REMOTE SENSING'S ROLE IN MODERN FOREST ECOSYSTEM MANAGEMENT

IN SUMMARY

Forests cover about 30% of Earth's land surface and play a significant role in the climate system, and are integral to numerous ecosystem, cultural, and economic services (Carlowicz, 2012). Given the large and often remote land area covered by forests, remote sensing technologies have been widely used by forest managers to monitor the extent, spatial distribution, percent cover, and temporal variability of forests to improve management and conservation practices.

Remote sensing is the science, or art, of acquiring information about Earth's surface without being in direct contact with it. To date, forest management practices have primarily used aerial photography and multispectral imaging. Emerging technology, such as hyperspectral imaging (HSI) combined with Light Ranging and Detection (LiDAR) has been shown to allow users to expand measurements to identify species, forest health and condition, stand structure, and even ecosystem function.

A number of new remote sensing applications using HSI and LiDAR can provide more rich and comprehensive information on forest ecosystems that can directly benefit forest management decisions. Novel applications include, but are not limited to (i) pest and pathogen detection; (ii) drought stress monitoring; (iii) wildfire fuel mapping; (iv) estimating forest carbon exchange; and even (v) mapping functional diversity.

However, despite the numerous potential benefits of this technology, its application in forest management has been extremely limited to date. Most work has been done in the realm of scientific research or pilot studies. This gap between scientific methods and applied operational management exists for a number of reasons including, but not limited to the: (i) inherent heterogeneity and complexity of forest ecosystems; (ii) high cost of HSI and LiDAR data; (iii) lack of information sharing; and (iv) lack of understanding between forest managers/ecologists and remote sensing specialists.

Introduction: *Effects of climate change are already apparent in our forests and are expected to intensify within the coming decades, leaving these forests increasingly vulnerable. Because of this, it is crucial for forest managers to fully utilize monitoring tools at their disposal. Recent technological advances have widened remote sensing's potential application in forest management; yet its actual integration is lacking. This research brief will discuss the potential uses and limitations to the widespread application of remote sensing in modern forest ecosystem management.*

What are types of Remote Sensing technologies?

***Passive* remote sensing:**

Passive remote sensing systems record the amount of electromagnetic radiation(EMR) originating from the sun that is reflected off Earth's surface at different wavelengths, or portions of the spectrum [i.e. blue, green, red, near infrared(NIR), or shortwave infrared (SWIR) light]. Structure and chemical bonds define the absorbing and reflecting properties of Earth's surfaces and therefore determine the amount of energy reflected over the electromagnetic spectrum (Ustin et al., 2004).

Multispectral sensors have the advantage of being more publically available, requiring less processing, and historically covering larger spatial and temporal extents. However, the emerging use of hyperspectral sensors can be attributed to the maximization of spectral resolution, or the number, spacing/coverage, and narrow width of sampled bands along the spectrum. These hyperspectral narrow bandwidths with continuous coverage along the spectrum (~0.4μm-2.5μm) are more sensitive to subtle variations in reflected energy that coincide with forest surface properties, which aids in more precise species classification and robust forest assessments (Ustin et al., 2004). A typical hyperspectral sensor acquires around 100-200 spectral bands with narrow 5nm-10nm bandwidths, while commonly-used multispectral sensors acquire 5-10 spectral bands with larger 70nm-400nm bandwidths. See Figure 1.

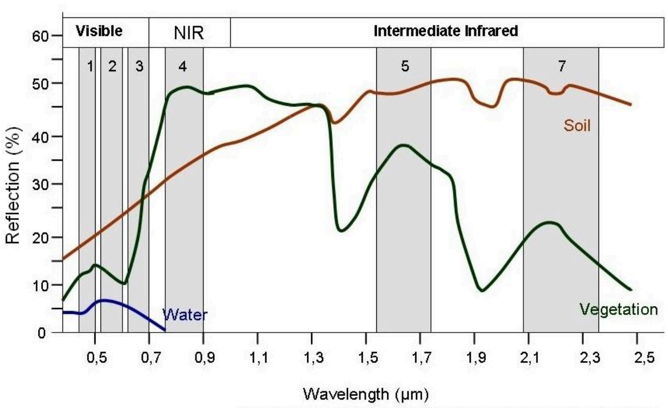


Figure 1: Comparison of spectral coverage and band width of continuous HSI vs. multispectral imagery (gray boxes)

***Active* remote sensing:**

LiDAR is an active remote sensing method that uses a laser to transmit a light pulse and receiver with highly sensitive detectors to measure the backscattered light. Distance to an object is determined by recording the time between the transmitted and backscattered pulse using the speed of light to determine the distance traveled. Over a flight, millions of data points are recorded to create a 3D "point cloud" that includes detailed information of various canopy elements such as stems, branches, and foliage that can be used to estimate forest structure. See Figure 2.

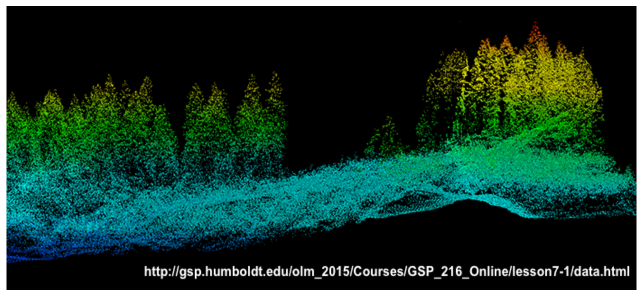


Figure 2: LiDAR Point Cloud

Data Fusion:

More recently, scientists have begun fusing HSI with LiDAR data. LiDAR has been shown to be the ideal technology to characterize canopy structure, including height, crown shape, leaf area, biomass, and basal area; while HSI can provide canopy biochemistry, species, and health information (Thenkabail et al., 2012). Together, these approaches have been applied to characterize forest properties such as height, canopy cover, leaf area, canopy chlorophyll content, and canopy water content. It should be noted that much of this work is primarily at the research stage.

What are some cutting edge uses of remote sensing in forest ecosystem management?

Infestation detection:

Pathogenic and pest invasions are a major source of disturbance in forest ecosystems. Remote sensing can provide large-scale measurements of tree mortality across a region or across a pathogen or pest's geographic range. Spectral reflectance measurements derived from HSI are used to assess the physiological status of vegetation such as the physiological stress from plant pathogens, drought, or nutrition deficiencies. For instance, stress will cause a decrease in photosynthetic pigments, which results an increase in red and blue reflectance and a decrease in near infrared reflectance (Ustin et al., 2004).

Meentemeyer et al., 2007 found spatially-explicit estimates of mortality density of Sudden Oak Death in two host vegetation types by comparing the total number of remotely assessed dead trees to an independent estimate of the total population of alive and dead trees.

More recently, Asner et al., 2018 combined field measurements of leaf spectra with HSI and LiDAR canopy measurements to develop a spectral signature for Rapid Ohia Death (ROD). ROD is a disease caused by the fungus *Ceratocystis fimbriata* that has killed millions of Hawaii's keystone endemic ōhiʻa tree since 2010. Without remote sensing that provides information on the condition of each tree in the forest, field crews wouldn't know where to best apply tactical control measures to contain the disease, such as cutting and covering contaminated trees.

There is currently a lack of quantitative understanding of how processes, such as drought-induced mortality, affect absolute and relative partitioning of changing foliar chemicals in trees. However, for this study, trees affected by ROD undergo a uniquely rapid rate of chemical-spectral change, as canopies change from green to brown in days to weeks (Asner et al., 2018). It is therefore crucial that HSI and LiDAR be made operational and carried out on a sufficiently frequent basis in order to capture differences in death rates.

Drought Stress Monitoring:

With the increased occurrence and severity of droughts, understanding how water stress is linked to future tree mortality across forest types has become increasingly important for forest management, conservation, and resource policy. Yet, pre-mortality indicators of tree death remain poorly understood. HSI and LiDAR physiological-based measures offer a means for large-scale analysis to understand and predict species-specific drought-induced mortality.

Broderick and Asner, 2017 found that high fractional changes in canopy water content lead to increased vulnerability to future mortality in the Sierra Nevada. They also found different patterns within different conifer communities, ranging from severe rates of mortality with increasing progressive water stress in Ponderosa Pine communities, but almost no relationship in the Closed-Cone Pine-Cypress community. See Figure 3.

However, it should be noted that drought stress itself is only one of several potential causes of mortality. Often drought causes stress within trees, which then succumb to death from bark beetle attacks. So, while changes in canopy water content may facilitate conditions that lead to mortality, water stress alone is often not the only cause of mortality, which leads to further uncertainty when predicting mortality.

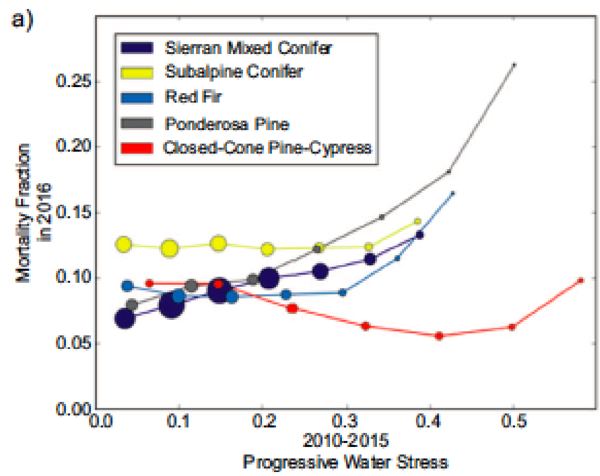
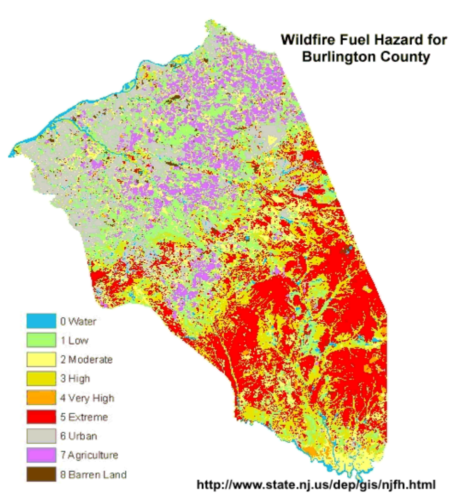


Figure 3: Relationships between progressive water stress from 2010 to 2015 and mortality fraction in 2016 for each of the five most common conifer communities in the sampled data. Dot size shows relative quantity of data at each point (Brodrick and Asner 2017).

Wildfire Fuel Mapping:

A comprehensive account of forest fuel types and their properties can help forest managers understand the process involved with the initiation and propagation of forest fires in order to evaluate fire hazard and risk. Wildfire fuels include all dead or living vegetation that can be ignited and their properties of interest include the horizontal and vertical structure and flammability of said vegetation. Fuel mapping is an extremely difficult and complex process requiring expertise in remotely sensed image classification, fuel and fire behavior modeling, ecology, and GIS (Keane et al., 2001).



HSI can provide a number of canopy properties relevant for forest fire issues such as green vegetation water content or biomass (Koetz et al., 2008). LiDAR has the ability to provide information about biophysical fuel properties such as tree height, fractional vegetation cover, canopy geometry, and above-ground biomass (Koetz et al., 2008). An additional advantage of LiDAR is the ability to produce high resolution digital elevation models to derive a detailed topography. This reliable distinction of vegetation classes of different heights can significantly improve the performance of forest fire behavior models, better supporting risk assessments and mitigation of forest fires.

Estimating Carbon Exchange:

Forests are the largest terrestrial carbon stores and make a significant contribution to the carbon cycle, which has a fundamental role in regulating Earth's climate. Existing empirical and model-based remote sensing products have been shown to miss crucial small-scale variation in GPP. Carbon sequestration is difficult to measure because it varies at many spatial and temporal scales and is therefore difficult to apply a modeling scheme that can adequately represent this variability.

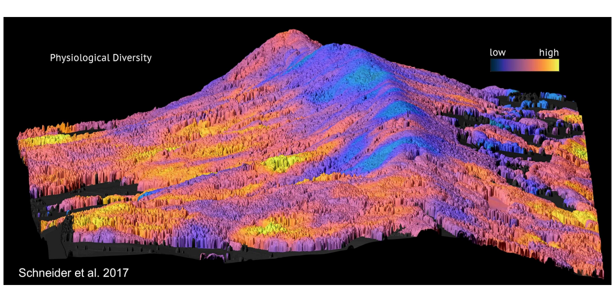
Multispectral sensors such as Landsat and MODIS are subject to large biases and primarily detect broad differences in GPP among ecosystem types and across vegetation density gradients, missing physiological influences on GPP from variations in leaf traits responding to winter dormancy, plant stress, and stomatal response. For instance, Ran et al., 2016 found that canopy heterogeneity led to large systematic errors when using sparse eddy covariance flux towers and MODIS, which could lead to large systematic errors when upscaling to model estimated NEP.

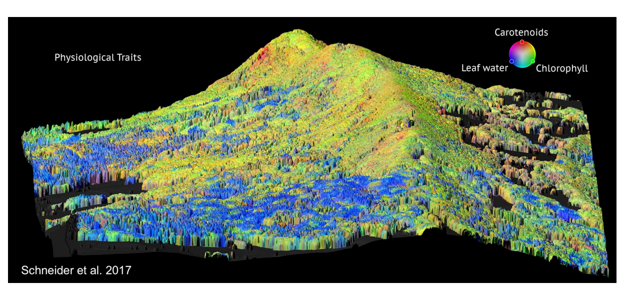
HSI provides new opportunities to more accurately monitor spatial and temporal variation in carbon exchange based on its sensitivity to leaf physiology. HSI's use of narrow bands measured continuously from the visible-through-shortwave-infrared (VSWIR) spectral region (400 - 2500nm), rather than multispectral's visible-through-near-infrared (400 - 1050nm) broadband observations, takes advantage of narrow spectral features related to specific leaf functional, chemical, and structural traits. Asner et al., 2011 analyzed thousands of humid tropical forest canopies to develop an upscaling method to find that photosynthetic pigments, water, nitrogen, cellulose, lignin, phenols, and leaf mass area were estimated with much greater precision and accuracy using the whole VSWIR region. In another study, DuBois et al., 2018 confirmed specific spectral wavelengths important to predicting eddy covariance system carbon flux measurements in spectral regions associated with leaf/canopy spectral traits also in the SWIR region. However, challenges still remain in handling diverse and open canopy structure and integrating across complex terrain, land management, and seasonally stressed ecosystems.

Mapping Functional Diversity:

Ecological studies have demonstrated positive relationships between plant diversity and ecosystem functioning. Forests with higher functional diversity are generally more productive and stable over long timescales than less diverse forests. Functional traits of plants have historically been measured by very labor-intensive fieldwork. This fieldwork is either limited to very few measurable traits on larger plots or many traits on smaller plots.

Researchers from The University of Zurich and NASA Jet Propulsion Laboratory have recently developed a method to map functional diversity of forests from small to large scales (Schneider et al., 2017). In a canopy with a more diverse structure, light can better spread between different vertical canopy layers and among individual tree crowns, allowing for a more efficient capture of light. LiDAR was able to detect morphological characteristics of forest canopy such as canopy height, foliage, and branch densities. Researchers also used HSI to characterize the forest biochemical properties. By measuring how leaves reflect light over the entire spectrum, they were able to derive physiological traits such as the content of leaf pigments (chlorophylls, carotenoids) and leaf water content, which provide information about the activity and health status of trees. To validate their method, researchers compared their results with leaf-level field measurements, species-level plot inventory data, and databases providing functional trait values (Schneider et al., 2017). Applied, these methods can be used to measure and monitor the diversity of forests, allowing managers to observe changes at large scales and providing spatial information for nature conservation and climate change mitigation strategies.

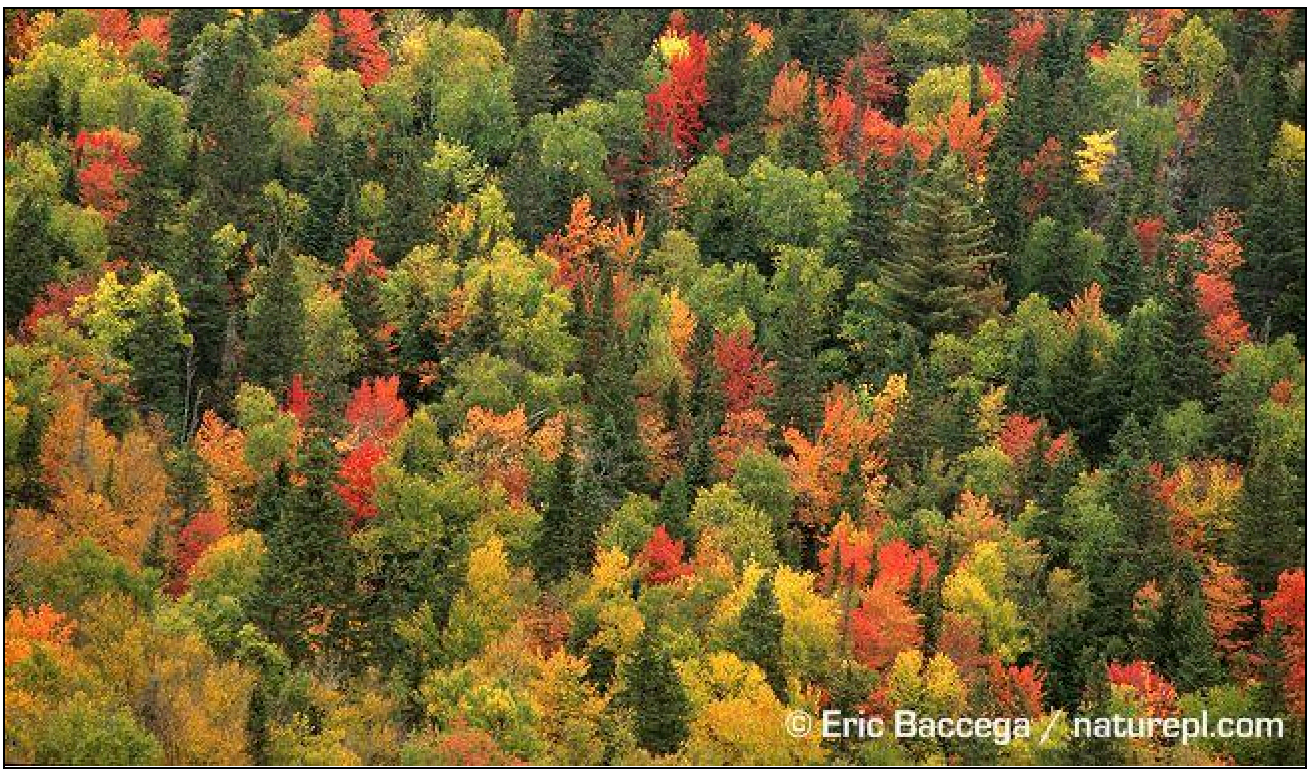




What is limiting remote sensing from reaching its full potential in modern forest ecosystem management?

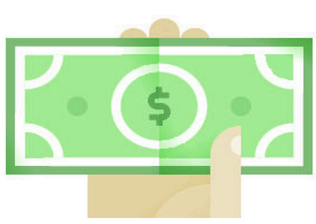
Complexities of forest ecosystems:

Many factors affect the reflectance of vegetation within a forest that complicate remote sensing analysis. Some of these factors include phenology, insolation, illumination geometry, soil characteristics, and spectral similarities between species (Thenkabail et al., 2012). When analyzing remote sensing data, this heterogeneity of a forest ecosystem can be further complicated by the pixel size of the sensor. For instance, if the size of a pixel is greater than the size of a single tree canopy, the remotely sensed spectral measurement will contain mixed effects of shadow, non-leaf reflectance, and different cover types. Spectral mixture analysis techniques can be used to estimate this percentage of each pixel's area that belongs to a given cover type. However, these correctional techniques often require intensive processing, ground truth data, and user training to be appropriately applied.



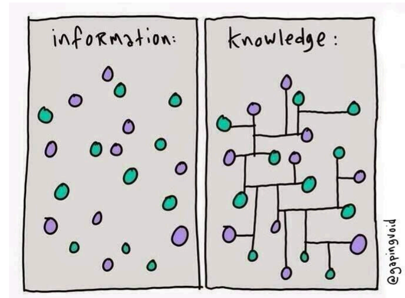
Cost:

Although many satellite products are freely available, higher quality HSI and LiDAR data are not. Most forest conservation practitioners and forest managers lack the financial resources to acquire large amounts of HSI and LiDAR data, especially over long periods of time over large geographic extents. Therefore, making government-funded remote sensing data freely available to all users is a key step to facilitate progress by the research and applied communities. Further, this processing and analysis of large datasets can be expensive given logistical requirements (i.e. hardware, software, qualified staff and training). Originally hindered by the complexity and lack of clear documentation, the use of free open-source software such as R, QGIS, and GRASS have been recently on the rise.



Lack of information sharing:

Data sharing can help avoid duplicate investment. Sharing raw satellite and ground truth data can be a direct means of reducing cost. Ground truth information is needed to assess how remote sensing data correlates with in situ data in different biodiversity/functional groups. Still, in situ data sharing is limited. Frameworks for recognizing and rewarding those who make their data available do exist (i.e. citing authors of data sets in scientific journals) but need to be more widely implemented. Sharing new algorithms and workflows that support the analysis and interpretation of remote sensing data needs to be improved in order to make remote sensing more accessible to forest managers (Takao et al., 2010).



Capacity Building:

Capacity building, or in this case, the process where forest ecosystem managers improve and learn new remote sensing techniques, is crucial for the integration of these developing technologies in forest ecosystem management. Manuals/handbooks and on-the-job training will be essential to adequately cover the concepts of the technology and for new users to apply the software by themselves. Other solutions include developing online resources documenting best practices and sharing relevant information on product reliability and access to data portals; planning and attending applied training sessions for remote sensing processing and analysis tailored for forest ecosystem managers and conservationists; continuing to improve the flexibility and user friendliness of open-source software; and promoting integrated, multidisciplinary graduate programs at the interface of remote sensing and ecology for the next generation of scientists (Takao et al., 2010).

On the other hand, remote sensing experts should develop technology that is as simple and inexpensive as possible; and not only transfer the technology, but also consult with users to create an effective system of interactive learning. As research continues to broaden the scope of remote sensing to support forest ecology, stronger links and communication between the ecological and remote sensing communities are essential to insure that remote sensing meets its full potential for forest ecosystem management.

What does the future hold?

Repeat, global HSI monitoring:

Arguably the greatest limitation to the widespread integration of HSI in forest management is the absence of consistent, repeated global monitoring. A spaceborne platform with a hyperspectral sensor that would offer the potential for more accurate products of biochemical and biophysical variables that drive regional forest processes. NASA's proposed HyspIRI mission will revisit a given area on Earth every 16 days (Hook). Such continuous data could provide information across forests continuously altered by disturbance, land use management and change, and climate change.

***Final Thoughts:** Full utilization of remote sensing technologies in forest management in the face of rapid climate change will, above all, require more collaboration and communication between remote sensing specialists and forest managers. Work still needs to be done to make this technology more user-friendly and affordable. However, for now, data sharing and proper training can begin to provide forest managers with the resources to begin adopting these new tools and techniques.*

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