One Earth

Gold Standard for the Global Goals
1 ton of CO_2 offset

CellPress OPEN ACCESS

Primer

Applications in Remote Sensing to Forest Ecology and Management

Alex M. Lechner,[1,*] Giles M. Foody,[2] and Doreen S. Boyd[2]
[1]School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Jalan Broga, 43500 Semenyih, Selangor, Malaysia
[2]School of Geography, University of Nottingham, University Park, Nottingham NG7 2RD, UK
*Correspondence: alex.lechner@nottingham.edu.my
https://doi.org/10.1016/j.oneear.2020.05.001

Remote sensing provides valuable insights into pressing environmental challenges and is a critical tool for driving solutions. In this Primer, we briefly introduce the important role of remote sensing in forest ecology and management, which includes applications as diverse as mapping the distribution of forest ecosystems and characterizing the three-dimensional structure of forests. We describe six key reasons why remote sensing has become an important data source and introduce the different types of sensors (e.g., multispectral and synthetic aperture radar) and platforms (e.g., unmanned aerial vehicles and satellites) that have been used for mapping a diversity of forest variables. The rapid advancement in remote-sensing technology, techniques, and platforms is likely to result in a greater democratization of remote-sensing data to support forest management and conservation in parts of the world where environmental issues are the most urgent.

Introduction

Remote sensing is the acquisition of information about some feature of interest without coming into direct contact with it. Popular forms of remote sensing used in the environmental sciences are images of the Earth's surface acquired from sensors mounted on airborne and spaceborne platforms. Remote sensing has been used for mapping the distribution of forest ecosystems, global fluctuations in plant productivity with season, and the three-dimensional (3D) structure of forests.

The range and diversity of sensing systems, as well as the variety of applications, have evolved greatly over the last century. The types of images used range widely from conventional aerial photographs that capture a view similar to that observed by the human eye to images that reveal elements that might be invisible to the human eye, such as the physical structure and chemical composition of the Earth's surface.

Remotely sensed imagery provides a view of the Earth's surface in such a way that allows features on it to be identified, located, and characterized. Moreover, although each image provides a snapshot of the environment, it is commonly possible to acquire imagery repeatedly in time. As a result, remote sensing has been used in a diverse range of forest ecology and management applications from mapping invasive species to monitoring land-cover changes, such as habitat fragmentation, to estimating biophysical and biochemical properties of forests.

This Primer seeks to briefly review the role of remote sensing in forest ecology and management. It focuses on non-terrestrial forms of remote sensing (i.e., it does not include terrestrial laser scanning or field spectroscopy); reviews the range of sensors, platforms, applications, classification methods, and choices of remote-sensing systems; and concludes by indicating future directions in this rapidly evolving interdisciplinary field.

The Ubiquity of Remote Sensing: Six Key Reasons

Given that many forest environmental variables can be estimated directly in the field, why has remote sensing become an important data source? We note six key reasons for this situation:

First, remotely sensed imagery provides a synoptic view. The vantage provided by an Earth-observing sensor ensures that imagery captures a complete picture of the environment in its field of view. Thus, every visible feature, including its location and its location relative to that of all others in the imaged area, is captured. In short, this gives imagery a map-like format that provides a complete survey of the imaged area rather than field data, which are often based on a very limited set of samples from which inter-sample site information would have to be inferred by some form of interpolation. Because of this complete survey, remote sensing allows wall-to-wall mapping and monitoring of important ecological variables, such as land-cover change.

Second, remotely sensed data are available everywhere and often at a range of spatial and temporal scales. Key environmental remote-sensing systems, such as those carried by the Landsat satellites, have provided a constantly updateable stream of imagery for the entire planet since the 1970s. Availability can sometimes be constrained by technical problems or cloud cover, but in principle, imagery should be available everywhere irrespectively of location, enabling *inter alia* study of sites no matter how remote or hazardous they might be. Furthermore, historical remote-sensing data allow us to go back in time to look at the causes of present environmental issues.

Third, remotely sensed imagery has a high degree of homogeneity. Critically, data from key environmental remote-sensing systems are acquired under relatively fixed conditions, and the data captured relate to the way in which radiation interacts with the environment, which is constant in space and time; there are no human-induced complications, such as differences in measurement practices from one country to another.

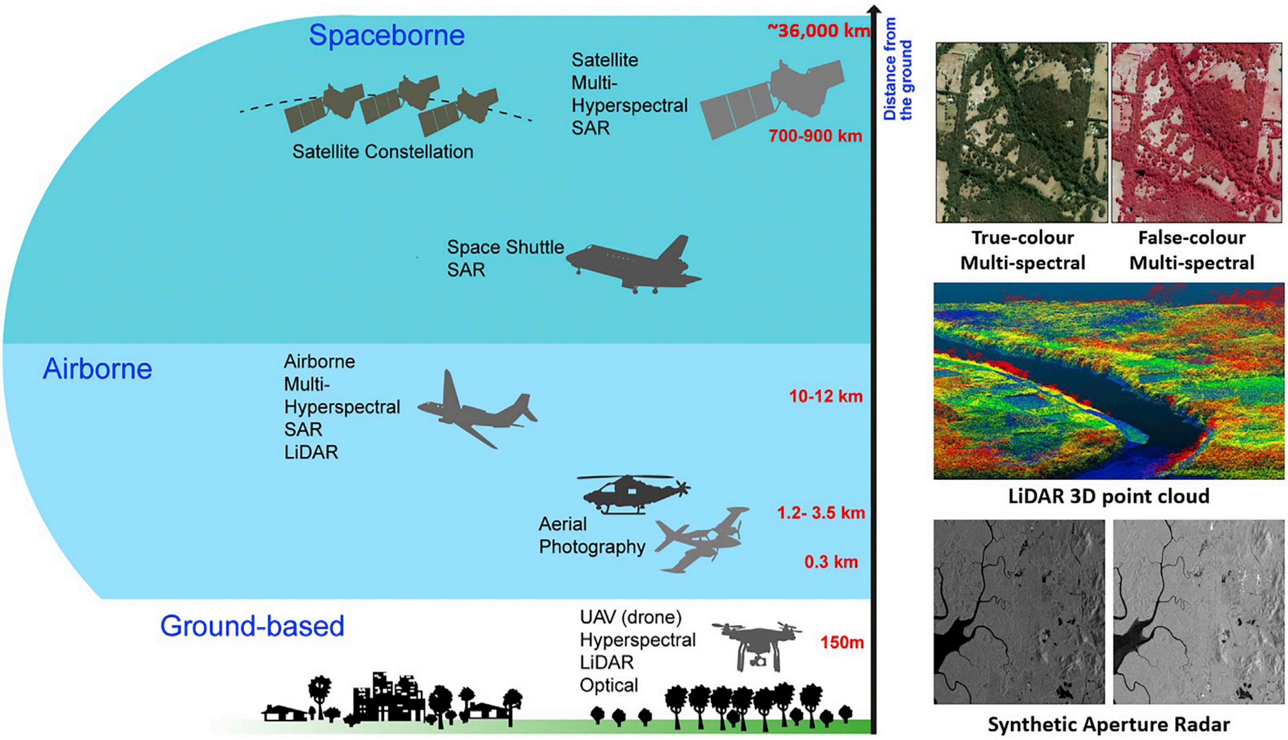

Figure 1. Common Remote-Sensing Platform and Sensor Combinations and Remote-Sensing Data
(Left) Platforms and most commonly utilized sensors for specific platforms.
(Right) True-color digital aerial photography and false color with NIR sensing (top), LiDAR point cloud of vegetation near a river (middle), and SAR data for two polarizations from Sentinel 1 (bottom).

Fourth, the imagery contains, or can easily be converted to, digital images and as such can be easily integrated with other spatial datasets in a geographical information system.

Fifth, per unit area, remote sensing is an inexpensive way to acquire data. Although the financial costs associated with remote sensing can sometimes be very large—for example, it is expensive to build, launch, and operate satellite remote-sensing systems, making some imagery expensive—much is freely available. Additionally, although commercial remote-sensing systems can appear costly, the data still provide inexpensive assessment on a unit-area basis. More critically, however, there has been an increasing trend to make key datasets for environmental science research freely and openly available. For example, the complete archive of the influential Landsat series of satellites is freely available, and recently the European Space Agency (ESA) launched a suite of new satellites and provides the data collected for free. Resources such as Google Earth Engine (GEE) also provide easy access to vast global datasets.

Sixth and finally, not only are data more readily available, but there has also been an increasing trend toward the provision of data products as well as the image data themselves. This reduces both the need for expert knowledge of remote sensing and image analysis and the communication gap between experts and environmental scientists, which has historically been a concern. Environmental scientists can now easily access science-quality data products obtained from remote sensing (e.g., leaf area index, land use, and land cover), although expert knowledge might still sometimes be needed.

Remote-Sensing Platforms and Sensors

Remote-sensing systems are available as a diverse array of sensors and platforms (Figure 1). Sensors can be divided into passive and active sensors, whereas platforms range from Earth observation satellites, planes, and helicopters to unmanned aerial vehicles (UAVs) with fixed wings and rotaries.

The most common sensor used in remote sensing is an optical imaging system, which is similar in design and application to a standard digital camera except that it can acquire data beyond the visible wavelengths (i.e., infrared and thermal wavelengths) across the electromagnetic spectrum. Materials reflect and absorb at different wavelengths, and through these differences, land covers (i.e., forest and canopy cover) can be identified. Optical sensors vary in terms of the number of bands (and the widths of those bands) from which image data are captured. Multispectral sensors have a limited number of bands, whereas hyperspectral sensors have thousands of much narrower bands (Figure 2). Optical systems (and thermal systems) are passive sensors, which rely on reflected sunlight or emitted thermal energy, and consequently cannot penetrate clouds or smoke, are affected by haze from clouds, and cannot be used at night.

Active sensors include light detecting and ranging (LiDAR) and synthetic aperture radar (SAR) systems. These sensors emit a pulse and measure the backscatter reflecting back to the sensor. A key advantage of such sensors is their ability to penetrate clouds and smoke and operate at night. SAR sensors can differentiate land-cover features according to their surface roughness, the 3D structure of the targets, and water content.

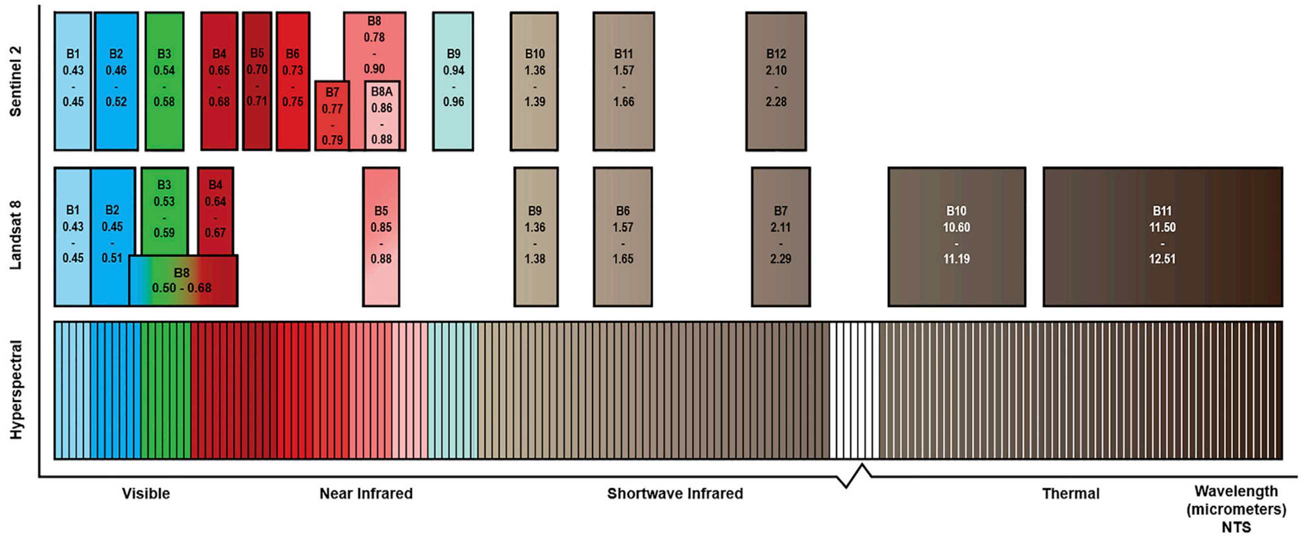

Figure 2. Comparison of Multispectral Sentinel 2 and Landsat 8 and Hyperspectral (Example Only) Bands

Depending on the wavelength of the sensor (e.g., X-band, L-band, or C-band), the signal can penetrate vegetation, canopy, and soil. Conversely, LiDAR systems emit pulse from lasers and measure distance to a target and the reflected light. Differences in laser return times and wavelengths can then be used for making digital 3D representations of the target.

In recent years, as a result of developments in sensor technology, all passive and active sensors have versions that can be mounted on all platforms, although larger platforms such as satellites and larger planes can carry heavier payloads, allowing for larger sensor systems that are of higher quality and accuracy. However, because of sensor miniaturization, rarely found combinations, such as SAR mounted on a UAV, are starting to be more common and affordable.

Spaceborne sensors take consistent measurements at specific time intervals according to the time it takes for the sensor to revisit the same location (e.g., Landsat sensors revisit the same location on Earth every 16 days). However, many commercial satellites, such as WorldView series, can be tasked for specific locations, whereby the sensor head turns to acquire data on an angle to increase revisit time. In addition, the latest satellites are commonly developed as part of a constellation of multiple satellites to increase revisit time (i.e., Sentinel). Conversely, airborne platforms have the advantage of being able to be flown in response to specific events, such as fire, and can also fly under clouds (especially UAVs), addressing this key limitation of Earth observation satellites. Airborne platforms such as UAVs can acquire very-high-centimeter spatial-resolution data.

Applications and Classification Methods

Within forest ecology and management, there is a diverse range of applications for remote sensing, including the measurement of cover, vegetation structure, vegetation chemistry and moisture, biodiversity, and soil characteristics (Table 1). These variables are critical for understanding forest ecosystem functions and processes, as well as classifying forests into specific communities, ecosystems, and biomes. For forestry applications, remote-sensing measurements can be used for producing forest inventories for calculating the number of trees per acre, the basal area, and the value of timber. For forest monitoring, measuring change in these variables is important for understanding ecosystem dynamics and anthropogenic impacts in both the short term (i.e., fire) and long term (i.e., climate change). From the day-to-day management perspective, monitoring forest change is critical for determining potential risks such as fire hazard due to fuel loads and overall forest health. Finally, forest monitoring with remote-sensing approaches underpins policies such as Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation (REDD+) and Roundtable on Sustainable Palm Oil certification. Common remote-sensing applications and methods are outlined in Table 1.

There are a range of ways in which remote sensing is used to represent different forest variables. Both optical and SAR data are provided in a (flat) raster format (i.e., as a grid of values), whereas LiDAR data are represented by 3D point clouds (Figure 1). These data are then classified into either categorical or continuous outputs. For example, land use and land cover are categorical, whereas foliage projective cover is continuous. However, depending on the resolution, the same variable can be represented as continuous or categorical. For example, medium-resolution Landsat can be used for classifying pixels according to the percentage of foliage projective cover, whereas high-resolution 5-cm data derived from a UAV can characterize the actual canopy extent. These two perspectives for representing forest variables determine the general types of analyses conducted with remote-sensing data. For continuous biophysical measurements (e.g., the fraction of absorbed photosynthetically active radiation and biomass), the correlation between field measurements and vegetation indices, such as the normalized difference vegetation index (NDVI), is most common. However, for categorical mapping, classification algorithms such as the maximum likelihood classifier and machine-learning approaches such as Random Forests are "supervised" with training data. For high-spatial-resolution data, pixels can be aggregated first to

Table 1. Key Forest Variables and Remote Sensing Systems Used for Mapping Them

Domain	Variables	Multispectral Fine Spatial Resolution	Multispectral Medium to Coarse Spatial Resolution	Hyperspectral	SAR	LiDAR (Airborne)	Examples
Land use and land cover	land use and land cover	✓✓	✓✓	✓✓	✓✓	✓✓	one of the most common applications for remote sensing is land-use and land-cover mapping
Cover	vegetation and bare ground cover	✓✓	✓✓	✓	✓✓	✓✓	vegetation indices such as NDVI are highly correlated with a range of vegetation variables and on their own are commonly used as a surrogate for greenness or forest health; with fine-resolution multispectral data, vegetation cover can be characterized by the extent of canopy cover versus ground cover, whereas with coarse-resolution remote sensing, the percentage of cover can be measured within pixels
	foliage projective cover	✓✓	✓✓	✓	✓✓	✓✓	
	tree density	✓✓	✓✓	✓	✓✓	✓✓	
	coarse woody debris	✓✓	✓✓	✓	✓✓	✓✓	
	greenness	✓✓	✓✓	✓	✓✓	✓✓	
	vegetation health	✓✓	✓✓	✓✓	✓✓	✓✓	
Vegetation structure	tree height	✓	–	–	–	✓✓	LiDAR is particularly good at characterizing vegetation structure and can also directly measure tree and ground height by constructing 3D representations of forest structure; high-resolution UAV and digital aerial photography can provide millimeter-resolution multispectral data along with 2.5D representations of forest structure for the identification of individual species
	vertical forest structure	–	–	–	✓	✓✓	
	above-ground biomass	✓✓	✓✓	✓✓	✓✓	✓✓	
	leaf area index	✓✓	✓✓	✓✓	✓✓	✓✓	
	basal area	✓✓	✓✓	✓✓	✓✓	✓✓	
	individual crowns and gap size	✓✓	–	–	–	✓✓	
Vegetation chemistry and moisture	foliar chemistry	✓	✓	✓✓	–	–	airborne hyperspectral data can be used for estimating foliar chemistry, such as nitrogen, on the basis of particular wavelengths and specific absorption features
	fraction of absorbed photosynthetically active radiation	✓✓	✓✓	✓✓	✓✓	✓✓	
	moisture content	✓	✓✓	✓✓	✓✓	–	

(*Continued on next page*)

Table 1. *Continued*

Domain	Variables	Multispectral Fine Spatial Resolution	Multispectral Medium to Coarse Spatial Resolution	Hyperspectral	SAR	LiDAR (Airborne)	Examples
Biodiversity	individual species identification	✔✔	✔✔	✔✔	–	✔✔	high-resolution multispectral data can be used for identifying tree species from both their crown characteristics and texture images
	biodiversity (e.g., alpha and beta)	✔✔	✔✔	✔✔	–	✔✔	
Disturbance	detecting forest disturbance and recovery over long and multiple time periods	✔✔	✔✔	✔	✔✔	–	temporal trend analysis of spectral data can be accomplished through the assessment of changes in a Landsat time-series stack for characterizing disturbance and recovery
	fire scar mapping	✔✔	✔✔	✔✔	✔✔	✔✔	
Soil	soil type	✔	✔	✔✔	✔✔	–	L- and C-band SAR can penetrate the canopy and soil to characterize soil moisture
	moisture	✔✔	✔✔	✔✔	✔✔	–	
	soil properties (e.g., pH and salinity)	–	–	✔✔	✔✔	–	

Remote sensing can be used for mapping and measuring virtually all key forest variables (e.g., tree density and basal area); this table highlights particularly common applications for specific remote-sensing systems. The double checkmarks refer to more common applications, and the single checkmarks refer to less common applications. It is important to note that there are examples in the literature for nearly all sensor and platform combinations. For example, UAV-mounted SAR is possible, but its application so far is unusual. Although measuring foliage projective cover with hyperspectral imagery is technically not a problem, in many cases it would be simpler to use multispectral imagery. Finally, remote-sensing data such as spectral indices (e.g., NDVI) can be used as inputs into physical and empirical models for characterizing a vast range of forest variables.

form objects that represent natural spatial units of relevance (e.g., individual trees) on the basis of their similar spectral and textural properties. Rather than being classified as pixels, these image objects are classified according to a method known as geographic object-based image analysis.

Where remote sensing can really demonstrate its great potential is in measuring forest variables for multiple time periods or between multiple locations (Figure 3). Although any remote-sensing application requires the acquisition of high-quality cloud-free data, for applications where more than a single scene is analyzed, this is even more important. A key decision point that will depend on the type of analysis is whether to pre-process data to reduce atmospheric effects (i.e., illumination and cloud haze) (Figure 3). For certain applications, radiometric correction is necessary for converting the raw remote-sensing data (digital numbers) into surface reflectance, which represents the fraction of incoming solar radiation that is reflected from Earth's surface.

Choice of Remote-Sensing System

Because of technical and financial limitations, there is no perfect remote-sensing system. Remote-sensing systems are typically the result of a trade-off between spatial, temporal, and radiometric resolutions (Figure 4). The choice of system will depend on this trade-off, the costs of purchasing and processing the historic archives, and the archives' availability. For example, whereas purchasing a UAV system is relatively inexpensive, paying to have a team fly and then process data to create high-quality orthomosaics could mean that for many applications, purchasing high-resolution WorldView 3 31-cm panchromatic satellite imagery might be cheaper and produce better-quality and more consistent results. Although SAR has great promise for remote sensing in cloudy parts of the world (such as the tropics), the data can be very noisy, and for the majority of applications, if a single scene of cloud-free imagery can be acquired, the resulting outputs can be much more informative because of the greater amount of information provided by optical data.

Key decisions in the selection of remote-sensing data will be determined through matching the spatial and temporal scales of the ecological phenomenon in question with the scale of the remote-sensing system (Figure 4). For example, UAV data can capture millimeter-scale spatial-resolution data, but at this scale the remote-sensing image captures tree branches, ground cover through gaps in the canopies, individual leaves at different angles, and shadows. For many classification algorithms, it is better to not differentiate between the individual elements of a tree, and for many ecological applications such precision is unnecessary.

Emerging Technologies and Approaches

The field of remote sensing is evolving rapidly, especially because it is at the interface between engineering, computer

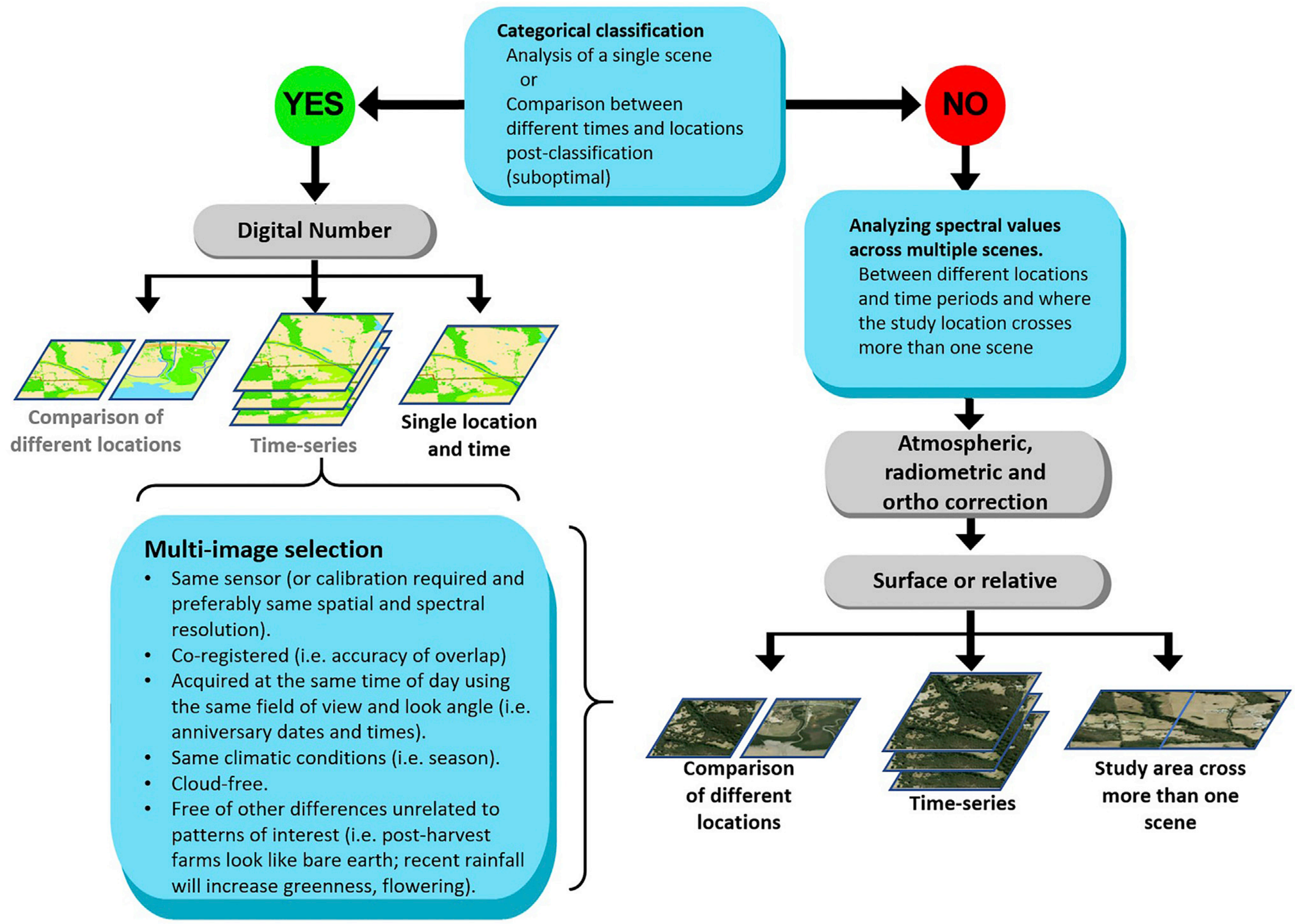

Figure 3. Image Selection and Pre-processing Decision Tree
Pre-processing is generally required when multiple scenes are being analyzed; however, post-classification comparisons (i.e., change detection) can also be carried out.

science, geography, and various disciplines that utilize the technology to support forest ecology and management. The number, range, and performance (i.e., number of bands and spatial resolution) of platforms and sensors are increasing dramatically, and more diverse players ranging from governments to private industry are developing and operating remote-sensing systems.

Earth observation systems are now being launched and operated as satellite constellations rather than single satellites, as was the case in the past. This provides greater revisit time and also supports data-fusion products (i.e., combining multispectral and SAR data) through overlapping image footprints and similar spatial resolutions. Recently, the ESA launched the Sentinel satellite constellation, which includes two multispectral satellites and two SAR satellites. The Sentinel series is expected to be joined by another ESA Earth observation satellite in 2024, the Fluorescence Explorer, to monitor chlorophyll fluorescence in terrestrial vegetation. Meanwhile, China recently launched the Gaofen (GF) series, which includes high-resolution multispectral (GF-1 and GF-2), SAR (GF-3), and hyperspectral (GF-5) remote-sensing satellites. At the other end of the spectrum, the private company Planet Labs has launched over 351 satellites, and more than 140 of these are in operation today (as of April 21, 2020). Its satellite constellation includes over 100 small (~5 kg) dove satellites that provide 3.7-m spatial-resolution imagery daily.

Closer to the ground, UAV remote sensing has a significant role in providing smaller organizations and research groups with the ability to capture remote-sensing imagery at unprecedented spatial resolutions and at any time. The most common sensors used are multispectral red-green-blue (RGB) and near-infrared radiation (NIR) sensors, although there is a trend toward miniaturizing all forms of sensor technology, including LiDAR and hyperspectral sensors. The production costs are also decreasing, meaning that such technologies are likely to become much more affordable and ubiquitous. For example, the cost of an airborne LiDAR survey can be quite prohibitive, which has meant that its application has been limited and is rarely used for monitoring where frequent recapture is required, even though it is unmatched in its ability to capture the 3D structure of forest ecosystems.

In parallel with the rapid advance in sensor technology and platforms, the classification and processing of remote-sensing imagery are advancing in leaps and bounds. Techniques from computer vision, along with the use of machine-learning

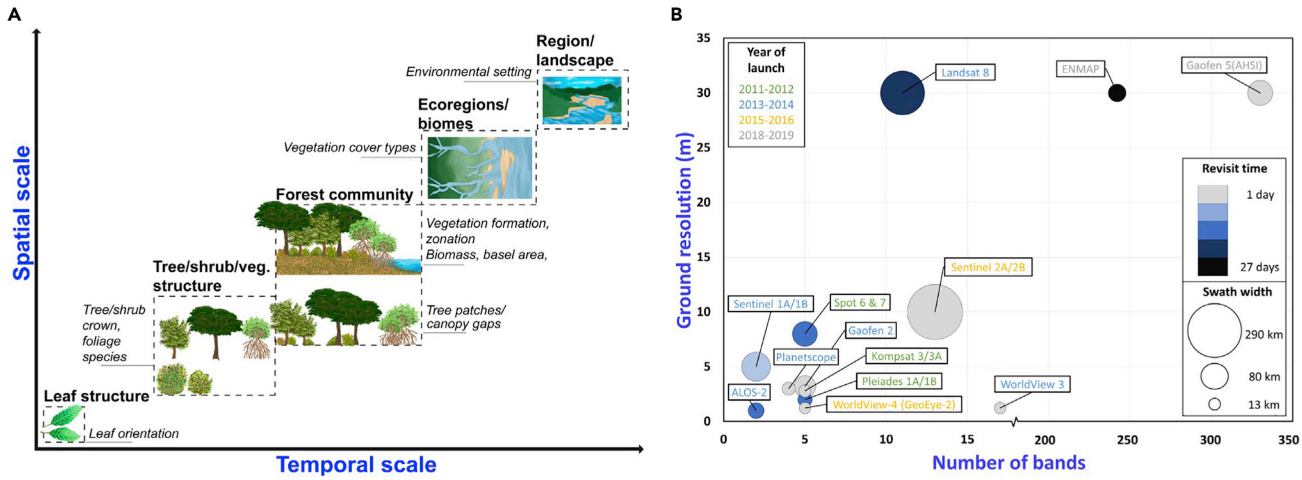

Figure 4. Ecological and Remote-Sensing Scales
(Left) Spatial and temporal scales of ecological phenomenon (concept adapted from Kamal et al., 2015).
(Right) Based on publicly available data, a remote-sensing sensor's spatial and temporal resolution and swath width for a sample of individual Earth observation satellites and satellite pairs (i.e., Sentinels 1A and 1B) launched after 2010. All values are for standard acquisition modes for the primary sensor (i.e., for archival purposes rather than for tasking). The spatial resolution is based on the band with the highest spatial resolution (excluding the panchromatic band). The number of bands includes the panchromatic band for multispectral sensors and the number of polarizations for SAR (ALOS-2, Sentinels 1A and 1B). Note that some remote-sensing systems, especially SAR, will have multiple modes with different resolutions that are often used when a sensor is tasked for a specific scene. The majority of satellites provide complete wall-to-wall coverage of the globe each revisit, but some primarily acquire data in tasking mode.

methods (including deep learning), are now being applied to remote sensing, and we are likely to see a dramatic transformation in the algorithms being applied, especially for specific types of applications, such feature detection. These approaches usually require high-performance computing, which is commonly provided in the cloud. Although private networks have been and continue to be developed, the freely available GEE platform has had enormous uptake in the remote-sensing community and beyond. It is a combination of image repository (it includes nearly all freely available remote-sensing imagery and products, such as surface reflectance and vegetation indices), high-performance computing, and web-based mapping application. Cloud computing has great potential for reducing remote-sensing workflows and also the ability to process data at much larger and even global extents. Using GEE computationally intensive applications, such as multitemporal mosaics (i.e., creating an image where pixels are based on the median annual value) and temporal trend analyses (e.g., analyses of disturbance and recovery with LandTrendr), is simplified. What formerly would have required huge computing resources, expertise, and a team of people can now be done on a desktop with an internet connection by a single operator.

Although processing methods and remote-sensing systems are advancing rapidly, freely available data from Landsat, the Moderate Resolution Imaging Spectroradiometer (MODIS), and the new Sentinel satellites are likely to still have critical roles in supporting forest ecology and management across the world, especially in developing nations. Most of the world's high-biodiversity and intact forests are found within the tropics in developing nations with limited budgets and technical expertise. Moreover, additional remote-sensing technical challenges are that, unlike temperate forests (which are often dominated by a single species), forests in these landscapes can be highly diverse and structurally complex and frequent cloud cover must be dealt with. However, the future is promising, remote-sensing data are coming down in price across the board, UAV technology is cheaper, there is more freely available remote-sensing data and pre-processed data products (i.e., Landsat surface reflectance products), and with platforms such as GEE, there is a reduced requirement for expensive information-technology infrastructure. These advances are resulting in a greater democratization of remote sensing to support forest management and conservation in parts of the world where environmental issues are the most pressing.

ACKNOWLEDGMENTS

The authors thank Michelle Ang and Darrel Tiang for their assistance with making some of the figures.

RECOMMENDED READING

Arévalo, P., Olofsson, P., and Woodcock, C.E. (2020). Continuous monitoring of land change activities and post-disturbance dynamics from Landsat time series: a test methodology for REDD+ reporting. Remote Sens. Environ. *238*, 111051.

Boyd, D.S., and Foody, G.M. (2011). An overview of recent remote sensing and GIS based research in ecological informatics. Ecol. Inform. *6*, 25–36.

Boyd, D.S., and Danson, F.M. (2005). Satellite remote sensing of forest resources: three decades of research development. Prog. Phys. Geogr. *29*, 1–26.

Dube, T., Mutanga, O., Shoko, C., Adelabu, S., and Bangira, T. (2016). Remote sensing of aboveground forest biomass: a review. Trop. Ecol. *57*, 125–132.

Gillespie, T.W., Foody, G.M., Rocchini, D., Giorgi, A.P., and Saatchi, S. (2008). Measuring and modelling biodiversity from space. Prog. Phys. Geogr. *32*, 203–221.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. (2017). Google Earth Engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. *202*, 18–27.

Kamal, M., Phinn, S., and Johansen, K. (2015). Object-based approach for multi-scale mangrove composition mapping using multi-resolution image datasets. Remote Sens. *7*, 4753–4783.

Kasischke, E.S., Melack, J.M., and Dobson, M.C. (1997). The use of imaging radars for ecological applications—a review. Remote Sens. Environ. *59*, 141–156.

Lausch, A., Erasmi, S., King, D.J., Magdon, P., and Heurich, M. (2017). Understanding forest health with remote sensing - Part II—a review of approaches and data models. Remote Sens. *9*, 129.

Lausch, A., Erasmi, S., King, D.J., Magdon, P., and Heurich, M. (2016). Understanding forest health with remote sensing - Part I—a review of spectral traits, processes and remote-sensing characteristics. Remote Sens. *8*, 1029.

Lechner, A.M., Langford, W.T., Bekessy, S.A., and Jones, S.D. (2012). Are landscape ecologists addressing uncertainty in their remote sensing data? Landsc. Ecol. *27*, 1249–1261.

Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H., and Turner, W. (2014). Satellite remote sensing for applied ecologists: opportunities and challenges. J. Appl. Ecol. *51*, 839–848.

Remote Sensing Research Centre (2019). Remote Sensing Toolkit (University of Queensland). https://www.rsrc.org.au/rstoolkit.

Wang, K., Franklin, S.E., Guo, X., and Cattet, M. (2010). Remote sensing of ecology, biodiversity and conservation: a review from the perspective of remote sensing specialists. Sensors (Basel) *10*, 9647–9667.

Warner, T.A., Foody, G.M., and Nellis, M.D. (2009). The SAGE Handbook of Remote Sensing (Sage Publications).