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Remote Sensing of Forestry Studies

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1. Introduction

Forestry can be simply explained as the science and technology linked with tree resources or forests. According to the Global Forest Resources Assessment 2010 (FRA 2010), "the world's total forest area was just over 4 billion hectares, corresponding to 31 percent of the total land area or average of 0.6 ha per capita". Forest as one of the most important resources on this planet plays a pivotal role in the progress of human civilizations. Forestry studies have always been the hot topic since the naissance of this discipline. With the advent of satellite remote sensing, the forestry studies have made the unprecedented development. This introductory review is intended to introduce the basics of remote sensing in forestry studies, summarize the recent development, and elucidate several typical applications in this area.

1.1 Remote sensing

Aerial photos (i.e. airborne remote sensing) or satellite imagery (i.e. spaceborne remote sensing) are widely used in forest studies. If the earliest platforms such as homing pigeons, kites, and hot air balloons, which were quite uncertain and unstable platforms with relatively low altitude, are taken into account, the history will be even longer (Colwell, 1964). Up to now, hundreds of Earth Observation Satellites are in orbit, and delivering assorted remotely sensed data ranging from optical data to radar data, from multispectral imagery to panchromatic imagery, and from local scale to global scale. Remote sensing has long been identified as an effective and efficient tool in forestry studies, such as forest inventory, forest health and nutrition, forest sustainability, forest growth, and forest ecology (Kohl et al., 2006).

Remote sensing is the "noncontact recording of information from the ultraviolet, visible, infrared, and microwave regions of the electromagnetic spectrum by means of instruments such as cameras, scanners, lasers, linear arrays, and/or area arrays located on platform such as aircraft or spacecraft, and the analysis of acquired information by means of visual and digital image processing" (Jensen, 2007). Franklin (2010) emphasized that “remote sensing is both technology (sensors, platforms, transmission and storage devices, and so on) and methodology (radiometry, geometry, image analysis, data fusion, and so on)”. There are numerous outstanding textbooks providing comprehensive introduction to the remote sensing science (e.g. Lillesand et al., 2007; Campbell, 2007; Jensen, 2007) and the digital image processing (e.g. Jensen, 2004; Richards and Jia, 2006; Lee and Pottiter, 2009).

1.2 Remote sensing process

Scientists generally summarized the remote sensing process into four phases: statement of the problem, data collection, data-to-information conversion, and information presentation (Jensen, 2007). Several notes derived from Jensen (2007) are provided as follows:

- A successful study or program must get started from properly stating the research question and forming the research hypothesis.
- Then in situ observation and/or remote sensing may be used for data collection. By far the most widely used remote sensing data in forest studies are optical satellite imagery, which utilizes the spectral information in visible and infrared portions (mainly ranging from 400 nm to 2500 nm) of the electromagnetic spectrum (Figure 1). The three types of optical remote sensing data are multispectral imagery (e.g. Landsat TM [Thematic Mapper] image), panchromatic imagery (e.g. SPOT [Satellite Pour l'Observation de la Terre] 5 panchromatic image), and hyperspectral imagery (e.g. Hyperion image). In addition, Radar (Radio Detection and Ranging) and Lidar (Light Detection and Ranging) are becoming research hotspots in forestry studies.
- Data-to-information conversion refers to remote sensing data analysis employing a range of image processing techniques, such as algorithms for image preprocessing, classification, feature extraction and change detection, and a variety of modeling methods.
- Information extracted from remote sensing data should be represented in a proper way in order to communicate effectively. In general, with the assistance of cartography, GIS (Geographic Information System), spatial statistics and the knowledge of research fields, the extracted information could be made into image map, thematic map, spatial database file, or graph. Poor information presentation results from the ignorance or violation of fundamental rules (e.g. cartographic theory or database topology design).
- The remote sensing process inevitably introduces errors to the generated information, especially in the phase of data-to-information conversion and information presentation, and these errors should be properly identified and reported (e.g. classification accuracy).

2. Forestry information needs and remote sensing

In practice, researchers choose one or several types of remotely sensed data according to their information needs. The information needs are converted to specific properties of remotely sensed data, such as spatial resolution, spectral resolution, temporal resolution, etc.

Tables 1 and 2 list commonly used sensors on Earth observation satellite that are still operational. These sensors provide diverse remotely sensed data with a unique configuration of image resolutions, such as spatial resolution, spectral resolution and temporal resolution (see Figure 2). Jensen (2007) defined spatial resolution as "a measure of the smallest angular or linear separation between two objects that can be resolved by the remote sensing system". In other words, the spatial resolution stands for how detailed information the remotely sensed data could provide. Temporal resolution can be defined as "how often the sensor records imagery of a particular area" (Jensen, 2007). For example, the well-known Landsat TM has 16-day temporal resolution. Another key property of a remote sensing system is spectral resolution, which is defined as "the number and dimension (size) of specific wavelength intervals (referred to as bands or channels) in the electromagnetic spectrum to which a remote sensing instrument is sensitive". Likewise, take the Landsat TM as an example. The Landsat TM imagery has 7 bands (6 optical bands plus 1 thermal band). It is noteworthy that the spectral resolution is mainly applied to describe optical imagery, and it cannot be used for Radar or Lidar remotely sensed data. In fact, the aforementioned data collection can be described as selecting the unique configuration of image resolutions (or properties), which can be used to meet certain research needs.

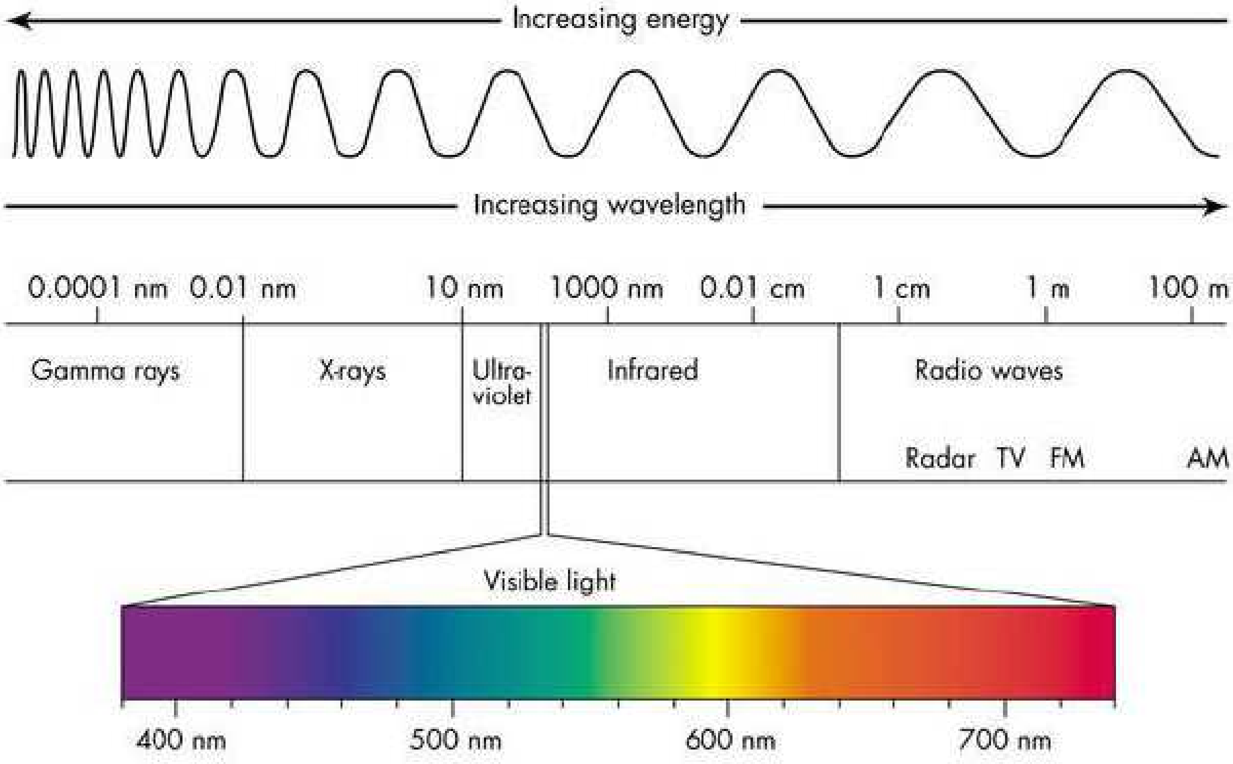

Fig. 1. Electromagnetic spectrum (Courtesy of the Antonine Education, UK) (http://www.antonine-education.co.uk/physics_gcse/Unit_1/Topic_5/topic_5_what_are_the_uses_and_ha.htm).

Wulder et al. (2009) endeavored to clearly demonstrate the relationship of information needs and the selection of appropriate data and processing methods in remote sensing for studies of vegetation condition. The issues need to be taken into account, including “the scale at which the target must be measured (e.g. landscape-level or tree level information); the attributes of interest (change, condition, spatial extent); cost; timeliness; and, repeatability” (Wulder et al., 2009).

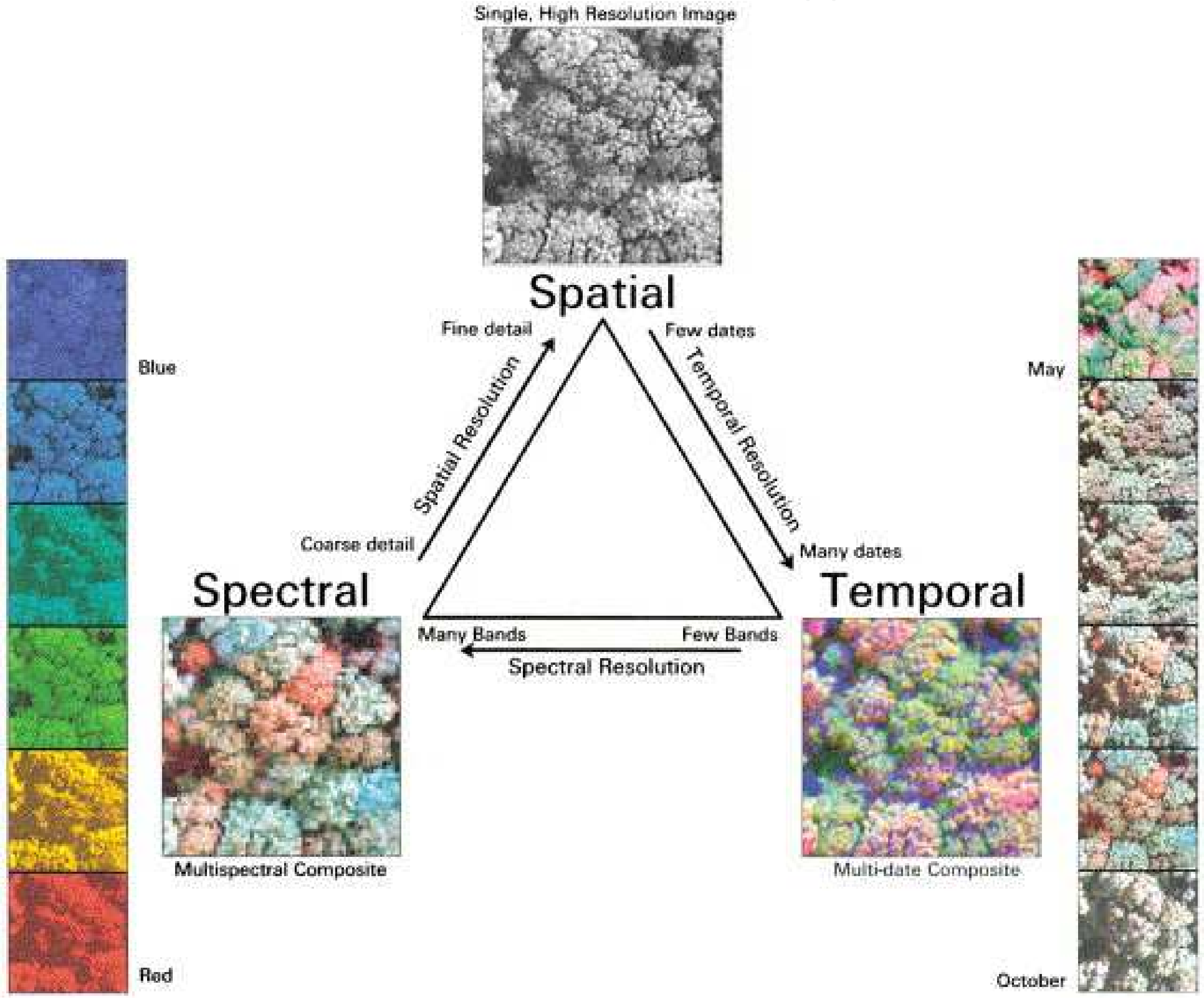

Fig. 2. Given a limited bandwidth, trade-offs have to be made between spectral, temporal, and spatial properties of the imagery acquired. For users who require high spatial resolution data, it is possible that multitemporal data can substitute for limited multispectral properties. (*With permission from* Key, T., T.A. Warner, J.B McGraw, and M.A. Fajvan. 2001. *Remote Sensing of Environment 75: 100-112*).

Satellite Program	**Satellite Platform**	**Sensor**	**Data Operator**
Optical Remote Sensing			
POES (Polar Orbiting Environmental Satellites)	NOAA 18	AVHRR	NOAA
EOS (Earth Observing System)	TERRA/AQUA	MODIS	NASA/USGS
Landsat	LANDSAT 5	TM	NASA/USGS
SPOT (Satellite Pour l'Observation de la Terre)	SPOT 4	HRVIR VEGETATION	Spot Image
	SPOT 5	HRG VEGETATION	Spot Image
IRS (Indian Remote Sensing Satellites)	IRS P6 (ResourceSat-1)	LISS III LISS IV AWiFS	ISRO (India Space Research Organization)
DMC (Disaster Monitoring Constellation)	Beijing-1	SLIM-6	DMC International Imaging Ltd
CBERS (China-Brazil Earth Resources Satellite)	CBERS-2B	CCD HRC IRMSS WFI	CAST (China)/INPE (Brazil)
Digital Globe Constellation	WorldView 2	WV110	DigitalGlobe Corporate
	QuickBird 2	BGIS 2000	DigitalGlobe Corporate
GeoEye	GeoEye-1	GIS MS	GeoEye Inc.
Radar Remote Sensing			
RADARSAT Constellation	RADARSAT 2	SAR	CSA/MDA
TanDEM-X	TanDEM-X	TSX-SAR	DLR/Astrium
TerraSAR	TerraSAR-X	TSX-SAR	DLR/Astrium

Table 1. The Current Commonly-used Optical and Radar Sensors

Medium resolution sensors	**Spatial resolution (m)**[a]	**Swath (km)**	**Spectral range (nm) / Bands**	**Temporal coverage**	**Revisit (day)**
Coarse spatial resolution optical sensors					
NOAA-18 (AVHRR)	1100	2900	Variable / 5	2005-Present	1
Terra/Aqua (MODIS)	250-1000	2330	Variable / 36	1999-Present	1-16
Moderate spatial resolution optical sensors					
Landsat (TM)	30	180	450-2350 / 6	1984-Present	16
IRS-P6 (LISS III)	23.5	141	520-1700 / 4	2003-Present	24
SPOT 4 (HRVIR)	20	60	500-1750 / 4	1998-Present	1-3
SPOT 5 (HRG)	10 (MS); 20 (SWIR)	60	500-1730 / 5	2002-Present	1-3
CBERS-2	20 (Pan and MS)	120	450-890 / 4	2003-Present	3
DMC (SLIM-6)	22/32	600	520-990 / 3	2002-Present	1
Fine spatial resolution optical sensors					
WorldView 2 (WV110)	0.46 (Pan); 1.85 (MS)	16.4	400-1040 / 8	2009-Present	1.1-3.7
QuickBird 2 (BGIS 2000)	0.65 (Pan); 2.62 (MS)	18.0	430-918 / 4	2001-Present	2.5-5.6
GeoEye-1 (GIS MS)	0.41 (Pan); 1.65 (MS)	15.2	450-920 / 4	2008-Present	2.1-8.3

[a] MS = multispectral, SWIR = shortwave infrared, Pan = panchromatic

Table 2. The Detail of the Current Commonly-used Optical Sensors

3. Underdeveloped remote sensing technologies in forestry studies

Optical sensors have been commonly used in forestry studies. However, the use of hyperspectral sensors, Radar and Lidar is still relatively underdeveloped. It is worth paying more attention to the application of hyperspectral sensors, Radar and Lidar in forestry studies.

3.1 Hyperspectral sensors

Optical sensors mentioned above, which are divided from the dimension of spatial resolution, are categorized into multispectral sensors. By contrast, there is a group of sensors called hyperspectral sensors, which accordingly generate hyperspectral data. Wang et al. (2010) stated that "hyperspectral data have the ability to collect ample spectral information across a continuous spectrum generally with 100 or more contiguous spectral bands". Shippert (2004) listed the existing hyperspectral sensors acquiring imagery from space, including the Hyperion sensor on NASA's EO-1 (National Aeronautics and Space Administration's Earth Observing-1), the CHRIS (Compact High Resolution Imaging Spectrometer) sensor on the European Space Agency's PROBA (PRoject for On-Board Autonomy) satellite, and the FTHSI (Fourier Transform Hyperspectral Imager) sensor on the U.S. Air Force Research Lab's MightySat II satellite.

3.2 Radar and lidar

Besides optical sensors, Radar and Lidar play more and more important roles in remote sensing of forest studies. Radar, the acronym of radio detection and ranging, is based on the transmission of long-wavelength microwaves (e.g., 3–25 cm) through the atmosphere and then recording the amount of energy backscattered from the terrain (Jensen, 2007). Wang et al. (2009) briefly introduced the Phased Array type L-band Synthetic Aperture Radar (PALSAR) on board Advanced Land Observing Satellite (ALOS), and RADARSAT-2 operated by the Canadian Space Agency (CSA) and MacDonald Dettwiler and Associates Ltd (MDA). Both could provide fully polarized SAR data to support PolSAR (Polarimetric SAR) technology (i.e., PolSAR decomposition), which has achieved promising results in many environmental researches (e.g., Lee et al., 2001; McNairn et al., 2009; Shimoni et al., 2009). Light detection and ranging (Lidar), also called Laser altimetry, is an active remote sensing technology that utilizes a laser to illuminate a target object and a photodiode to register the backscatter radiation (Lim et al., 2003; Hyyppa et al., 2009). It has been widely accepted that Lidar is capable of accurate (or even precise) vertical information (Wang et al., 2010). Therefore, it is believed that Lidar will bring forestry studies into an unprecedented age.

4. Case studies

Young and Giese (2003) summarized forest science and management into three categories: A. forest biology and ecology (e.g. forest biomes of the world, forest ecophysiology, forest soils, forest ecosystem ecology, landscape ecology, and forest trees: disease and insect interactions); B. forest management and multiple uses (e.g. forest management and stewardship, nonindustrial private forests, measuring and monitoring forest resources, silviculture and ecosystem management, forest-wildlife management, forest and rangeland management, forest and watershed management, forest and recreation behavior, behavior and management of forest fires, timber harvesting, wood products, and economics and the management of forests for wood and amenity values); and C. forests and society (e.g. urban forest, and social forstry: the community-based management of natural resources). As a matter of fact, remote sensing has more or less served all the three categories. Several examples in remote sensing of forestry studies are provided as follows. The selected examples were included in the papers that were either highly cited or newly published Science Citation Index (SCI) papers.

4.1 Species composition (biodiversity)

Turner et al. (2003) stated that the recent advances in remote sensing, such as the availability of remotely sensed data with high spatial and spectral resolutions, make it possible to detect key environmental parameters, which can be applied to determine the distribution and abundance of species across landscapes via ecological models. This approach, in general referred to as indirect remote sensing of biodiversity, plays a major role in this research area. For example, Defries et al. (2000) applied the 1km Advanced Very High Resolution Radiometer (AVHRR) to estimate and map percentage tree cover and associated proportions of trees with different leaf longevity (evergreen and deciduous) and leaf type (broadleaf and needleleaf).

4.2 Forest ecophysiology

Kokaly and Clark (1999) developed an approach to estimate the concentrations of nitrogen, lignin, and cellulose in dried and ground leaves using ban-depth analysis of absorption features (centered at 1.73 μm, 2.10 μm, and 2.30 μm) and stepwise multiple linear regression. As mentioned above, hyperspectral remote sensing was used to estimate the leaf pigment of sugar maple (*Acer saccharum*) in the Algoma Region, Canada, and promising results were obtained (Zarco-Tejada et al., 2001).

4.3 Forest ecosystem ecology

Jin et al. (2011) developed an algorithm based on a semi-empirical Priestley-Taylor approach to estimate continental-scale evapotranspiration (ET) using MODIS satellite observations. The seasonal variation in ET has been indicated as a key factor to the soil moisture and net ecosystem CO_2 exchange through water loss from an ecosystem. Lefsky et al. (2002) reviewed Lidar remote sensing for ecosystem studies. Lidar is capable of accurately measuring vertical information besides the horizontal dimension, such as the three-dimensional distribution of plant canopies and subcanopy topography (Lefsky et al., 2002). More specifically, lidar can provide accurate estimates vegetation height, cover, canopy structure, leaf area index (LAI), aboveground biomass, etc (Lefsky et al., 2002).

4.4 Forest trees: Disease and insect interactions

Due to the difference between dead, diseased, and healthy trees in visible and near-infrared reflectance values, Everitt et al. (1999) used color-infrared digital imagery and successfully detected oak wilt disease in live oak (*Quercus fusiformis*). The outbreak of mountain pine beetle (MPB) has resulted in a huge monetary loss in the western of the North America. It is urgent to efficiently survey the location and the extention of beetle impacts. Wulder et al. (2006) indicated the potential and limits of the detection and mapping of MPB using remotely sensed data, and suggested methods and data sources accordingly.

4.5 Measuring and monitoring forest resources

Cohen et al. (1995) stated that "remote sensing can play a major part in locating mature and old-growth forests", and applied a number of remote sensing techniques to estimate forest age and structure. Over a 1,237,482 ha area was investigated and an accuracy of 82 per cent was obtained. Maps of species richness have been recognized as a useful tool for biodiversity conservation and management due to its capability of explicitly describing information on the spatial distribution and composition of biological communities (Hernandez-Stefanoni et al., 2011). Hernandez-Stefanoni et al. (2011) tested remotely sensed data with regression kriging estimates for improving the accuracy of tree species richness maps, and concluded that this research will make a great step forward in conservation and management of highly diverse tropical forests.

4.6 Forest-wildlife management

Stoms and Estes (1993) proposed a framework to guide the application of remotely-sensed data in mapping and monitoring biodiversity. From then on, there are lots of works focusing on this field, e.g. Tuomisto et al. (1995), Nagendra (2001), Kerr and Ostrovsky (2003), Wang et al. (2009), Wang et al. (2010). From the perspective of remote sensing techniques, Franklin et al. (2001) developed an integrated decision tree approach to mapping land cover using remotely sensed data in support of grizzly bear habitat analysis.

4.7 Forest fires

Giglio et al. (2003) presented an enhanced contextual fire detection algorithm in order to identify smaller, cooler fires with a significantly lower false alarm rate, and promising results were obtained. Lentile et al. (2006) reviewed "current and potential remote sensing methods used to assess fire behavior and effects and ecological responses to fire".

4.8 Urban forest

Jensen et al. (2003) investigated the relationship between urban forest leaf area index (LAI) and household energy usage in a mid-size city, and concluded that the increase of LAI resulted in the less energy usage. Zhang et al. (2007) applied remote sensing to map the distribution, classification and ecological significance of urban forest in Jinan city.

5. Annotated bibliography of selected reference books

Franklin, S.E. 2001. *Remote Sensing for Sustainable Forest Management*. CRC Press, Boca Raton, FL, USA.

This book provided tools for "understanding and selecting remote sensing solutions to problems of forest management and sustainability". Examples of forest change detection, forest defoliation monitoring, forest classification, and forest growth modeling were provided, with highlights on methods from an operational perspective. The author underlined that "the remote sensing methods that need to be adopted and adapted to the forest science issues that are emerging through the sustainable forest management approach".

Wulder, M.A., and S.E. Frankllin, eds. 2006. *Understanding Forest Disturbance and Spatial Pattern: Remote Sensing and GIS Approaches*. CRC Press, Boca Raton, FL, USA.

This book provided the in-depth, detailed information through "the general biological or landscape ecological context of forest disturbance" to "remote sensing and GIS technological approaches and pattern description and analysis". Examples in this book allowed readers to "develop an understanding of the application of both remote sensing and GIS technologies to forest change and the impacts of fire, insect infestation, forest harvesting, and other potential change influences – such as extreme weather events".

Jensen, J.R. 2007. *Remote Sensing of the Environment: An Earth Resource Perspective, 2nd ed*. Prentice Hall, Upper Saddle River, NJ, USA.

This popular book introduced "the fundamentals of remote sensing from an earth resource (versus engineering) perspective". It covers the topics as follows: electromagnetic radiation principles (Ch. 2), photogrammetry (Ch. 6), image interpretation basics (Ch. 5), remote sensing platforms (Ch. 3: aerial platforms, Ch. 7: multispectral remote sensing systems, Ch. 8: thermal remote sensing systems, Ch. 9:active and passive microwave remote sensing, and Ch. 10: Lidar remote sensing), applications of remote sensing technology (Ch. 11 to Ch. 14), and in situ remote sensing (Ch. 15). This book has been chosen as the textbook for the course of introduction to remote sensing by many North American universities.

Jensen, J.R. 2004. *Introductory Digital Image Processing: A Remote Sensing Perspective, 3rd, ed*. Prentice Hall, Upper Saddle River, NJ, USA.

This book presented "digital image processing of aircraft- and satellite-derived, remotely sensed data for Earth management applications" with extensive illustrations. A state-of-the-art synopsis of the remote sensing processing algorithms and methods were provided.

Warner, T.A., M.D. Nellis, and G.M. Foody, eds. 2009. *The SAGE Handbook of Remote Sensing*. SAGE Publications Ltd., London, UK.

The handbook summarized the recent development of environmental remote sensing from theory to application, from data to algorithm, and from history to future direction. A professor graded this book as "a who's who of contemporary remote sensing". It is an excellent textbook for independent learning in advanced studies.

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This book is dedicated to global perspectives on sustainable forest management. It focuses on a need to move away from purely protective management of forests to innovative approaches for multiple use and management of forest resources. The book is divided into two sections; the first section, with thirteen chapters deals with the forest management aspects while the second section, with five chapters is dedicated to forest utilization. This book will fill the existing gaps in the knowledge about emerging perspectives on sustainable forest management. It will be an interesting and helpful resource to managers, specialists and students in the field of forestry and natural resources management.

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