A Study on Remote Sensing Implementation in the Forest Management

– Applications to the Boreal Forest Inventory and Monitoring –

森林管理へのリモートセンシング実用化の研究

－北方林の調査と監視への応用－

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INTRODUCTION

Ignoring my tender flesh and warm blood, why can you be eager to talk about morals?

– Akiko YOSANO, 1901

Since the last decades of the 20th century, people had become serious for the sustainable use of the limited resources and environment on Earth. Coincidently, the first earth resource satellite, Landsat-1, was launched in 1972, which had frightened people with its clear images of the forest destructions in remote areas, for example. Accordingly, people and researchers had assumed the satellite remote sensing as a promised tool for monitoring and managing the forest and the environment.

Now that more than three decades after the first launch, however, the satellite remote sensing has been rarely utilized in the operation of forestry in spite of a broad array of research efforts and the archive of the images. What has been wrong so far? How can these treasures be more utilized in an operational manner? These classic yet critical questions are the start of the present study.

Researchers should take a large responsibility for the situation. They have taken a great effort to what can be extracted from the remotely sensed data, but have paid little attention to how they can contribute to the forest management practices, in terms of the required information, the scale, or the frequency. In addition, their preference for universal methodologies might have hindered developing local applications for an each specific vegetation and environment.

The objective of this thesis is, thus, to develop possible operational forest inventory and monitoring systems using satellite remote sensing by analyzing the basic properties of a specific forest ecosystem in a specific climate zone and their empirical relationships with the remotely sensed data. Constant data availability is the prerequisite for the operational use, thus the data acquired in the season with the maximum data availability are to be exclusively used.

The present study specifically focuses on the boreal forest, which occupy a broad area of Earth's land surface and is supposed to be most affected by the global climate change. Clear satellite images have been acquired regularly and frequently during winter over a wide portion of the boreal forest, however, few forest researchers have paid attention to these snow-covered images in spite of such favorable properties for a regular use. Utilization of such images is studied exclusively.

The study will firstly review the history of the remote sensing for forestry applications and address the required properties of the remote sensing methodologies for forest management. Then, local forest monitoring and inventory methodologies will be developed on two specific locations, namely the Russian Far East and Central Yakutia. And finally, the methodologies will be evaluated and the roles of remote sensing in the new era of forest management will be discussed.

CHAPTER 1
BACKGROUND AND OBJECTIVES – FOREST MANAGEMENT AND REMOTE SENSING

1.1 A Brief History of the Global Policies on Forest Conservation and the Sustainable Forest Management

Since the last decades of the 20th century, the human being had become aware of the fact that our resources and environments on Earth were limited like on a single spaceship, in which we "must find (our) place in a cyclical ecological system which is capable of continuous reproduction of material form (KENNETH, 1966)". In 1972, MEADOWS *et al.* (1972) analyzed the exponential growth of the world population and economy, and predicted their "limits of growth," at best, or catastrophic falls induced by the pollution and the depletion of resources and foods. In 1980, the U.S. Government made a broad array of prediction of the world's population, resources, and environments in the next few decades (Government of the U.S., 1980), in which they predicted a denser population, more widely spread pollutions and the degraded environment in 2000 than at that time. For forest and forestry, in particular, they predicted forest destructions especially in the developing countries, a massive reduction of the biotic diversities, and potential impacts of the destruction on the global climate change. Fortunately, not all of the predictions have yet come out true by 2000, however, the critical point of these reports was that they issued a warning that we had to alter the policies immediately and actively before the problems fell in uncontrollable.

In 1990's, the sustainable management of the environment, forest in particular, became a big concern of the people over the world and the international politics. In 1992, United Nations Conference on Environment and Development (UNCED), or the "Earth Summit", was held in Rio de Janeiro. The participants of more than 180 countries and territories came to an agreement that the sustainable development and the international cooperation were important, as stated in The Rio Declaration. In other agreements, the necessities of the sustainability, international cooperation and the criteria and guidelines of forest management were emphasized, such as stated in Chapter 11 in the Agenda 21, and Preamble (c), (d)/8(d) in the Forest Principles.

Under the agreements and with the shared sense of crisis, the world then started to take effort on quantifying the forest functions as the measure for desirable conditions. In response to the requirements on the criteria and guidelines of the sustainable forest management stated in UNCED, the Criteria and Indicators (C&I) for sustainable forest management were formulated for each region with countries of similar climate and forest types (Global Environmental Forum, WWW). Japan is one of the twelve participating countries of the Montreal Process, which defines 7 criteria and 67 indicators.

The Kyoto Protocol, which was adopted in 1997 in response to The Framework Convention on Climate Change signed at UNCED, imposed on the developed countries the reduction of their overall emissions of the greenhouse gases by at least 5% below 1990 levels in the commitment period 2008 to 2012 (Article 3.1). Forestry activities will be accounted as a carbon sink, and the removals of such gases by forest should be reported in a transparent and verifiable manner (Article 3.3).

The quantifications are accomplished by measurement. Basically, a measurement is carried out by direct contact with the objects, either destructive or non-destructive. For dealing with a vast area of forest, however, also required is a methodology that can measure the whole area at once, if not as accurate as the direct measurements, and it is remote sensing (KONDO (ed), 1979). Remote sensing can play an important role in monitoring some of the (C&I's) indicators (FRANKLIN, 2001), and in the Kyoto Protocol it should be an approach for monitoring and verifying the sink activities (YAMAGATA *et al.*, 2001; YAMAGATA *et al.*, 2002).

The concept of the 'sustainable forest management' has been changing along with the changes of the recognition of forest and environment. DAVIS *et al.* (2001) classified the historical changes of the sustainable forest management into four viewpoints as below.

Viewpoint 1: Sustainable yield; this is a traditional aspect of the sustainable forest management that had dominated the forestry in Japan until recently. Following the classic German forestry principles, KATAYAMA and TANAKA (1954) defined the forest management as the method to achieve to a management goal by a well-controlled production. It must be noted, however, that even in this era the guiding principles of forest management included environmental factors such as the consistency with nature, the public welfare, and the land conservation (INOUE, 1985; NAGUMO and OKA, 2002)

Viewpoint 2: multiple use – sustained yield; At this viewpoint, heroic efforts were made to attach a market dollar value to all forest outputs (DAVIS *et al.*, 2001) to evaluate the all benefits from forest in terms of money. In Japan in 1970's, for example, the Forest Agency had estimated the public benefits from the forest as 12.8 trillion yen per year (KUMAZAKI, 1977).

Viewpoint 3: Naturally functioning forest ecosystems; it excludes the human effects from forest strictly. Though this viewpoint of the preservationists has not been common in practice in the populated land of Japan, some efforts yielded the results in the Strict Natural Reserves.

Viewpoint 4 is the latest concept of the forest management in that all of the previous three viewpoints are integrated. It is also referred as "ecosystem management" or "ecological forestry". It largely depends on the idea of sustaining ecosystems as the Viewpoint 3, while it accepts effects by the people near or in the forest and envisions the coexistence of man and nature (DAVIS *et al.*, 2001). At the same time, this view gives up the stable flow of wood as a universally dominant management objective (GORDON, 1994). Public understanding and participation are also emphasized (DAVIS *et al.*, 2001).

In Japan, the Basic Law of Forestry was revised and renamed the Basic Law of Forest and Forestry in 2001 for the first time since its enactment in 1962, so as to meet a broad range of recent interests and demands of the citizens on forest (Forest Agency, 2001). That meant a shift of the Japan's forest policies from the production-oriented (Viewpoint 1 or 2) to the ecology-oriented (Viewpoint 4).

Natural disturbance patterns and processes are a key concept as a guide to implement the ecological forestry (DAVIS *et al.*, 2001). The central axiom of ecological forestry is that manipulation of a forest ecosystem should work within the limits established by natural disturbance patterns (SEYMOUR and HUNTER, 1999). To describe a specific disturbance regime, at least three parameters must be quantified; return interval, severity, and spatial pattern (PICKETT and WHITE, 1985; SEYMOUR and HUNTER, 1999; DAVIS *et al.*, 2001), which should be observed carefully statistically analyzed adequately so that the ecological forestry can emulate the disturbance regime.

Though the concept of the ecological forestry should be suitable for today's forest management, its implementation to the real management is rather difficult and the methodology has not quite established yet. One of the reasons should be that it requires seeing a forest from varied aspects, such as the disturbance regime, which are often difficult to measure by conventional means.

As will be reviewed in the following sections, remote sensing has its advantages in its coverage of space and time that cannot be achieved by any other means. Thus, remote sensing should be able to contribute to measuring some of the aspects for the modern sustainable forest managements.

1.2 Forest Planning and Remote Sensing

No matter which one of the forest management concepts is adopted, treatments of a forest are to be planned prior to any activities. Forest planning is a process that usually consists of five steps; 1) identify goals and resources for planning, 2) assess forest condition and history, 3) develop plan alternatives, 4) make a decision, and 5) prepare plan documents (DAVIS *et al.*, 2001). Any kind of planning must be followed by the implementation of the plan and the assessment of the implementation (HIRATA, 1983). Therefore, the forest managers must know where the natural resources occur and what their condition is (HELLER *et al.*, 1983). A prior assessment of the forest during the planning (step 2) and a posterior assessment during or after the implementation are, thus, indispensable, which are referred to 'inventory' and 'monitoring', respectively.

There are three levels widely used in the forest planning, namely, strategic, tactical, and operational (WEINTRAUB and CHOLAKY, 1991; HOLMGREN and

THURESSON, 1998; FRANKLIN, 2001; DAVIS *et al.*, 2001). The strategic planning is an overall and long-term planning at forest or ownership level, in which a broad resource allocation is required, but the spatial resolution and precision are of less importance. The tactical planning is the assignment of forestry activities 'where,' 'when,' and 'how' to each stand. For this level, each stand description and spatial relationship among the stands is to be known. A database with a complete coverage of stands in the forest is required. The operational planning is a list of procedures within a target stand in a very short-term. This level needs local and present condition's information with a sub-stand level spatial accuracy and precision.

To accomplish the forest inventories and monitoring at each of the three levels, numerous methods and techniques of the forest mensuration as well as the computation and estimation of forest resource distribution have been developed and implemented (KINASHI, 1978; BITTERLICH, 1984; OSUMI (ed), 1987; NAGUMO and MINOWA, 1990; SHIVER and BORDERS, 1996). The multistage statistical sampling technique has been usually adopted for the forest resource estimations of broad area in conjunction with stand and tree measurements. Aerial photos and/or satellite images have been introduced as upper stages of the multistage sampling, either experimentally or operationally, from relatively early time since their invention (NAKAJIMA *et al.*, 1970; KONDO (ed), 1979; HELLER *et al.*, 1983; STELLINGWERF and HUSSIN, 1997).

Such remote sensing means like aerial photos or satellite images are superior to other forest measurement means at their simultaneous extensive coverage of ground and the repetition (KONDO (ed), 1979). In addition, after several decades since the beginning of aerial photos and satellite images, the archives of such data allow us the retrospective monitoring of forest to describe the present conditions from historical viewpoints. Appropriate combination of the remote sensing means, ground measurements and other records and descriptions will be critical for the inventory and the monitoring (DAVIS *et al.*, 2001)

Numerous researches regarding the implementation of the aerial and satellite remote sensing to the forest inventory and monitoring have been carried out. In the next section, the principle of the remote sensing and its current state for the forest management will be reviewed.

1.3 Remote Sensing for the Forest Management

Remote sensing has been a valuable source of information over the course of the past few decades in mapping and monitoring forest activities (FRANKLIN, 2001). Foresters have been among the first to use aerial photographs and remote sensing data (HELLER *et al.*, 1983). In Japan, aerial photographs have been taken every five years all over the land by either Forest Agency or Geographical Survey Institute since 1950's (WATANABE, 1987) and used widely for the forest management and planning practices.

The development of satellite remote sensing, in particular, has coincided with the changes of the global environmental policies as mentioned in the previous section. It was 1972 when the first earth observation satellite, Landsat-1, was launched. The satellite contributed to first expose, for example, the large forest destruction in a remote area of Amazon (Government of the U.S., 1980). Since then, a fleet of the earth observation satellites has been launched from the U.S., Europe, Japan and other countries.

So, what is actually the remote sensing? Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (LILLESAND and KIEFER, 1994). Electromagnetic energy is most widely used as the energy source to be remotely sensed, though other sources (*e.g.* sonic waves, seismic waves, or gravitational force) can be also used (LANDGRABE, 1978). Among the use of the electromagnetic energy, optical/infrared energy and its sensors, that is, aerial photos and optical satellite images, have been the most common in forestry (FRANKLIN, 2001). In this section, thus, the optical/infrared remote sensing will be further reviewed. Radar (radio detection and ranging), especially synthetic aperture radar (SAR), is widely studied for forest inventory and monitoring (*e.g.* MITSUZUKA *et al.*, 2000), though, it would not be further reviewed since its unique and different properties, processing methodology, and problems than the optical/infrared. In addition, though lidar (light detection and ranging) (*e.g.* OMASA *et al.*, 2003) and high resolution images (*e.g.* AWAYA *et al.*, 1998) are definitely promising data sources for forest management for their possibility to describe the height and volume of individual trees, they would not be mentioned here since their scales are larger and coverage are smaller than the conventional optical/infrared sensors.

By definition, some ground measurement techniques, such as the Bitterlich's method (BITTERLICH, 1984) or hemispherical photo measurements (PEARCY, 1989; RICH, 1990), are also remote sensing techniques. However, the following review will limit its scope to the air-borne and satellite remote sensing that have their advantage in their extensive coverage on ground as already mentioned.

Many authors listed the fields in the forest management for which remote sensing can be applied. SAWADA (1998) argued six possible applications of remote sensing, namely, forest distribution estimation of an extensive area, forest type mapping for regional forest managements, estimation of crown closure and standing volume, monitoring of forest health and disease outbreaks, monitoring of disasters such as fires or landslides, and landscape parameter estimation for the ecological process estimation. HOLMGREN and THURESSON (1998) divided into two large classes, the inventory and the monitoring. Then, the inventory was further divided to land classification, estimating forest variables, forest segmentation, landscape ecology, and large scale forest inventories, and the monitoring was divided to damage monitoring and forest operation monitoring. FRANKLIN (2001) organized, from a rather technical point of view, as classification of forest cover type, estimation of forest structure, and forest change detection. These insights can be summarized that the remote sensing techniques for forestry are divided into the corresponding needs of forest observation, that is, 1) the inventory, by which the current forest status is described by either discrete classifications or continuous variable estimations, and 2) the monitoring, by which the expected or unexpected changes in forest are delineated through time.

<u>1) Forest inventory</u>

<u>1-1) Classification</u>: Image classification is a fundamental technique of mapping by

remotely sensed images that automatically categorizes all pixels in an image into land cover classes or themes (LILLESAND and KIEFER, 1994). The keys for a successful classification is 1) totally exhaustive, 2) mutually exclusive, and 3) hierarchical class assignment (GREEN, 1994). Numerous methods of classification have been proposed and applied, which usually use multivariate (multi-spectral, multi-temporal, multi-source, *etc.*) data processed by either parametric or non-parametric methods, and either supervised or unsupervised methods.

From early days, multi-spectral data consisting of different wavelength channels were used to classify the forest types (*e.g.* AWAYA *et al.*, 1983; NAKAKITA *et al.*, 1989). Multi-temporal images taken in different phenological stages within a short period are widely used for improving the classification accuracy (*e.g.* CONESE and MASELLI, 1991; WOLTER *et al.*, 1995; YAMAGATA *et al.*, 1996). This type of classification in many cases utilizes the fact that the amount and the spectral characteristics of foliage change through season and they depend on species (AWAYA and TANAKA, 1999). As the spatial resolution became as high as 30m of Landsat TM and more, the image texture, or measures of image roughness, was combined in the classifications (*e.g.* TSUYUKI and OHNUKI, 1986; PEDDLE and FRANKLIN, 1991). In areas with steep terrain, digital terrain models were introduced to compensate the differences of illumination depending on the slope to increase the classification accuracies (*e.g.* SENOO *et al.*, 1990; FRANKLIN *et al.*, 1994).

A different approach of classification is the endmember classification (ADAMS *et al.*, 1995), which assigns to a pixel a composition of a limited number of endmembers with unique spectral patterns in a multi-spectral space, instead of assigning only one class to each pixel as above-mentioned methods. This method allows estimating a small portion of an endmember within a mixed pixel. It is used for scaling up the satellite image observation from fine to coarse resolution (TAKEUCHI *et al.*, 2003), or describing forest structures (NAKAZONO *et al.*, 2000; ONO and FUJIWARA, 2002). This approach plays an important role in the forest canopy models, as discussed later in this section.

<u>1-2) Forest structure estimation</u>: here this means any methods to estimate some

continuous forest-related parameters from remotely sensed data. First, let's look around some empirical attempts; AWAYA (1997) and AWAYA (1998) estimated the stand ages of spruce plantation from Landsat TM images using the fact that the reflectance of forest canopy reduced with age. They suggested, though, the reflectance of the spectral bands represented not only the ages but also the canopy structures, *e.g.* the age after thinning. AWAYA *et al.* (2000) also estimated the dominant tree height and stand volume using CASI data. LEE and NAKANE (1997) empirically estimated biomass of different types of forests in western Japan from several types of vegetation indices derived from Landsat TM images. They found different indices were suitable for different forest types for the estimation. ANDERSON *et al.* (1993), GEMMELL (1995), and TROTTER *et al.* (1997) estimated the stand biomass or volume from Landsat TM images, and they found adequate aggregations of pixels promoted the estimation accuracies, which suggested the TM pixels of 30m by 30m contained a certain amount of local random variation.

Canopy reflectance models based on geometric-optical modeling are semi-empirical approaches to basically estimate the canopy closure. The common characteristics of these models is that they take into account the three-dimensional shape of tree crown and its heterogeneous distribution on the ground, and calculate the reflectance as a mixture of tree crown, floor, and shadow of the crown cast by the sun, which often results as an endmember model. As a result, they yield in the multi-spectral reflectance space a trajectory from the open floor to the completely closed canopy that plots not a straight line but a curve through darker reflectance caused by the shadow. LI and STRAHLER's model (1985) is one of the first such models. ROSEMA *et al.* (1992) proposed an easily invertible model, FLIM. JUPP and WALKER (1997) applied a geometric-optical model to separate shrubs from woods. HUEMMRICH (2001) made a discontinuous canopy reflectance model, GeoSail, based on a homogeneous canopy reflectance model, SAIL (VERHOEF, 1984). COHEN *et al.* (1995) and JAKUBAUSKAS (1996) found the similar trajectories from their observations of forests and imagery and suggested the effect of shadow in sparse canopies.

In contraposition to the empirical and semi-empirical models, a process-based model implies a model of a system and its behavior, at whatever level of complexity, based on the (sub-) models of the constituent processes that together determine the behavior and responses of the system (LANDSBERG, 2003). In such models, remotely sensed data are used as model inputs, model testing, model adjustment, or for model inversion (PLUMMER, 2000). Remote sensing's contributions as input to the models are mainly the frequent estimation of leaf area index (LAI), fraction absorbed photosynthetic active radiation (f_{APAR}), and, as consequence, net primary product (NPP) (SELLERS, 1989; GOWER *et al.*, 1999). Many authors argued the advantage of the process-based models over the conventional empirical models as the flexibility to extrapolate the prediction to a never-happened condition, and the disadvantage as their complexity (HOLMGREN and THURESSON, 1998; WULDER, 1998; FRANKLIN, 2001; LANDSBERG, 2003). Thus, the combined approaches of empirical and process-based models are recommended for an increase in the ability to estimate forest inventory and biophysical parameters (WULDER, 1998; FRANKLIN, 2001; LANDSBERG, 2003).

2) Forest monitoring

As previously reviewed, forest management requires monitoring of the forest of interest to confirm the implementation of a forest plan. The monitoring is accomplished by detecting the expected and/or unexpected changes occurred in the forest, such as forestry operations, either scheduled or unscheduled (illegal), any kind of damages, or forest growth. The change detection techniques of remote sensing can be applied to such forest change detections.

The change detection is an important branch of remote sensing that relies on various techniques (SINGH, 1989; COPPIN and BAUER, 1996; LUNETTA, 1999). The principal component analysis (OHNUKI *et al.*, 1982) and the change vector analysis (AWAYA *et al.*, 1986) have been among the widely used techniques. HAYES and SADER (2001), and WILSON and SADER (2002) used the unsupervised classification of RGB-NDVI color composite (SADER and WINNE, 1992) to detect multitemporal canopy changes. MUCHONEY and HAACK (1994) found that forest defoliation could be monitored well by both the changed component of the principal component analysis and the image differencing. COHEN *et al.* (1998) used image differencing to map forest clear-cuts. For image differencing, several relative radiometric normalization methods were proposed such that the difference of unchanged points would distribute around null (SCHOTT *et al.*, 1988; HALL *et al.*, 1991; HEO *et al.*, 2000; DU *et al.*, 2002).

The change detection techniques have been applied to the cut detection (*e.g.* OHNUKI *et al.*, 1982; AWAYA *et al.*, 1986; TAKAO *et al.*, 1989; TAKAO, 2004), or the damage detections, such as insect outbreaks (*e.g.* FRANKLIN, 1989; HIGASHI, 1990; KAMATA, 1990), windfalls (*e.g.* TAKAO, 1992; SAITO and NAKAKITA, 1999), landslides (*e.g.* KAMIBAYASHI and ISHIMORI, 1990), and fires (*e.g.* CUOMO *et al.*, 2001; ROY *et al.*, 2002). TAKAO (2004) also suggested the ability to detect the recovery of vegetation after clear cuts by satellite images.

For the change detection using multi-temporal images, the precise overlaying of the images of different dates is critical. Using the first generation sensor of Landsat MSS whose geometric registration was not as good as today's sensors, TAKAO *et al.* (1989) found that the mistakenly extracted cut stands occurred mainly at forest edges between forest and open land. To reduce such mistakes from the imprecisely geo-registered images, they detected the whole forest edges by image processing prior to the cut detection and removed them from the subject of the change detection, and then they earned a higher accuracy of the cut detection. Today, the geometric registration of the recent sensors are much more precise than before, and the images can be more precisely overlaid by removing the terrain distortions using digital elevation models (ITTEN and MEYER, 1993). However, cautions and adequate treatments have yet to be exercised for the registration of multiple images for the change detections.

In addition to the inventory and the monitoring, landscape analyses (*e.g.* Goshawk's preference along forest edges (TAKAO *et al.*, 2003)) or large scale forest inventories (*e.g.* Finnish national forest inventory (TOMMPO, 1996)) are examples of the complex applications of remote sensing in multi-source manner. In such complex applications, geographic information systems (GIS) are indispensable (SAWADA, 1990; FRANKLIN, 2001), and the remote sensing data are indispensable for such geographic analyses on GIS because the remote sensing can reflect the ever-changing nature of vegetation and other landuses (AMANO, 1981). GIS can be used for the preprocessing of remotely sensed data as well (SENOO *et al.*, 1990; ITTEN and MEYER, 1993; MURAKAMI, 2002). Analyses of remotely sensed data on GIS are to be, and have already been, the standard procedures for any kind of applications.

1.4 Is the Remote Sensing Actually Implemented in the Forest Management?

In spite of the huge endeavor on the researches, many authors gave negative answers to the question above. HOLMGREN and THURESSON (1998) concluded after a review that satellite remote sensing is, for many applications, not suitable for supporting forestry planning. WYNNE and CARTER (1997) stated, despite much hype and promise, satellite remote sensing was rarely used in day-to-day forest resource management. Even FRANKLIN (2001) stated in his book "*Remote Sensing for Sustainable Forest Management*" that remote sensing had not yet succeeded in the practical world – the world of application.

The problems can be summarized to three factors; the resolution and accuracy, the lack of mutual comprehension between the researchers and the managers or the remote sensing people and the foresters, and the data availability. The coarse resolutions of the conventional satellite images, such as Landsat TM with a ground resolution of 30m, have not satisfied the forest managers (WYNNE and CARTER, 1997), and the cost of evaluating the accuracies are too expensive (HOLMGREN and THURESSON, 1998). The resolutions and their appropriate scales are inherent in the sensors. Though the resolutions are not sufficient for the landscapes with patches of landuse or forest type as small as the resolutions, still they are sufficient for the other landscapes with larger patches. The evaluation cost can be reduced if the time and labor of the ground truth collection are reduced due to simple and easy measurements.

The lack of mutual comprehension is a big issue. There appeared to be real differences between problems that were found to be resolvable by remote sensing and the problems that people actually needed to have solved (FRANKLIN, 2001), and the difference has been left between the remote sensing people and the possible users. For example, LAI has been well estimated using satellite remote sensing, however, it will not be of any major assistance to forest management decision-makers (HOLMGREN and THURESSON, 1998). Forest managers expect from the remote sensing the same or comparable parameters as measured on the ground, *e.g.* tree species, stand age, mean DBH, mean tree height, basal area, or growing stock, *etc.* The researcher's interests tend to explain phenomena more precisely and smarter, which usually result in complicated models demanding many sorts of input and output. Such fancy models often fall into overfitting (HOLMGREN and THURESSON, 1998) because of the more complexity of the real nature. Above all, foresters can hardly measure all the required parameters for such models at all the managed stands. So, these kinds of models can hardly be used in practice. Forest managers want a simple, robust and easy-to-understand model that explains the whole forests but merely within the extent of management, but such models have rarely stimulated the researchers' interests.

When one attempts to develop a remote sensing method robust enough for the operational and regular use, the stable image availability in the region of interest is among the first things to be considered. TAKAO (2000) searched Landsat TM scenes with the cloud-cover equal to or less than 20% in the Russian Far East from 1984 to 1999, and he found that only 0.4 scenes per year had been acquired from June to August while 1.9 scenes per year from January to March. Though virtually all the remote sensing methodology so far to observe vegetation used the images of the vegetation-growing season, this statistics revealed such methodology can hardly be applied to the region. WOLTER *et al.* (1995) improved the classification accuracy by using the satellite images taken in autumn when the deciduous trees changed their leaf color. However, it should be very difficult to take appropriate images regularly during the phenologically unstable season, or even impossible in mountainous region where the phenological season changes along with elevation. For operational use of remote sensing data, only suitable are the methods that utilize the images of the season when the chance of good image acquisition is high and the vegetation and other conditions are stable.

Scientists must evaluate what forest attributes are best observable, how they can be measured by current optical sensor, and how these attributes relate to important functional processes (PETERSON and RUNNING, 1989). Forest managers require robust, easy-to-measure and regularly updated information on their own forests. As the obstacles reviewed above indicate, there has been no universal methodology that suffices both the scientists and the managers of all over the world. However, still there might be room for such methodology in a specific landscape. If one can find out within a limited landscape a certain relationship between the ground measurements and the satellite images that are supplied in regular manner, these images will provide stable and regular information to the managers in the region, while the relation will give the scientists insights of the response of forest structure on the images even if it can not be extrapolated to other landscapes directly. Thus, a possible scenario to develop a remote sensing application to the local forest management is 1) specifying the landscape of interest, 2) identifying the season when the satellite images can be taken regularly, then 3) exploring empirical relationships between the images and the ground-measured forest parameters.

1.5 Boreal Forest – the Landscape of Interest

Hereafter throughout the thesis, the landscape of interest is exclusively targeted to the boreal forest in Russia.

Boreal forest is one of the biggest ecosystems on the earth that occupies 11% of the land surface and accounts for nearly a half of the carbon that is contained in the forest of the world. In addition, the most significant temperature change is predicted there in association with the global warming (See Chapter 2 for details). In consideration of the important roles of the boreal forest in the global environment as discussed in the Chapter 2, there is an urgent need for reliable and robust means of the inventory and monitoring to support the local forest management practices in the boreal forest.

In the boreal forests, the winter precipitation is much less than the summer's at many locations (BONAN and SHUGART, 1989), which suggests that there are more chance to take cloud-free images through the clear sky in winter than in summer (TAKAO, 2000). Winter lasts long in the boreal and the vegetation keeps dormant and stable during the winter. Snow covers the forest floor and simplifies the components of a forest ecosystem into snow, trees, and their shadow, which is supposed to allow the winter satellite images to be correlated to the trees more strongly than the summer images with complex floor. These simplified components, with relatively simple species compositions and rather sparse canopies of the boreal forests, would also allow correlating the reflectance empirically with the stand parameters such as volume. Landsat images are utilized so that the vegetation can be retrospectively monitored back to more than three decades ago.

In spite of the above-mentioned favorable characteristics of the winter images for forest observation, there have been few precedent studies (*e.g.* HAFKER *et al.*, 1982; FERNANDES *et al.*, 2002), though there have been so many studies by snow researchers who have attempted to remove the vegetation to observe the snow below (*e.g.* HALL *et al.*, 1998; KLEIN *et al.*, 1998; SAITO and YAMAZAKI, 1999).

1.6 The Objectives of the Thesis

The reviews in the previous sections led the author to a need for developing remote sensing methodologies for forest management that suffice the following conditions;

1) Describing the current forest condition by stand parameters conventionally measured by and familiar for foresters,
2) Depending on the characteristics of local ecosystems and climate,
3) Utilizing images taken in the season when the sky is clearest and the phenology is stable,
4) Using images of the conventional optical/infrared sensors so that the forest can be retrospectively monitored, and

5) Utilizing the winter satellite images with snow in the boreal forests.

The objective of this thesis is to develop possible operational forest inventory and monitoring systems using satellite remote sensing in boreal forests that suffice the five above-mentioned conditions by analyzing the basic properties of boreal forests and their empirical relationships with the remotely sensed images.

In Chapter 2, the current status and the reflectance properties of the boreal forests will be discussed further, respectively. Then, a forest monitoring system with indices derived from a time series of winter satellite images will be proposed in Chapter 3. In Chapters 4 and 5, a forest inventory model will be proposed in which the stand growth of the local vegetation are measured and analyzed for the model construction. Finally, the role of remote sensing in the era of the new forest management concepts will be discussed in Chapter 6.

CHAPTER 2
BOREAL FOREST

2.1 Boreal Forest

The boreal forest encompasses a circumpolar belt from approximately 47 to 70° north latitude comprising an area of 14.7 million km^2, 11% of the earth's land surface, which includes areas of Russia, China, Norway, Sweden, Finland, and from Newfoundland to Alaska (BOURGEAU-CHAVEZ, 2000)(Figure 2.1). They are covered by homogeneous arboreal stands, dominated by conifers (*Abies, Picea, Pinus, Larix*) during later stages of succession, and by arboreal members of the birch (*Betula, Alnus*) and willow (*Salix, Populus*) families in early successional stages (SOLOMON, 1992). The climate is characterized by strong seasonal variation with short, moderately warm, and moist summers and long, extremely cold, and dry winters (BONAN, 1989). Throughout the boreal forest, annual rainfall is relatively light, but even in extremely arid regions, sufficient moisture for tree growth is provided by the slow thawing of permafrost (BONAN, 1989). Because of the low temperature and the water-saturated condition induced by the permafrost, the rates of decomposition in the soil are very low, which results a large amount of carbon storage in the soil compartment (KASISCHKE, 2000).

The permafrost, which is almost coincided with the boreal forest (BONAN, 1989; KANE, 1992; KASISCHKE, 2000), had been formed by the last glacial period of about 14 thousand years ago. It has not disappeared in the post-glacial warming period not as the ice sheet has, because of the delay of thermal conduction into the underground and the vegetation covers that rapidly recovered and insulated the heat (FUKUDA and TAKAHASHI, 1999). This current condition is called the thermal destabilization of the permafrost, which can be easily broken by removal of the vegetation then lead to a irreversible vegetation cover change (FUKUDA and TAKAHASHI, 1999). Once the vegetation is removed, and if the underground ice beds shallow, the heat melts the ice and consequently the ground subsides, and then the place becomes a lake called 'alas' (FUKUDA, 1997)(Figure 2.2).

The boreal forest accounts for nearly half of the carbon that is contained in the forest of the world, that is, 88Pg in the boreal out of 359Pg in the world in vegetation, 471Pg out of 787Pg in soils, and 559Pg out of 1146Pg in total (DIXON *et al.*, 1994). Several general circulation models predict that the most significant temperature changes associated with global warming will occur in regions of boreal forest and tundra (STOCKS *et al.*, 2000), which will result in vast changes in the vegetation of these regions. On the other hand, the vegetation changes in boreal forests are expected to alter the climatic changes (BONAN *et al.*, 1992). In this century, the boreal forest is likely to shift from a net sink to a net source of atmospheric carbon by the deforestation activities and an increase of disturbances (fire and insects and pathogens) caused by the climate change (KASISCHKE, 2000).

Boreal forest is subject to several kinds of disturbance. Fire is the most important factor affecting forest structure (GOLDMMER *et al.*, 1996; KOROVIN *et al.*, 1996; LEVINE *et al.*, 2000). Annually 8 million ha of the boreal forest is burned in average (LEVINE *et al.*, 2000), though the number and area of fires varied by years (KASISCHKE, 2000). In Russia, the annually burned area varied between 2,000 and 27,000 km^2 per year according to the official record from 1947 to 1992 (KOROVIN, 1996). However, in 2002, nearly 120,000 km^2 of forest fire was detected by remote sensing in the Asian part of Russia alone (SUKHININ *et al.*, 2003). It should be noted, though, that Russia's official estimates are usually much lower than the ones from remote sensing (STOCKS *et al.*, 1996; SHVIDENKO and NILSSON, 2000). The prevalence of wildfire has lead to adaptations to fire for many boreal tree species (BOURGEAU-CHAVEZ, 2000). For example, *Larix gmelinii*, *L. sibirica*, *Pinus sylvestris*, or other boreal tree species are fire-tolerant due to their thick bark (NIKOLOV and HELMISAARI, 1992). The mortality of trees against a given intensity of fire depends on the succession stage of the stand, and once a stand-replacing fire occurs, dominant species are often replaced with others (SHVIDENKO and NILSSON, 2000). Main natural causes of fire ignition are lightning, but they occupy only 15% of the total fire causes in Russia, and many others are anthropogenic causes, *i.e.* negligence and arson (KOROVIN *et al.*, 1996).

Logging is another disturbance. In the Russian Far East, where the study of Chapter 3 was carried out, forest resources have been consistently diminishing since the Soviet era through exploitation or other disturbance (KAKIZAWA, 2002a), even though the forests there support a very high level of biodiversity (World Bank, 1997). Clear cutting, which accounts for 90% of harvesting (KAKIZAWA, 2002a), exploits the forest in operations of very low efficiency (KAKIZAWA, 2002b). In addition, there are so many illegal loggings in the region, the estimates of which vary greatly depending on the source (NEWELL *et al.*, 2000; YAMANE and KAKIZAWA, 2002).

The boreal ecosystems have been studied for long time and from varied aspects, and there have been several comprehensive campaigns of the boreal forest studies. The Boreal Ecosystem-Atmosphere Study (BOREAS) was a large-scale international investigation focused on improving the understanding of the exchanges of radiative energy, sensible heat, water, CO_2, and other radiatively active trace gases between the boreal forest and the lower atmosphere (SELLERS *et al.*, 1997). It was carried out in Canada and the USA. GAME-Siberia was a Japanese-run study of terrestrial ecosystems and the atmosphere in Siberia (*e.g.* OHTA *et al.*, 2001). There have been prescribed fire experiments. FIRESCAN (the Fire Research Campaign Asia-North) was one of them, which burned a forest stand, 'Bor Island', in 1993, and the pre-fire history, the emission from the burning fire, the post-fire regeneration, *etc.* were comprehensively studied (FIRESCAN Science Team, 1996). FROSTFIRE was another prescribed fire of a watershed scale burned in 2000 in Alaska (HINZMAN *et al.*, 2003). In Russia, there has been a huge amount of research archives, though few of them are available in English for foreigners (SCHULZE *et al.*, 1995).

2.2 Reflectance of Snow and Forest

Boreal forests are covered by snow during its long winter, and snow has a unique spectral reflectance. At the visible wavelengths, the spectral reflectance approaches unity, which is the reason why snow looks white. At the mid-infrared wavelengths (1.4 – 2.5 μm), the spectral reflectance is lower than 0.3 (DOZIER, 1989). The reflectance at the near- and mid-infrared wavelengths is sensitive to the grain size of snow, while that at the visible wavelengths is sensitive to finite depth and the presence of impurities (DOZIER, 1989)(Figure 2.3).

When trees project through snow cover, the surface reflectance at visible wavelengths becomes much lower than that of the pure snow cover. HALL *et al.* (1998) showed that the reflectance of snow-covered low vegetation was as high as that of snow-covered lakes while that of forests was lower than that of snow-covered lakes. KLEIN *et al.* (1998) modeled and measured the surface reflectance of deciduous and coniferous (evergreen) canopies with/without snow cover, and proposed a supplemental envelope to NDSI–NDVI (normalized difference snow index – normalized difference vegetation index) space, to detect the snow under forest canopies. SAITO and YAMAZAKI (1999) measured the reflectance of model stands of fir seedlings on snow and showed that even the sparsest model stand had significantly lower visible reflectance than pure snow. They proposed improved vegetation and snow indices by combining the visible, near-infrared and mid-infrared bands.

Given that no tall manmade objects are present within images and the snow cover is deep enough to hide the floor vegetation, the brightness of a snow-covered image is a function of the forest cover, regardless of the forest floor condition (Figure 2.4).

The boreal summer is short, which makes the chance for acquiring satellite images of fully foliated vegetation much less than in the warmer climatic zones. If winter images can be utilized, then satellite remote sensing can achieve wider and more intensive application in monitoring and management of boreal forests.

In spite of these supposedly favorable characteristics of the snow-covered images for forest observation, there have been few precedent studies. HAFKER *et al.* (1982) briefly pointed out an advantage of snow-covered images over summer images on the clear-cut interpretation. FERNANDES *et al.* (2002) used winter images taken by the air-borne CASI to estimate the leaf area index of a spruce stand of the BOREAS plots. Several reasons for the limited precedence can be supposed. One is the low sun elevation angle; in the high latitude regions where boreal forests locate, the sun elevation angle is low especially in winter, which makes the dynamic ranges of image quite low, and observation is even impossible at northern slopes of rugged terrain. Another reason might be the snow suspended on canopy (*e.g.* NAKAI *et al.*, 1999), which had not been taken into account neither in the precedent studies nor will be in the present study.

Figure 2.1 Distribution of the boreal forest

(from Natural Resources Canada

http://atlas.gc.ca/site/english/learningresources/theme_modules/borealforest/borealcircum.gif/image_view)

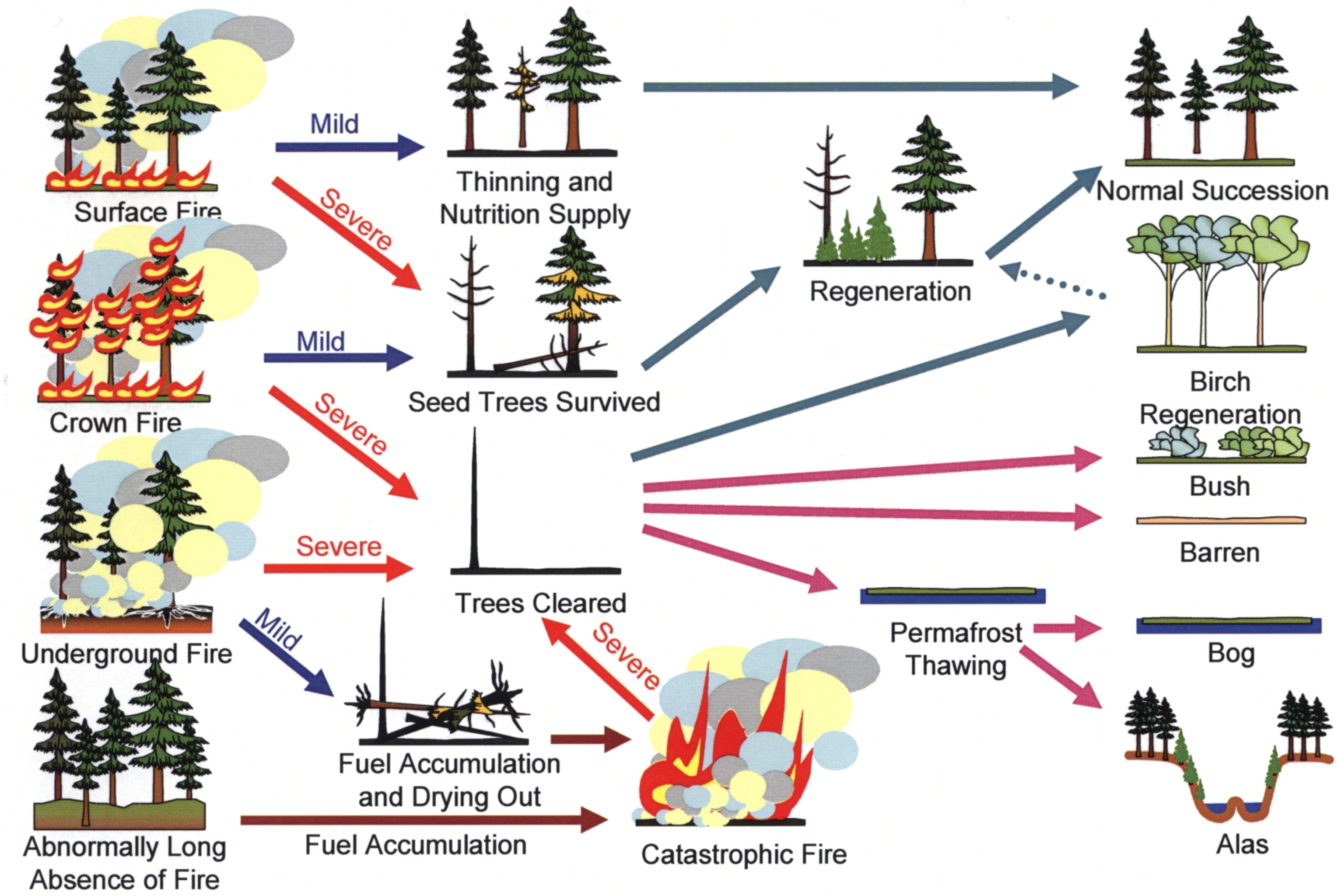


Figure 2.1 Fire and forest on the permafrost

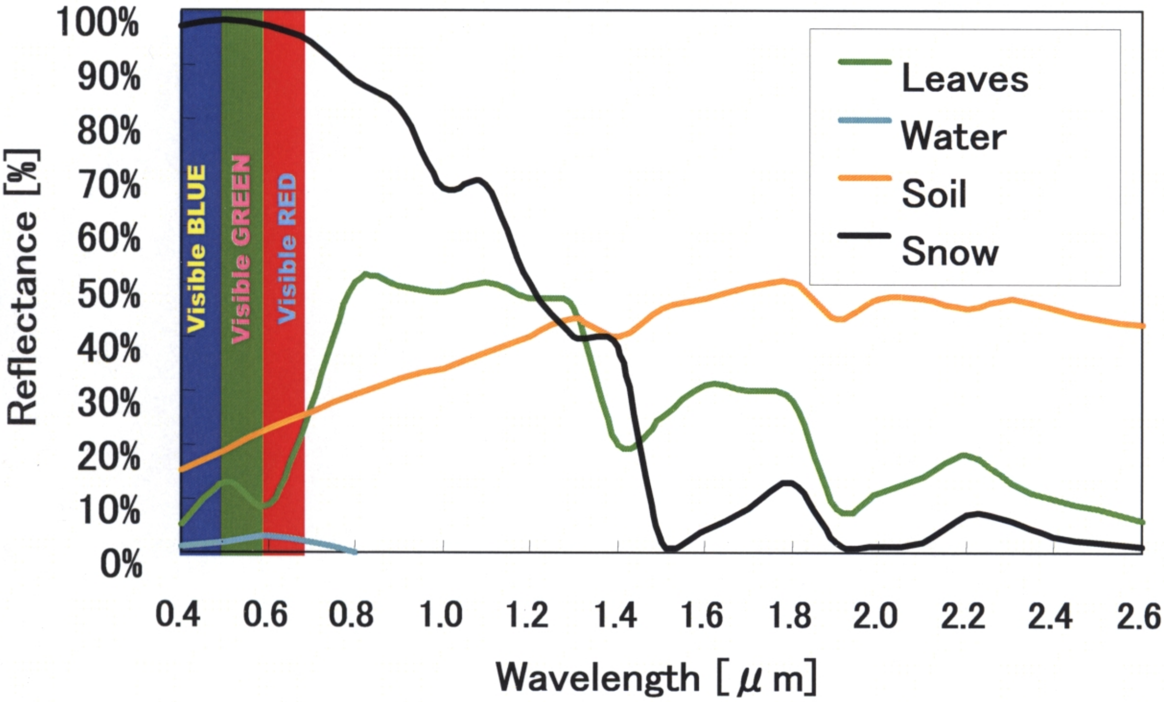
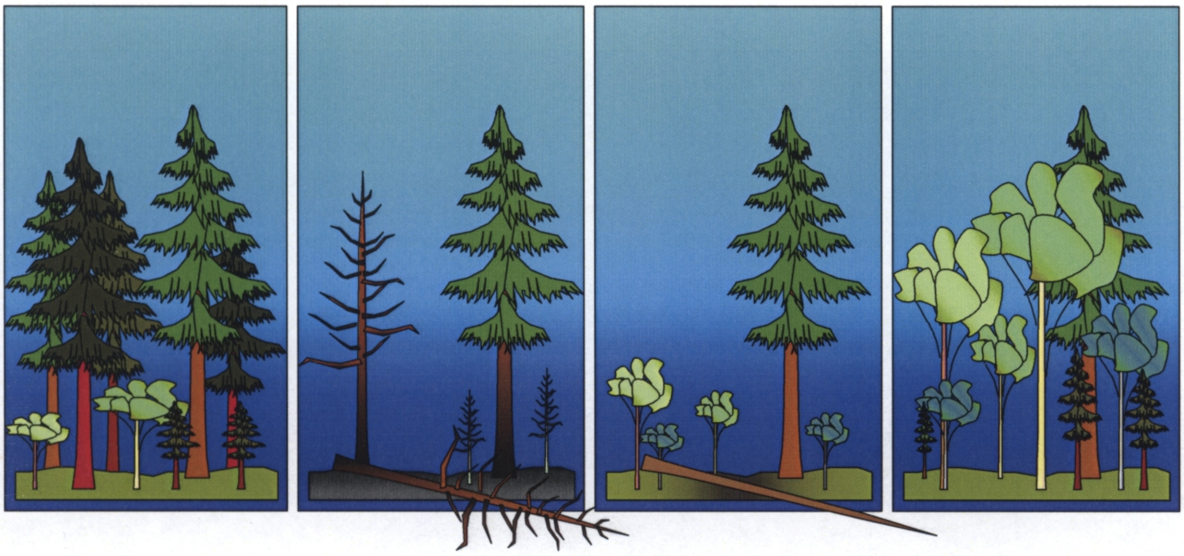
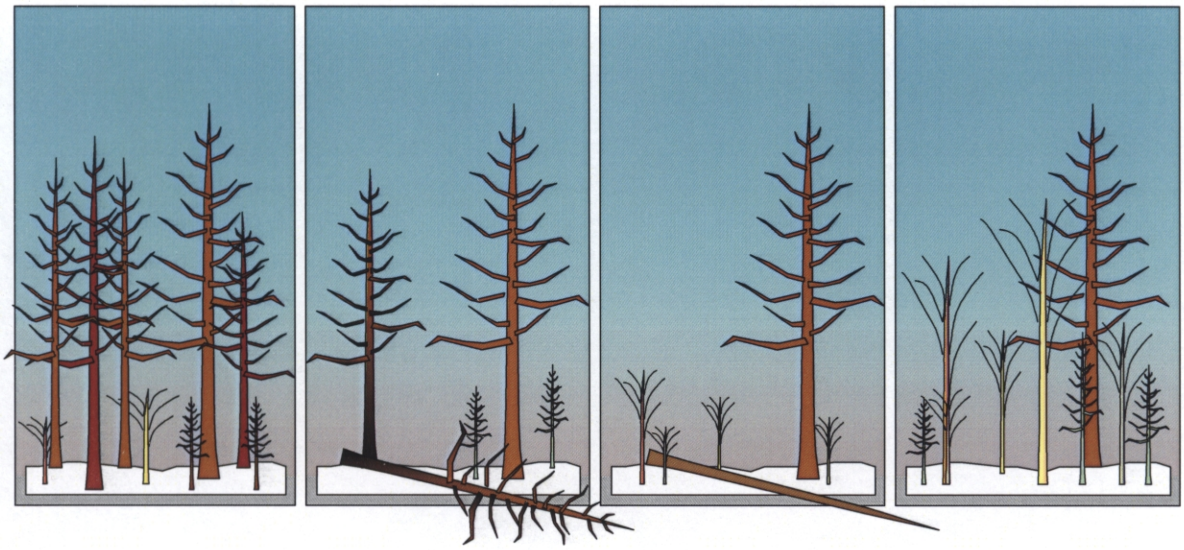


Figure 2.2 Spectral reflectance of snow and vegetated land covers

(drawn after DOZIER, 1989)



(a) Summer



(b) Winter with snow cover

Figure 2.3 Schematic diagrams of the dynamics of forest canopy and floor through disturbance and recovery

In summer, the forest is observed from above as a mixture of the canopy of high trees and the floor. In winter, snow as a homogeneous media hides the floor and only the canopy is observed from above, though all the living and dead trees look alike in deciduous forests.