehurst (2003) and Lucas *et al*. (2007) noted that where extensive root systems occurred (e.g., in mangroves dominated by *Rhizophora* species), a subsequent decrease in the backscatter occurs in proportion to increases in biomass. Such decreases typically occur once mangroves have attained a height threshold, with Lucas *et al*., (2007) suggesting 10 meters as an appropriate threshold. By exploiting these observed characteristics of mangroves, new mangrove mapping techniques have been developed that can differentiate between mangrove type (with/without aboveground roots) and species.

Monitoring Ecosystem Change

Monitoring impacts from blue carbon ecosystem restoration/conservation efforts and rates of degradation/deforestation from land use change is valuable for national carbon accounting programs and for monitoring climate mitigation and adaptation strategies. However, despite their importance, no systematic maps of coastal ecosystem change at regional to global scales currently exist.

For regional assessments, the use of moderate (< 30 meters) spatial resolution optical (e.g., Landsat) data has been successfully demonstrated and is generally recommended (Spalding *et al*. 1997; Giri *et al*. 2011). However, routine detection of change has proved difficult, partly because persistent cloud cover in the tropics prevents regular observation. In some cases, this has been overcome using SAR (e.g., Souza-Filho & Paradella 2003; Nascimento Jr *et al*. 2013). SAR can be used to detect change within and away from existing baselines (when baseline maps are available), and that data can further be complimented with corresponding biomass data. Exploiting the dense time-series of Landsat sensor data, including data provided by the recently launched Landsat-8, can also increase the level of change detected.

Carbon Estimations

Combining maps of ecosystem extent, species, and biomass with average carbon stock values derived from field data enables national, regional, and global estimates of carbon stocks (DeFries *et al*. 2007). Similarly, this data can then be used to monitor changes to the carbon stock and estimate carbon emissions (emitted or removed) based on degradation, conservation, and restoration of blue carbon ecosystems. Historic remote sensing data can be used to construct a history of carbon stocks and emissions that can be used for reference scenarios (Gibbs *et al*. 2007). This technique has been done with mangroves, but research into expanding the technique to include salt marshes and seagrasses is a high priority.

Numerous books and reviews devoted to creating carbon stock maps and measuring carbon emissions using remote sensing are available and can provide more detailed background information and methods.

VALIDATING WITH FIELD DATA

To make use of remote sensing data for inventories, and in particular to relate land cover to land use, it is good practice to complement the remotely sensed data with ground reference data (often called ground truth data). Land uses that are rapidly changing or that are easily misclassified should be more intensively ground-truthed than other areas, preferably from actual ground surveys collected independently. High-resolution aerial photographs or satellite imagery may also be useful.

Parameters that can currently be measured remotely are presence and absence of the ecosystem, species, leaf area and canopy cover, canopy height, and vegetative biomass. Therefore, similar parameters should be measured for ground truthing. Ideally, each field plot should encompass a similar area to that of a single pixel and span the entire range of the ecosystems macro-structural attributes. In wetland ecology, typical plots are in the orders of meters and may not be appropriate for remote sensing applications. Instead, plots of 1 hectare would enable accurate characterization of canopy heterogeneity and provide excellent calibration for remote sensing measurements. If that is not feasible, plot sizes of a few tens of meters can be used if they are representative of the local (hectare scale) structure.

The opportunity exists to involve local communities in the collection of ground truthed data. While significant progress has been made toward building capacity and communicating the importance of blue carbon ecosystems to local, national, and international decision makers, these efforts are still in their infancy and continued work is needed to ensure the ongoing success and implementation of these and other related projects. Opportunities for field work increase relationships within the community and create a sense of ownership that stimulates continued support for conservation and restoration efforts long after the study has been completed.

CONCLUSION

When remote sensing systems are used wisely, including complementary combinations of different satellite and airborne sensors, they can provide data that enhances the research and management of coastal ecosystems. Each type of sensor has its own unique measurement in which to record subtle and obvious changes to coastal environments. Therefore, combining data from various sensors have and will continue to provide pertinent information regarding the biophysical and structural components of the coastal landscapes. One of the key advantages of remote sensors is that they can monitor and assess long-term trends and short-term changes of vegetation and hydrology faster, more completely and at lower cost per unit area than field or ship surveys alone (Klemas 2013).