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Remote Sensing of Natural Disturbance Caused by Insect Defoliation and Dieback: a Review

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Preface

The objective of this report is to review the requirements for disturbance information, the manifestation of damage patterns that may be encountered, and to provide an overview of remote sensing sensors and change detection methods that have been, or could be applied to mapping of insect defoliation and aspen dieback. It was developed with financial support from the Canadian Space Agency (CSA) by the Canadian Forest Service (CFS) and the Canada Centre for Remote Sensing (CCRS) as part of a Government-Related Initiatives Program (GRIP) project entitled “Gauging the Health of Canada’s Forests: Accounting for Insect Defoliation and Dieback in the Indicators of Sustainability for Canadians”. The report was first submitted as a deliverable to the CSA in 2007 and reviews the utility of both optical and radar remote sensing sensors and change detection approaches. For this release of the report as a Geomatics Canada Open File, the text was revised in part to relay major developments regarding the availability of satellite sensors and change detection methods in particular. A comprehensive review of literature published after 2007 was beyond the scope of the revision. A recent review paper by Hall et al. (2016) draws from this report but is limited to a discussion of the utility of optical sensor systems and change detection methods.

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1.0 Introduction

Knowledge about natural disturbances in Canada's forests is fundamental to understand their impacts on carbon and carbon stock changes (Kurz and Apps 1999). Particularly in the boreal forest, the frequency, size and severity of disturbances largely control the inter-annual and inter-decadel changes to its carbon balance (Bernier and Apps 2005). The nature of climate and insect disturbance relationships, however, complicate studies into the effects and impacts of natural disturbances (Bernier and Apps 2005). Climate change reportedly affects forest dynamics by altering the frequency, severity, duration, and timing of disturbances (Dale et al. 2001). A changing climate can also lead to widespread disturbance events that could accelerate changes to forest composition, structure and productivity, thus understanding the extent and severity of pest damage is knowledge that is relevant to determining the sustainability of Canada's forests (Volney and Hirsch 2005).

Pest outbreaks and drought are among the primary natural disturbances to the forest landscape (Dale et al. 2001). Droughts can occur in nearly all forest ecosystems and their effects can lead to species decline, dieback and mortality (Dale et al. 2001). Pest outbreaks caused by insect defoliators and climate-related drought resulting in dieback, are considered natural disturbances that have carbon consequences (Volney and Fleming 2000; Bhatti et al. 2003; Hogg and Bernier 2005). Repeat defoliation and dieback results in mortality, reduced growth rates, dead tree tops and loss of foliage, all of which will impact carbon stocks and reduced ability to sequester carbon from the atmosphere (Hogg et al. 2002; Bhatti et al. 2003). While current projected estimates of impact from these kinds of disturbances are tenuous at best, the combined losses from insect defoliators alone on a national scale in Canada, have been reported at more than 10 million ha that account for the loss of 56.6 million m^3 of wood per year from our sustainable timber supply (Hall et al. 1998; Simpson and Coy 1999; Fleming 2000; Canadian Council of Forest Ministers 2006). Impacts from dieback have been most frequently observed with trembling aspen (*Populus tremuloides* Michx.) in west central Canada, and recent studies are just beginning to understand its impacts, and the processes that govern its occurrence, magnitude and distribution (Hogg et al. 2002; Frey et al. 2004; Hogg et al. 2008).

The success in the application of remote sensing data to detect and map insect defoliation has been highly variable at best, (Leckie and Ostaff 1988; Riley 1989; Hall et al. 2006a), and almost non-existent for mapping dieback (Sampson et al. 2000). A cursory review of literature on use of remote sensing for mapping insect defoliation suggests there is no consistent approach that has been reported (Hall et al. 2006a). While most studies tend to employ two or more dates to represent before- and after- defoliation time periods, the timing of imagery is notably coincident with the period when the damage is most visually obvious. Acquiring imagery at these critical time frames can be a particular challenge because of difficulties in obtaining cloud-free images. Sensor continuity, particularly in the case of the Landsat program (Williams et al. 2006), and scaling from multi-sensors relative to spectral and spatial resolution are also important issues within the context of an operational program. Patterns of insect defoliation range from a physical loss of foliage to changes in foliage color. This variability in damage has contributed to the diversity of remote sensing methods employed that have included band ratios, image transformations (e.g., principle components, tasseled cap), image differencing and various image classification approaches (Franklin 2001; Hall et al. 2006a). Greater insights are needed into the strengths and weaknesses of these various methods relative to the possible effects from vegetation response to these disturbances.

The objective of this report is to review the requirements for disturbance information, the manifestation of damage patterns that may be encountered, and to provide an overview of remote sensing sensors and change detection methods that have been, or could be applied to mapping of insect defoliation and aspen dieback. This information will help to define the prospects of an operational monitoring system for these types of disturbances. Meeting this objective entails integrating knowledge of the dependencies among disturbance agent, host tree species, and remotely sensed image, with the latter comprising both the remote sensing data source and the change detection procedures employed (Coops et al. 2006; Hall et al. 2006a). This review was structured by three primary questions considered relevant to the application of remote sensing to natural disturbance from insect defoliation and dieback:

1. What disturbance information is required and what are the damage patterns and relevant insect defoliator biology from these disturbance agents?
2. What are the relevant remote sensing data sources and methods that could provide consistent and spatially precise mapping of damage caused by insect defoliation and aspen dieback? and
3. What are the requirements for an operational monitoring system, and what are the research issues that need to be resolved for this system to be operational? Ultimately, an operational monitoring system must be capable of deriving damage polygons with levels of severity that could be used to assess impacts and consequences to carbon stocks.

2.0 Insect Defoliation and Aspen Dieback in Canada

2.1 Information needs

Within the framework of the Kyoto Protocol and the United Nations Framework Convention on Climate Change, Canada must quantify carbon stocks and stock changes in forest ecosystems for which information about disturbances is necessary (Wulder et al. 2004; Kurz and Apps 2006). Detailed temporal and spatial observations about disturbances are required to meet this information need and to improve understanding about the interactions among disturbance types (Bernier and Apps 2005). Carbon accounting tools that operate at stand, management unit, provincial and national scales are being developed to better inform national policy makers and resource managers on the impacts of natural disturbances on forest carbon stocks (Kurz and Apps 2006). The needs for disturbance information, however, are also relevant to monitoring the state of health of Canada’s forests (Canadian Council of Forest Ministers 2006; Natural Resources Canada 2006). Canada’s National Forest Inventory and National Forest Carbon Accounting and Reporting System are being developed as frameworks to monitor Canada’s forests from which information about disturbances can be ingested (Wulder et al. 2004; Gillis et al. 2005; Kurz and Apps 2006). Information about the location, extent and severity of insect defoliation is needed to support these systems for use in Canada’s national and international reporting requirements on environmental and sustainable development indicators (Canadian Council of Forest Ministers 2003, 2006). Being able to map and quantify the areal extent and severity of disturbances through space and time will also help to derive knowledge about its impact, including its magnitude, dynamics, and ecological consequences.

A previous role of the Canadian Forest Service was to conduct annual insect and disease surveys that were used to create annual regional and national reports on the state of forest pests in Canada (Brandt 1997; Hall et al. 1998). This responsibility was turned over to provincial/territorial agencies in 1996. Since then, provincial/territorial agencies have conducted aerial surveys over predominately managed areas that are within their jurisdictional responsibility. The timing for summarizing this information nationally is variable, and there is a need to address a data gap for the years of 1997 to 1999 that occurred during the transition of the aerial survey mapping process from the Canadian Forest Service to the provincial/territorial agencies. Information data gaps may also exist as insect pest damage may occur in areas outside of jurisdictional interest by provincial/territorial agencies resulting in some areas without mapped information. Other than a composite atlas of the major forest pests in Canada from 1980 to 1996 (Simpson and Coy 1999), there has been no published annual report on the status of forest pests in Canada since 1995 (Hall et al. 1998). As a result, there is a need to rely on independent contributions of provincial survey reports, and there is no current system to compile a national status report of major insect pest activity on an annual basis.

A long-term plot monitoring study called CIPHA (Climate Impacts on Productivity and Health of Aspen) was established to better ascertain the effects and impacts of climate and other factors on trembling aspen and how these were changing over time (Hogg et al. 2005). Aspen stands are particularly sensitive to drought and increasing evidence of reductions in growth and increases in mortality represented as dieback (Hogg et al. 2008) have resulted in concerns about the sustainability and productivity of the aspen resource (Hogg and Bernier 2005). An emerging challenge is the ability to detect, map and quantify the extent of dieback, particularly as it occurs across large, heterogeneous landscapes (Hogg et al. 2008). Meeting this challenge requires a means by which ground observations can be scaled to the landscape level. Drought is a primary disturbance agent causing dieback whose increasing presence is demanding more attention for information than what current national/provincial agencies provide. Under a changing climate, increased water stress and increased peak summer heat stress are also projected to result in large-scale dieback of boreal forests (Lenton et al. 2008). Being able to determine the areal extent and severity of aspen dieback is necessary to monitor the effects of these stressors. As a result, the need exists for information about disturbances that includes both insect defoliation and aspen dieback.

2.2 Manifestation of damage: implications for remote sensing

Insect defoliation may cause a variety of symptoms that include foliage reddening, foliage loss, and chlorosis (yellowing) and these effects result in changes to the morphological and physiological characteristics of trees (Murtha 1982). For defoliators that cause foliage to turn color, the degree of red discoloration is a visible indicator of defoliation severity used during aerial surveys (Volney 1988). The red discoloration is also likely the stage at which the greatest spectral change occurs relative to the normal pattern (Hall et al. 1995). Using remote sensing to detect defoliation would be based on observing changes to spectral reflectance between two dates that correspond to pre- and post-defoliation stages during the time when the red discoloration was most visible (Ahern and Leckie 1987). Significant or repeat foliage loss, measured as a reduction in leaf area, reduces the photosynthetic capacity of the tree (Hall et al. 2003), and these stresses will weaken or reduce tree vigor and growth rates, or predispose trees to attack by secondary agents (Kulman et al. 1963). These factors can also influence changes in tree characteristics that govern how damage may be represented on a remote sensing image. Using remote sensing to detect foliage loss would be best based on detection of spectral changes resulting from loss of leaf area during the time when this loss was expected to be at or near its maximum.

Dieback in aspen is a condition where the top or a portion of the tree crown starts to die resulting in loss of foliage followed by mortality of branches or portions of the main tree stem. Its manifestation of damage does bear some resemblance to that of insect defoliation although patterns of damage can be extremely variable and patchy. Dieback in trembling aspen has been attributed to a combination of factors that include drought, insect defoliation, freeze-thaw events and fungal pathogens (Frey et al. 2004; Hogg et al. 2005). The main difference between defoliation and aspen dieback is that with defoliation, deciduous trees that survive will replace foliage the following growing season whereas with aspen dieback, the damage is permanent as portions of the tree that die do not recover, and once onset, these trees will often continue to deteriorate (Frey et al. 2004). An advantage is that once the location of dieback has been identified, one can image the same area repeatedly because unlike that of defoliators, dieback damage does not change its location from year to year. While there is more flexibility in image acquisition dates, the timing for image selection should represent the same phenological stage between pre and post images. Dieback damage is characterized by a physiological weakening caused by drought that leads to mortality of tree tops, branches and loss of foliage. The nature of dieback and mortality is dynamic because trees that die eventually fall, resulting in greater exposure of the understory vegetation and consequent challenges in associating the severity of the impact with an obvious remote sensing spectral response pattern.

The combined changes to the morphological and physiological characteristics of trees from defoliation and dieback result in changes to spectral reflectance patterns that serve as the foundation for its detection by remote sensing. Observed differences in color on remote sensing imagery have often been related to differences in leaf area caused by insect defoliation (Leckie et al. 1992). The problem is that different stressors can result in the same physiological response on leaves, or the response can be different depending on the original condition of the vegetation and the duration of the stress (Franklin 2001). As a result, knowledge of the characteristics of trees when they are healthy has long been considered the key towards understanding and interpreting changes as a result of disturbance that may be observed in reflectance characteristics (Puritch 1981). This knowledge becomes highly relevant when selecting the appropriate remote sensing sensor and methods. To further understand the manifestation of damage relative to its detection by remote sensing, some understanding of insect defoliator biology and its nature of damage is necessary.

2.3 Major insect defoliators in Canada

In North America, 6 insect defoliators are among the major defoliators of deciduous and coniferous forests that include the aspen defoliators (forest tent caterpillar (*Malacosoma disstria* Hubner) and large aspen tortrix (*Choristoneura conflictana* Wlk.)), gypsy moth (*Lymantria dispar* L.), spruce budworm *Choristoneura fumiferana* (Clem.), jack pine budworm (*Choristoneura pinus pinus* Freeman), and eastern hemlock looper (*Lambdina fiscellaria fiscellaria* (Guen.) (Hall et al. 1998; Simpson and Coy 1999; USDA 2007; Volney and Fleming 2000). Of the 6 major defoliators, two feed on deciduous tree species that are predominately trembling aspen, three feed on conifers, and one feeds on both (Table 1). These pests can cause periodic outbreaks over large areas that can result in changes to the composition or result in replacement of forest stands (Simpson and Coy 1999; Volney and Fleming 2000).

The forest tent caterpillar and large aspen tortrix are the most serious defoliators of trembling aspen and a chronic problem in the prairie/boreal forest ecotone in Central Canada (Ives and Wong 1988). Both of these defoliators emerge in the spring coincident with bud flush

Table 1. Comparative biology table of four major deciduous and coniferous defoliators*.

Species	Egg stage	Larval stage	Pupal stage	Adult stage	Feeding preference	Preferred hosts	Morphological damage	References
Aspen defoliator: Forest tent caterpillar	Overwinters in egg bands	5 instars, emerges in spring, feeds 5-6 weeks to early July	Mid-late July, adults emerge in 10 days	Late July – early August	Aspen foliage	Trembling aspen, other deciduous species	Consumes foliage, results in loss of leaf area	Ives and Wong 1988; Peterson and Peterson 1992; Volney and Fleming 2000
Aspen defoliator: Large aspen tortrix	Laid from mid-June to early July. Hatches in 2 weeks during early - late July	5 instars, overwinters as 2nd instar feeds until early – mid June.	Early - mid-June, adults emerge in 10 days	7-14 days following pupal stage in mid-June to early July	Aspen foliage	Trembling aspen, willow	Feeds on epidermis of leaves webbed together and consumes foliage leading to loss of leaf area	Ives and Wong 1988; Peterson and Peterson 1992
Spruce budworm	July - August	6 instars, *fumiferana:* overwintering larvae emerges as 2nd instar in late April – May *occidentalis*: emerges in spring, feeds to late June	*fumiferana*: June *occidentalis*: Late June – early July	*fumiferana*: Late June – July, mainly adult dispersal *occidentalis:* emerges 10 days following pupation	Male flowers, young foliage	Many hosts: *fumiferana*: balsam fir, white spruce, black spruce *occidentalis:* Douglas-fir, grand fir, white fir, subalpine fir	Eats needles at the base and leaves the remainder. Mass of frass, drying needles turns the tree to a reddish-brown color. Top-kill and mortality occurs from severe defoliation	Martineau 1984; Ives and Wong 1988; Volney and Fleming 2000

Jack pine budworm	August – September, emerging 6-10 days after deposit	7 instars, spring to early July, 2nd instar overwinters	Early to mid-July on branches	July – August, deposit eggs	Male staminate flowers, young foliage	Jack pine, scots pine, red pine, lodgepole pine	Consumes only basal portion of needles. Mass of frass, drying needles turns the tree to a reddish-brown color. Top-kill and mortality occurs from severe defoliation.	Kulman et al. 1963 Ives and Wong 1988; Cadogan 1995; Volney and Fleming 2000
Hemlock looper	Overwintering egg laid from August to October	Emerges in May/June, 4 instars through to late July	August – September in the soil/litter, bark crevices, moss on bark	September - October	Young foliage	Many hosts: Eastern hemlock, balsam fir, white spruce, deciduous, many others	Consumes only the edges of needles and leaving central filament that dries and curls. Feeds initially on young foliage. Trees turn reddish-brown since all age classes of foliage are consumed	Martineau 1984; Raske et al. 1995; MacLean and Ebert 1999

* Adapted from Table 4.1, Hall et al. (2006a).

and feed on developing buds and shoots in the early spring (Volney and Hirsch 2005). Foliage is consumed during larval feeding that is completed in the middle of June for large aspen tortrix and end of June or early July for the forest tent caterpillar (Table 1). Defoliation results in the physical loss of foliage that is best detected near the culmination of larval feeding that occurs approximately between the middle of June to early July. By mid to late July, trembling aspen with sufficient vigor will produce a second flush of foliage and thus images acquired after this date would no longer be suitable for assessing defoliation. The severity of defoliation has been correlated with the degree of leaf area that has been replicated over a multiple-year time series (Hall et al. 2003; Hall et al. 2006a). These image maps has been validated with trends that were similar to independent aerial surveys and damage patterns that were visible on oblique aerial photographs (Hall et al. 2006b). While mapping the severity of aspen defoliation is technically feasible with remote sensing, there are factors such as multi-scene image normalization, and developing a strategy to ensure large outbreak areas can be mapped annually that would need to be addressed.

The gypsy moth is a major defoliator of trees that is known to feed on hundreds of different tree species in North America (United States Department of Agriculture 2009) with a range that also extends throughout southern Canada (Liebhold et al. 1992). While it is a primary defoliator of red oak, species such as white birch, red maple and eastern white pine have also been defoliated by gypsy moth (Hall et al. 1998). During 1999 to 2001, it was a more significant defoliator in the United States compared to Canada, with a decreasing trend from 2002 to 2004 (Hall et al. 2006a). Trends have since reversed resulting in an overall increased area by more than 90% from 2005 to 2006 (approximately 270,000 ha to an area greater than 500,000 ha) (USDA 2007). In addition, while climatic barriers and aggressive pest control (Nealis and Erb 1993) has largely prevented a wide-spread invasion into Canada, future projections suggest a greatly increased risk to Canadian forests from this pest (Régnière et al. 2009). The gypsy moth life cycle starts with the larvae emerging in late April to early May, and while feeding begins immediately, the major defoliation damage occurs from older, larger larvae during early to mid-June (Table 1). Because this pest has such a wide host base that include deciduous and coniferous species, their detection and mapping by remote sensing can be challenging. As a result, a multitude of remote sensing techniques including band ratioing, supervised and unsupervised classifications, image differencing, and change vector analysis to name a few, have been employed in gypsy moth studies (Joria et al. 1991; Muchoney and Haack 1994; Hurley et al. 2004; Townsend et al. 2004). While refoliation in deciduous stands is often considered a bounding condition on image selection windows, Hurley et al. (2004) used three dates of a near infrared simple ratio representing before-defoliation, after-defoliation and refoliation time periods to increase circumstantial evidence in the detection of gypsy moth defoliation events. Change vector analyses based on the soil brightness, vegetation greenness and surface wetness from the Tasselled Cap transformation between non-defoliation (1999) and defoliation (2000, 2001) time periods were used to generate indices of forest change attributable to gypsy moth defoliation (Townsend et al. 2004). Coarser resolution sensors such as imagery from the Moderate Resolution Imaging Spectro-radiometer (MODIS) are becoming potentially suitable tools as the area of outbreaks reach some of the large areas reported by the USDA (2007). Normalized Difference Infrared Indices generated from daily MODIS data has been applied and considered more effective for monitoring defoliation conditions than use of 8-day and 16-day composites due to the ephemeral character of gypsy moth disturbances (de Beurs and Townsend 2008).

The spruce budworm reportedly causes more damage than any other insect in North America's boreal forest (Volney and Fleming 2000). Larval emergence and feeding begins during the early spring, and during latter stages of larval feeding, visible signs of damage become obvious when residual portions of needles and frass turn the tree to a reddish brown color. While principle hosts include white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) BSP) and *balsam fir* (*Abies balsamea* (L.)), other host species are also susceptible (Table 1). Defoliation damage results in reduced photosynthetic capacity from loss of foliage, growth loss, and top kill (MacLean 1990). Spruce budworm outbreaks typically last 5 to 15 years, and several consecutive years of severe defoliation can result in large areas of mortality and subsequent stand replacement (Fleming 2000). The time window for detecting current defoliation during the reddish-brown color stage is extremely narrow, consisting of only two to three weeks, and difficult because only the remains of the damaged foliage turns red-brown (Ahern et al. 1986). As a result, most remote sensing studies have focused on detection of cumulative defoliation (Leckie et al. 1992; Franklin and Raske 1994). A challenge is in rating the severity of defoliation that may best be determined through yearly monitoring efforts to document changes in conifer foliage loss attributable to defoliation.

The jack pine budworm is the most damaging insect of jack pine (*Pinus banksiana* Lamb.) in Canada's boreal forest (Fleming 2000). The life cycle of the jack pine budworm is similar to the spruce budworm with larval feeding beginning in the spring (Table 1). The feeding pattern tends to occur from the top of the tree downwards and from the outside of the crown inwards resulting in a red discoloration to young foliage that is used as an indicator of defoliation severity (Moody 1986; Volney 1988). Severe defoliation results in growth loss, top kill, and mortality that may be precipitated through predisposition to secondary host pathogens such as root diseases (Kulman et al. 1963; Mallett and Volney 1990; Gross 1992). Severe defoliation tends to occur more frequently in semi-mature to mature jack pine growing on poor sites (Gross 1992; Fleming 2000). The red color stage coincides with the stage when the spectral change is likely the greatest, but the time period for mapping defoliation during this stage from late June to early July is very short. To date, there have been relatively few remote sensing studies specific to jack pine budworm (Hopkins et al. 1988; Hall et al. 1995; Radeloff et al. 1999; Leckie et al. 2005). Reported success was highest from spectral mixture analysis when independent field data on species composition and insect populations were incorporated into the analysis (Radeloff et al. 1999).

The eastern hemlock looper is a predominately conifer defoliator that occurs mostly in eastern Canada although its range in Canada extends from Alberta to Newfoundland (MacLean and Ebert 1999). This defoliator is an aggressive pest that can feed on many hosts and on foliage of all age classes (Table 1). Larval feeding begins in the spring on new needles while late instar larvae will feed on all age classes until its culmination in late July (Table 1). The intense red color that can occur when populations are high results in a spectral response so obvious that it has even been mapped from single date Landsat Thematic Mapper (Landsat TM) data (Luther et al. 1991). While not frequent, large outbreaks can occur including an infestation that was recorded at over 400,000 ha and observed on 1-km coarse spatial resolution satellite data (Fraser and Latifovic 2005).

Typical with all of these insect pests, the optimal time for selection of images is relatively narrow and timed to best detect spectral differences when they are assumed at their maximum, and attributable to either foliage loss or the red color stage. Because the availability of cloud-free images during this narrow time frame is often limited, timing windows that may coincide with other damage patterns has been used in remote sensing. In the case of spruce budworm, identifying time frames representative of cumulative rather than current defoliation result in a wider opportunity for selecting images. The manifestation of damage then reverts from the red color stage representative of current defoliation to cumulative loss of needle foliage.

Damage patterns from insect defoliators vary considerably ranging from foliage loss to foliage color change, and severe defoliation results in reduced tree vigor and tree growth, mortality, and top-kill in the case of spruce budworm and jack pine budworm (Table 1). The effects of many of these changes are interrelated as foliage loss and top kill for example, not only reduces the photosynthetic capacity of the tree, but will also reduce growth and tree vigor (Kulman et al 1963). Understanding the role these damage effects may have on the resulting spectral response change on the image is a key requisite toward the successful use of remote sensing for defoliation damage.

3.0 Assessment through Field and Aerial Surveys

Areas of insect disturbances are largely mapped from aerial surveillance (Simpson and Coy 1999; Ciesla 2000). While the inherent value of long-term, annual aerial surveys are without question, they are limited to broad spatial detail, largely confined to managed forests resulting in an omission of pest damage information in remote areas, and are limited to the extent that they can be used alone to relate defoliated areas to impact (MacLean 1990). Mapping and quantifying both the areal extent and severity of disturbances through space and time will help to derive the knowledge about its impact, including its magnitude and dynamics.

Field and aerial surveys have routinely been undertaken in Canada (Hall et al. 1998; Allan 2001) and the United States (Alexander and Palmer 1999) as a means to report and assess forest ecosystem health. As can be expected for any forest health survey, there are a multitude of methods, sampling procedures, indicators and indices that can and are being used to assess the health status of forests (Ferretti 1997). Trembling aspen defoliation has been evaluated from a sampling of 10 to 20 randomly selected trees within sample plots, from which defoliation ratings to 10 percent classes were assigned by a trained observer with the aid of binoculars (Michaelian et al. 2001). To assess spruce budworm defoliation, Alfaro et al. (2001) reported a trained observer using binoculars divided the living crown into thirds, and then estimated the amount of total foliage missing from the crown. Rectangular plots were established with stand sizes that varied to include approximately 10 sample trees from which the amount of jack pine budworm defoliation in light, moderate or severe classes were assessed ocularly on current shoots (Volney 1998). MacLean and Ebert (1999) rated defoliation of hemlock looper through an ocular assessment of each tree for total defoliation and through selective branch sample assessment from which cumulative defoliation was estimated. Field procedures and approaches used to assess or rate defoliation vary considerably, and while there were some similarities between methods, they are not standardized. One approach that is frequently employed, however, is the use of observer ratings of defoliation severity. The accuracy of such field-based assessments is notably affected by the observer’s experience, time available, season, weather, illumination, tree species, stand density, tree age and the natural variation of defoliation (Heikkilä et al. 2002). To help reduce variation in observer ratings, training, calibration and procedure documentation is essential to achieve consistent, field-based health assessments (B.C. Ministry of Forests 2001).

Aerial sketch-mapping, also known as aerial surveys, is a technique in forest health assessments that involve the delineation of damaged areas onto a map by a trained observer from an aircraft (Ciesla 2000). These types of aerial surveys may be conducted from fixed- or rotary-wing aircraft whereby the observer outlines the area of damage, rates the severity and identifies the causal agent (Brandt 1997). Mapping is often done on 1:250,000 scale topographic maps but other map scales may also be used. Larger-scale maps allow for greater accuracy and detail with map scales as large as 1:50,000 being used for operational surveys (B.C. Ministry of Forests 2001). Aerial surveys are conducted when damage conditions are most observable and guarantee data acquisition provided that the weather conditions are favorable for flying. Concerns with this technique include the subjectivity of observer assessments, the spatial precision with which delineations may be completed, observer knowledge and experience, and ability to delineate pest damage in its correct map location (MacLean and MacKinnon 1996; Ciesla 2000). Errors may also occur due to incomplete coverage as it is often infeasible to fly over all affected areas within a given year (de Beurs and Townsend 2008). While few studies have evaluated the accuracy of defoliation ratings and position errors in aerial sketch-mapping, one study did report that 56% of spruce budworm defoliated areas were correctly identified with this method (MacLean and MacKinnon 1996).

There has been considerable interest in implementing digital capture systems that may result in more rapid and consistent maps of the aerial extent of pest conditions compared to conventional, manual aerial surveys (USDA 2005). Digital capture systems involve technological integration of computers, geographic information system (GIS) software and global positioning system technology that provides a real-time map during the aerial survey, and from which defoliation boundaries can be delineated directly into the GIS database (Schrader-Patton 2003). Such systems remove the necessity of manual digitization processes for transferring line work from topographic maps. With the efforts to improve the quality of the aerial sketch maps, aerial surveys are expected to continue to be the method of choice for mapping forest health conditions, at least until consistent and reliable maps from remote sensing can contribute to the process.

The various methods employed in both field and aerial surveys exemplify that the methods and indicators used tend to depend on who is undertaking the survey, and the level of resources and training that may have been invested in the conduction of health surveys. Review of these methods support observations that levels of survey efforts vary, and that survey procedures are not standardized (Allan 2001; de Beurs and Townsend 2008). If the potential for integrating field and aerial surveys with remote sensing is to be explored, then such surveys need to be conducted so that sampling, plot location, and health ratings are undertaken with the intent for its association to the remote sensing image. In particular, there has been some success in establishing direct field-image associations for insect defoliation (Luther et al. 1991; Hall et al. 2003); however, they are notably absent for dieback. Timing field and remote sensing observation, while logical to do in the same year, may vary by up to a year as studies suggest disturbance levels may not change dramatically from one year to the next (Heikkilä et al. 2002). This guideline will vary with the disturbance agent because while that may apply for dieback, it may not apply to all insect defoliators as the severity of defoliation could vary widely from year to year (Volney and Hirsch 2005).

4.0 Assessment through Remote Sensing

4.1 Characteristics of image resolution

The four characteristics by which a remote sensing image can be described include its spectral, spatial, radiometric and temporal resolution (Lefsky and Cohen 2003). The key to successful application of remotely sensed data for mapping and monitoring the severity of insect defoliation and dieback is in relating the manifestation of damage to the sensor that has the appropriate image resolution characteristics from which the damage can be detected.

Spectral resolution refers to the number and spectral width of the image bands that are characterized by a particular sensor (Coops et al. 2006). Sensors that contain a relatively large number of image bands of narrow spectral width are considered those of higher spectral resolution (Lefsky and Cohen 2003). Landsat 7 ETM+ for example, has eight image bands that correspond to the reflective portion of the electromagnetic spectrum, which is of lower spectral resolution compared to the 220 image bands on-board the HYPERION sensor (Pearlman et al. 2003). For microwave sensors, spectral resolution refers to the combination of the number of bands and polarizations for a given sensor (Lefsky and Cohen 2003). Many of the remote sensors used for insect defoliation studies are passive in that they rely on reflected light from the portion of the electromagnetic spectrum that the sensor is sensitive to (Hall et al. 2006a). The potential capability of a given remote sensor for insect defoliation and dieback studies is a function of the inter-relationship between spectral and spatial resolution. For a given pixel, its spectral response is a function of the spectral reflectance of the objects that occur within a given resolution cell. The larger the pixel, the greater the number of surface features whose spectral responses would be weighted by its relative proportions within that given pixel. In order for a remote sensor to be able to detect defoliation, its manifestation of damage must result in a spectral response that would be large enough to occur within its range of spectral sensitivity at a given pixel size.

Spatial resolution refers to pixel size that describes the smallest area on the earth's surface that can be detected by a given sensor (Lillesand and Kiefer 2000). The medium resolution AWIFS sensor for example, has a nominal spatial resolution of 56 m. High spatial resolution sensors such as Rapideye which offers a nominal spatial resolution of 6.5 m, record the spectral response of smaller objects more purely. However, the increased object spatial resolution is typically achieved at the expense of decreased areal coverage. For example, the RapidEye sensor has a foot-print of 77 km (at nadir) while cross-track foot-print of the medium resolution AWIFS sensor measures 740 km. Areas subject to insect defoliation and dieback must be large enough to be detected by the spatial resolution of the sensor to be employed. In turn, large outbreaks may require multiple image scenes, in order to image its areal extent. Some compromise is needed between the desired spatial resolution and its spatial footprint because multiple scenes are logistically more difficult to acquire within the narrow time frames often necessary to optimally detect its manifestation of damage spectrally.

Radiometric resolution is the number of intensity levels that a sensor uses to record reflected energy, and it is an indicator of the information content contained within an image (Lillesand and Kiefer 2000). With an optical sensor this signal is the at-sensor radiance for which the Landsat 7 ETM+, is quantized to 8 bits or up to 256 gray levels within each image band (Lefsky and Cohen 2003). Sensors such as Landsat 8 OLI and Spot 6 have a radiometric resolution of 12 bits that potentially provides a higher level of sensitivity to differences in reflectance that may correspond to finer differences in recorded radiometric responses compared to 8 bit sensors. In studies of forest disturbance, radiometric resolution is seldom an issue of significant consideration because the sensors most often used have a constant radiometric resolution of 8 bits (Coops et al 2006).

Temporal resolution is the frequency upon which a particular sensor will return to obtain imagery over a particular area of interest (Lefsky and Cohen 2003). Many of the newer satellites launched within the last ten years have higher revisit capabilities because of programmability, but the trade-off is that an area of interest could be imaged at an angle of view other than nadir. In order to detect and monitor disturbance such as defoliation, images acquired at different years corresponding to before and after disturbance events are often employed (Coops et al. 2006). These "anniversary date" images need to be acquired at approximately the same time of year to minimize differences in solar illumination and vegetative phenology. For detection of aspen dieback, considerations to before and after dieback disturbance would still need to be applied, but while timing images to anniversary dates are desirable, there are less restrictions to do so. Trees with dieback exhibit mortality of twigs and branches that do not recover (Alexander and Palmer 1999). Having a temporal window that corresponds to nominal growing season images increases the opportunity of acquiring cloud-free images compared to the more restrictive time frames that apply when selecting images to detect insect defoliation.

4.2 Data sources

4.2.1 Optical remote sensing data

Optical, multispectral remote sensing data is generally categorized according to its spatial resolution that can be defined as coarse, medium and high spatial resolution. Table 2 lists spaceborne optical sensors that are currently in orbit. The number of these multispectral data sources from satellite platforms has increased substantially over the past thirty years (Goward et al. 2006). While several have been designated as 'experimental' most are designated as 'operational,' and some have remained operational long past their initial life expectancy (Williams et al 2006). Several of the multispectral sensors described in Table 2 also acquire panchromatic imagery, but their perceived low applicability for detection of insect defoliation or dieback preempted their inclusion for this review. The appropriate selection of image sensor and image acquisition dates is as important to the detection of disturbance as is the selection of a change detection algorithm (Coppin and Bauer 1996). Due to the advantages of repetitive data acquisition and its synoptic view past and current sensors such as Landsat TM, SPOT Vegetation and HRVIR, AVHRR, and MODIS were/are among those most frequently used in change detection studies (Lu et al. 2004).

There are several operational, coarse spatial resolution sensors continuously acquiring and storing imagery whose advantages include high temporal frequency and large spatial footprint at the expense of pixel spatial resolution (Table 2). The high temporal resolution of these sensors offers a greater potential to acquire images at or near the peak defoliation time period of most defoliators compared to medium resolution sensors whose revisit time is generally longer. The larger number of revisits increases the likelihood of securing relatively cloud free image data over the area of interest (van der Sanden et al. 2006).

Operational routines for atmospheric correction of many coarse resolution images have been developed, including estimates of aerosol optical depth (Béal et al. 2004) and atmospheric correction of MERIS (Santer et al. 1999) data, correcting for ozone and water vapor absorption from AVHRR (El Saleous et al. 1994) data, and surface reflectance retrieval from AVHRR (Cihlar et al. 1997) and MODIS (Vermote et al. 2002). Coarse resolution imagery can be used to

Table 2. Characteristics of selected optical, multispectral satellites, operating at coarse, medium and high spatial resolutions.[1]

Spaceborne sensors[2]	# of bands	Spectral regions	Nominal spatial resolution (m)	Swath width @ nadir (km)	Quantization (bits)	Temporal resolution (days)
Coarse Resolution						
MODIS	7	blue, green, red, NIR, SWIR (3)	250, 500	2330	12	1
VIIRS	6	pan, red, NIR, SWIR, MWIR, LWIR	375	3000	12	1
VÉGÉTATION-P	4	blue, red, IR, SWIR	333, 666	2285	12	2
Sentinel-3 OLCI	21	modifiable band position and width	300	1270	12	2
Medium Resolution						
AWIFS	4	green, red, NIR, SWIR	56	740	12	5
HYPERION	220	visible, NIR, SWIR	30	7.5	12	16
Landsat 7 ETM+	8	pan, blue, green, red, NIR, SWIR (2), LWIR	15, 30, 60	185	8	16
Landsat 8 OLI	9	pan, violet, blue, green, red, NIR, SWIR (3)	15, 30	185	12	16
ASTER	14	green, red, NIR, SWIR (6), LWIR (5)	15, 30, 90	60	8	8[3]
LISS-3	4	green, red, NIR, SWIR	23.5	141	10	24
SLIM6	3	green, red, NIR	22	650	10	1-3[3]
Sentinel-2 MSI	13	visible (3), red edge (3), NIR, SWIR	10, 20	290	12	5
Spot 5 HRG	5	pan, green, red, NIR, SWIR	2.5, 10, 20	60x2	8	1-5[3]
High Resolution						
Rapideye REIS	5	blue, green, red, red edge, NIR	6.5	77	16	1[3]
Spot 6 (and 7) NAOMI	4	pan, visible (3), NIR	1.5, 6	60x2	12	1-3[3]
ResourceSat-2 LISS-4	3	green, red, NIR	5.8	23.9	10	5[3]
Kompsat-3 AEISS	5	pan, blue, green, red, NIR	0.7, 2.8	16	14	1-4[3]
Pleaides HIRI	4	pan, blue, green, red, NIR	0.5, 2	20	20	1-2[3]
Geoeye-1 GIS	5	pan, blue, green, red, NIR	0.5, 2	15.2	11	4[3]
Worldview-3 WV110	9	pan, violet, blue, green, red, red edge, NIR(2)	0.3, 1.2	13.1	11	1[3]

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[1] After Hall et al. (2016)

[2] Full name for sensor acronyms in the table: ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer (on board NASA's Terra); AWiFS, Advanced Wide Field Sensor (on board ResourceSat satellites); Geoeye-1 GIS, GeoEye Imaging System; HYPERION, Hyperspectral Instrument on board NASA's EO-1; Kompsat-3 AEISS, Advanced Electronic Image Scanning System; LISS, Linear Imaging Self-scanning Sensor (on board ISRO satellites; two different sensors, LISS-3 and LISS-4); Landsat 7 ETM+, Enhanced Thematic Mapper plus; Landsat 8 OLI, Operational Land Imager; MODIS, Moderate Resolution Imaging Spectroradiometer (on board Terra and Aqua); Pleaides HiRi, High-Resolution Imager (on board Pleiades constellation); REIS, RapidEye Earth Imaging System;

Sentinel-2 MSI, Multi-Spectral Imager (on board ESA's Sentinel-2 constellation); Sentinel-3 OLCI, Ocean and Land Colour Imager (on board ESA's Sentinel-3 constellation); SLIM6, Surrey Linear Imager Multispectral 6 channels (on board the Disaster Monitoring Constellation -DMC); Spot HRG, Haute Résolution Géométrique (on board SPOT 5); Spot NAOMI, New AstroSat Optical Modular Instrument (on board SPOT 6 and 7); VÉGÉTATION-P, SPOT-VGT instrument for the PROBA-V satellite; VIIRS: Visible–Infrared Imager Radiometer Suite (on board NASA and NOAA satellites; note that VIIRS has other imaging mode at 750 m with 17 bands); Worldview-3 WV110, World View 110 camera. Sensor acronyms appear in upper-case letters; for less-known sensors, the name of the carrying satellite precedes them in lowercase.

[3] Enabled by cross-track pointing capability; depends on latitude, maximum off-nadir angle, and number of satellites

assess changes in vegetation over very large areas through time (Tateishi and Ebata 2004); however, there are potential limitations to using such imagery for defoliation or dieback assessment purposes. The coarse spatial resolution can be insensitive to detection of defoliation or dieback if individual pixels also contain relatively large amounts of healthy vegetation or non-vegetated cover. Shabanov et al. (2005) assessed the ability to derive LAI estimates over broadleaf forests with MODIS imagery and reported the accuracy of LAI predictions was lower over mixed and small-parcel forests. MERIS images have reportedly been used for detection of aspen defoliation, but accurately predicting the severity of defoliation has proven difficult (van der Sanden at al. 2006). Large areas of severe defoliation were considered relatively easy to detect, but signatures from light or moderately defoliated forest stands were spectrally similar to those of healthy stands. Coarse spatial resolution sensors can potentially be used to detect and identify the location of large outbreaks that could then be more precisely mapped from targeted acquisition of medium or high spatial resolution sensors.

Satellite images from medium resolution sensors have been the most frequently used of all sensors for insect defoliation mapping studies (Franklin 2001; Hall et al. 2006a). Medium resolution sensors tend to offer the best compromise for detection and mapping of disturbance at finer spatial detail than coarse resolution sensors while offering larger footprints than high spatial resolution sensors (Table 2). The nominal 30m spatial resolution of the Landsat 7 ETM+, for example, permits detection to approximately 0.1 hectare, which considerably improves the ability to discern severity levels of defoliation compared to the 6.25 or 25 hectare size of MODIS image pixels.

Compared to coarse resolution imagery, medium resolution imagery has a much smaller footprint (Table 2), making detection or mapping over large areas more complicated because more than one image scene would be required. The most notable drawback to using medium resolution imagery for defoliation mapping is the longer revisit time period. For example, the late-June to early-July peak defoliation period for forest tent caterpillar defoliation throughout much of the Canadian boreal forest, usually allows for at most two or three Landsat image acquisitions (Hall et al. 2006a). If all post-defoliation images were excessively cloudy over the area of interest, alternative image sources would be required. Other medium resolution sensors, such as the SPOT series of sensors, can provide shorter revisit periods by ‘pointing’ the sensor to collect off-nadir imagery (Moran et al. 1995). Such procedures can, however, introduce radiometric distortion to the imagery, such as increased effects of bidirectional reflectance (BRDF) that would create difficulties when implementing change detection techniques, particularly if the off-nadir look-angle was not consistent between non-defoliated and defoliated images (Asner and Warner 2003; Davi et al. 2006). Furthermore, imagery from medium resolution sensors capable of off-nadir viewing is generally more expensive than Landsat, and because such imagery requires sensor programming, it also requires custom ordering, thus a historic non-defoliation or pre-dieback image may not be available. There have been concerns regarding Landsat data continuity, following the permanent failure of the scan-line corrector on the ETM+ instrument in late-May 2003, and problems with the solar array drive on-board Landsat-5 (Williams et al. 2006). The launch of Landsat 8, originally known as the Landsat Data Continuity Mission (LDCM), in 2013 remedied the problem. Within the framework of an operational remote sensing system for insect defoliation and dieback, ensuring alternative sensors can be used along with appropriate image preprocessing protocols would best ensure image data could be processed to generate change products of interest.

High spatial resolution multispectral sensors offer the ability to detect and map defoliation or dieback at very high levels of spatial precision, including at the individual tree level in some circumstances (Leckie et al. 1992), at the expense of spatial footprint size which tends to be small (Table 2). Multispectral imagery from the Geoeye-1 sensor for example, is collected at a nominal spatial resolution of 2 m, which would require 2500 individual pixels per hectare. Many high resolution sensors also collect panchromatic imagery at even finer resolutions (e.g., Worldview-3 at 0.3 m), which allows for creation of a pan-sharpened image to assess defoliation or dieback, combining the spatial resolution of the panchromatic data with the spectral data from the multispectral bands (Dare et al. 2001). While these types of sensors may offer an improved ability to detect light or sporadic defoliation or dieback compared to coarser resolution sensors, operational mapping of large regions can be cost-prohibitive since multiple images would be required, and logistically more difficult because of the need to program sensors for image acquisition (White et al. 2005). The requirement to program sensors does result in limited opportunities for both pre- and post-disturbance imagery to be available. The limited swath width of high resolution sensors may also increase requirements for off-nadir imaging of areas of interest that are cloud-free, and this can increase potential for radiometric distortions, particularly when viewing forest canopy conditions with extreme look-angles (Peddle et al. 2003). Off-nadir view angles resulting in geometric distortion of trees and the high contrast of images from image features representing sun-lit trees and shadows also complicate the use of change detection methods when applied to such data (Im and Jensen 2005). When defoliation events are obvious, there has been a reported study of insect defoliation from airborne imaging spectrometers, such as the Compact Airborne Spectographic Imager (CASI) (Moskal and Franklin 2004). Overall, there appears to be relatively little research on mapping defoliation from high spatial resolution spaceborne sensors (Franklin 2001), which may be attributable to limitations in viewing geometry and spatial coverage, and requirements for programming multi-date image acquisitions. Using high spatial resolution images within a sampling context in concert with medium and coarse resolution images and consideration of object-based approaches to change may offer greater opportunities for its use in disturbance monitoring (Wulder et al. 2008).

4.2.2 RADAR remote sensing data

The operating wavelength of a particular Synthetic Aperture Radar (SAR) satellite governs the manner in which the microwaves as transmitted by the sensor interact with the forest observed. The extent to which forest vegetation components (e.g. leave, branch, trunk) reflect incident microwaves back towards the SAR sensor, i.e. generate backscatter, depends strongly on their *effective* size. The effective size of a component is defined as its size relative to the incident wavelength and is a function of its physical dimension, shape and orientation. In practice, however, a radar sensor does not observe individual scattering particles but rather a collection of scatterers that typically vary widely in terms of architectural and material properties. Therefore, radar backscatter measurements of forests rarely expose the specific, and possibly extreme, backscattering behavior of the component particles.

There are several sources of radar remote sensing data (Table 3). The satellites currently in orbit are second-generation and are preceded by European systems such as ERS and Envisat ASAR and Canada’s RADARSAT-1. In recent years, the number of SAR satellites, and countries launching them, has increased considerably. This newer generation of SAR satellites offers enhanced capabilities in terms of operating wavelength (and by extension frequency),

Table 3. Characteristics of selected present and planned satellites that include a microwave, Synthetic Aperture Radar (SAR) sensor.[1]

Spaceborne sensors[2]	**Frequency band**	**Wavelength (cm)**	**Polarization transmit – receive**	**Nominal spatial resolution (m)**	**Swath width (km)**	**Quantization (bits)**	**Orbit repeat cycle (days)**[3]
Present							
RADARSAT-2	C-band	5.5	H and/or V – H and/or V	3 - 100	20 - 500	2 - 8	24
TerraSAR-X & TanDEM-X	X-band	3.1	H and/or V – H and/or V	1 - 16	15 - 100	2 - 8	11
Cosmo-Skymed [4]	X-band	3.1	H and/or V – H and/or V	1 - 100	10 - 200	3 - 8	1, 3, 4, 8, 16
ALOS-2/PALSAR	L-band	22.9	H and/or V – H and/or V Compact Pol	3 - 100	25 - 350	3 - 8	14
Sentinel-1A	C-band	5.4	H or V – H and/or V	5 - 40	20 - 400	3 – 10	12
RISAT-1	C-band	5.6	H and/or V – H and/or V Compact Pol	1 - 50	10 - 225	3 - 6	25
Planned (launch date)							
SAOCOM-1[4] (2016)	L-band	23.5	H and/or V – H and/or V	10 - 100	65 - 320	8	16
RADARSAT Constellation Mission [4] (2018)	C-band	5.5	H and/or V – H and/or V Compact Pol	5 - 50	20 - 350	32	4, 8, 12

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[1] References used to compile table information include: CEOS Catalogue of Satellite Missions (http://www.eohandbook.com/eohb05/ceos/part3_3.html) and Earth Observation Portal (https://directory.eoportal.org/web/eoportal/satellite-missions)

[2] Full text for sensor acronyms in the table:

ALOS-2/PALSAR: Advanced Land Observing Satellite 2/ Phased Array L-band SAR
Cosmo-Skymed: Constellation of Small Satellites for Mediterranean basin Observation
SAOCOM-1: Satelite de Observation y Communicacion
RISAT-1: Radar Imaging Satellite 1

[3] Orbit repeat cycle > repeat imaging capability; the latter is a function of the: geographic location, imaging mode, beam mode , # of satellites in the constellation

[4] Constellation: Cosmo-Skymed 4 satellites, SAOCOM-1 2 satellites, RADARSAT Constellation Mission 3 satellites

polarization and spatial resolution. In addition, there is a distinct trend towards the launching of satellite constellations. Relative to single-satellite systems, constellations have a much shorter orbit repeat cycle which means that they can image a given area more frequently. For application to the mapping and monitoring of insect defoliation and dieback in forests, the wavelength of operation can be considered the most important sensor characteristic.

As a rule of thumb, the principal sources of radar backscatter in a closed forest observed by a SAR operating with a relatively short wavelength, e.g. X- or C-band, are the leaves, twigs and secondary branches. On the other hand, the backscatter signal of a system operating with a relatively long wavelength, e.g. L-band, will be governed by secondary branches, primary branches, trunks, and possibly the forest soil. Thanks to their sensitivity to leaves, X- and C-band radar systems have potential for application to the mapping and monitoring of insect defoliation and dieback. Compared to optical satellites, radar satellites make a more dependable data source because radar sensors can acquire images independent of cloud cover and, indeed, of solar illumination. This is of particular importance for the mapping of insect defoliation since the observation time window is often limited.

Few studies have directly evaluated radar imagery for damage detection. In theory there should be backscatter changes associated with forest damage but evidence from imagery suggests the likelihood of detecting or quantifying most damage patterns from radar imagery is small, except perhaps in very severe occurrences (Leckie and Ranson 1998). Reports on differences in backscatter from loss of foliage in deciduous and coniferous trees suggest changes in radar backscatter may occur for at least severe defoliation conditions (Hoekman 1990; Pulliainen et al. 1992). In practice, however, backscatter responses may not be unique and changes observed may be subtle resulting in a need for local knowledge, abundant ground information and contextual information in order for the radar application to be successful (Leckie and Ranson 1998).

4.3 Geometric and radiometric preprocessing

4.3.1 Geometric preprocessing

The most important preprocessing steps for change detection include geometric correction and multitemporal image registration, radiometric and atmospheric corrections (Lu et al. 2004). Geometric correction rectifies spatial distortion in the images and registers pixel coordinates to its corresponding location on the Earth’s surface. It is particularly critical when comparing images over time to detect changes in Earth surface features that may be attributed to disturbance and for subsequent integration with other spatial datasets (Stow 1999; Coops et al. 2006). There are a number of geometric and orthorectification methods for digital images whose selection depend somewhat on the intended use of the image (Toutin 2004). While there has been some debate on the degree of spatial precision required, there is consensus that subpixel registration accuracies are required (Coppin et al. 2004). This degree of registration precision is necessary to ensure the detection of change, and particularly the definition of change/no-change boundaries is not influenced by corresponding pixels between image dates pointing to different geographic locations.

4.3.2 Radiometric preprocessing

Satellite images are subject to atmospheric effects and variations in sensor responses that result in systematic and non-systematic errors that require corrections prior to analysis (Peddle et al. 2003). In addition, seasonal phenology and variability in ground conditions could further complicate and influence spectral responses (Song and Woodcock 2003) that may have little to do with the change response associated with disturbance. Particularly when analyzing a multi-temporal data set, some level of radiometric correction is considered essential to differentiate real change from noise (Schroeder et al. 2006). Employing change detection methods generally requires either an absolute correction for atmospheric affects or a relative correction (i.e., normalization through pseudo-invariant features) between the two or more images that represent pre- and post-disturbance time periods (Song et al. 2001; Coppin et al. 2004; Lu et al. 2004).

Methods and/or correction coefficients have been published for many radiometric correction techniques, including conversion to top-of-atmosphere reflectance (Chander and Markham 2003; Chander et al. 2007), dark-object subtraction (Chavez 1988; Teillet and Fedosejevs 1995), measuring or estimating atmospheric aerosols to derive surface reflectance (Liang et al. 2001; Thome 2001), applying radiative transfer functions (Moran et al 1992), empirical line calibration (Moran et al 2001), and haze removal (Richter 1996), to name a few. More detailed reviews and summaries of radiometric image processing entailing terminology, sensor radiometric calibration, surface reflectance retrieval, image normalization and topographic corrections are also available and have been reported by Richards and Jia (1999), Liang et al (2001, 2002), Peddle et al. (2003) and Schaepman-Strub et al. (2006). Interestingly, Song et al. (2001) suggested such procedures may be unnecessary for some applications as long as the data to be classified are in the same relative scale. Similarly, a relative normalization between two images was applied to forest mortality mapping by only applying histogram matching or linear correction between pseudo-invariant targets (e.g., deep water, healthy vegetation) (Collins and Woodcock 1996). Atmospheric correction is considered essential, however, if multi-band ratioing such as vegetation indices will be used in the detection of change (Gong and Xu 2003). Thus, while the selection of the appropriate level of atmospheric processing does depend on the intended application and the nature of the disturbance being detected, the general consensus is that radiometric and atmospheric corrections are imperative when analyzing multi-temporal optical images (Lunetta and Elvidge 1998; Coops et al. 2006; Schroeder et al. 2006).

Unlike in the case of optical remote sensing images, there is no need for atmospheric correction of radar remote sensing images. This can be explained by the fact that radar sensors are active (i.e. image independent of solar illumination) and largely insensitive to variability in atmospheric conditions. However, the radar return signal of forest and other targets does vary as a result of environmental change, most importantly, changes in moisture status caused by variability in rainfall. The direct effect of rainfall is the wetting of the canopy due to interception. According to Bernard et al. (1987), Lichtenegger (1996) and van der Sanden (1997) this effect may cause the backscatter in C-band to increase by about 0.6 to 1 dB. This effect is relatively short-lived due to evaporation and through fall. Longer term, e.g. seasonal, rainfall fluctuations will affect the water content of tree components and enhance the radar return signal in a more indirect fashion. Experimental results indicate that a 0.1 g g^{-1} increase in the gravimetric moisture constant of deciduous leaves causes the backscatter, in C-band, to increase by about 1.5 dB (Ulaby, 1992). The detection of temporal change in backscatter is complicated by the presence of speckle. Similar to variability in target characteristics (e.g. foliage changes), speckle causes backscatter variability. Reliable detection of change in SAR images requires the reduction of speckle or, in other words, the enhancement of radiometric resolution by means of multi-looking or speckle filtering. Unfortunately, any improvement in radiometric resolution is accompanied by a loss spatial resolution. Rignot and van Zyl (1993) derive the relationship between the level of speckle and the level of confidence for detecting a given backscatter change by means of image ratioing. The detection of backscatter changes ≥ 1 dB at a confidence level of about 80% can be shown to require a speckle level, expressed as equivalent number of looks, on the order of 100.

4.4 Digital change detection methods for disturbance monitoring

4.4.1 Change detection concepts and considerations relevant to insect defoliation and dieback

Change detection involves the comparison of images from a given location at two or more points in time (Lefsky and Cohen 2003). Change is often discriminated by whether the rate of change is abrupt, as caused by fire or some types of insect defoliation, or gradual, such as through normal biomass growth (Coppin et al. 2004). Change is thus perceived as either a class variable that best represents abrupt change, or as a continuum that can represent how ecosystems change over time.

Detecting change by a digital sensor is complicated by image characteristics that are defined by its spectral, spatial, thematic and temporal domains (Lefsky and Cohen 2003). Natural disturbances are characterized by the type of disturbance (eg., defoliation, mortality), its duration, spatial extent, rate of change, and magnitude or severity (Coops et al. 2006). The assessment of forest damage is also influenced by stand and site characteristics defined by species composition, age, density, slope, aspect, and elevation (Ekstrand 1990; Brockhaus et al. 1993). These factors will influence the nature of the spectral response and spatial patterns that may be associated with defoliation and dieback damage conditions. For example, while a reduction in reflectance with increasing defoliation is often reported (Ekstrand 1990; Franklin 2001), decreases in the near infrared has also been observed with corresponding increases in the middle infrared reflectance as a result of the loss of foliage (Leckie and Ostaff 1988; Falkenström and Ekstrand 2002). These changes in spectral response are in turn, influenced by forest composition and structure. Combined, this makes digital change detection an intricate and difficult task to perform (Coppin et al. 2004). The application of remote sensing change detection to insect defoliation and dieback offers challenging problems that are compounded by the wide variation in damage conditions and symptoms that could be exhibited over a range of ecological, forest stand and local site conditions.

Change detection can be undertaken with a single-date image or by analyzing a sequence of images representing the before and after disturbance time periods (Gong and Xu 2003). The use of a single post-disturbance image is feasible when the spectral and spatial characteristics of the disturbance event are clearly separable from other features on the landscape. Severe hemlock looper and spruce budworm defoliation are examples of insect defoliators that have been successfully detected with single date imagery (Franklin 1989; Franklin and Raske 1994; Royle and Lathrop 1997). Spruce budworm and bruce spanworm (*Operophtera bruceata* (Hulst)) defoliation has also been assessed from single date digital airborne scanner and hyperspectral sensors (Ahern et al. 1986; Leckie et al. 1992; Moskal and Franklin 2004). Insect defoliation and dieback damage tends to occur in a continuum, and the differences between damage levels are often subtle. As a result, a multitemporal approach is more frequently employed (Hall et al. 2006a) because it provides a greater opportunity to detect the more subtle differences in spectral response patterns associated with these disturbances than from the use of a single image alone.

There are a plethora of methods for change detection and different methods applied to the same image data set can result in different change maps (Singh 1989). The selection of the appropriate change detection method can therefore take on considerable significance (Coppin et al. 2004) particularly since there is no single approach that is optimal and applicable to all cases (Lu et al. 2004). Aside from the method itself, there is also no consensus on which data transformations or vegetation indices that would best represent biophysical features in terms of monitoring green vegetation (Nackaerts et al. 2005). Because the manifestation of damage resulting from defoliation and dieback varies, the optimal change detection approach and which image features to use are expected to depend on the nature of natural disturbance being detected. This review focuses on methods that have either been used for, or are considered applicable to, detection of changes in forest vegetation that encompasses insect defoliation, vegetation dieback, and vegetation monitoring problems. As a result, many of these methods tend to be pixel-based as this method predominates in the literature (Table 4). Fundamental to the selection of method is the objective of the change detection to begin with. While past studies have tended to be focused on capturing the change event itself, there is an increasing need to be able to analyze changes in trends to seek ecological understanding of the nature of the change (Coppin et al. 2004).

4.4.2 Change detection algorithms and methods

Singh (1989), Coppin et al. (2004) and Lu et al. (2004) presented a number of change detection algorithms and methods that may be generally grouped into 6 categories:

1. Visual analysis (e.g. multi-date image enhancement for visual interpretation)
2. Image algebra (e.g. ratioing, regression, differencing)
3. Image transformations (e.g., principal components, tasseled cap)
4. Classification (e.g. post-classification comparison, unsupervised)
5. GIS (e.g. integration of remote sensing with GIS for change detection)
6. Advanced models and new/evolving methods of change detection (e.g. object-based methods, data fusion, trend analysis of dense image stacks)

A comparison of these methods, including main features, advantages and disadvantages has been summarized in Table 4. Similar to the findings of Coppin et al. (2004) and Lu et al. (2004), many of the techniques for change detection have been applied to Landsat TM or SPOT image data that have similar characteristics defined by spatial, spectral and radiometric resolution. To date, there are no known examples of studies that applied radar remote sensing data and change detection techniques.

4.4.2.1 Visual analysis

Visual analysis, also referred to as multidimensional temporal feature space analysis (Coppin et al. 2004), involves the creation of a digital image enhancement of a bi-temporal image composite from which visual interpretation and on-screen digitizing of changed areas is undertaken (Lu et al. 2004). A selection of three image bands which are judiciously selected into the red, green and blue color guns are used to create an image enhancement from which features of interest are readily identified (Coppin et al. 2004). From this process, the appropriate colors for interpretation can be derived. This method requires an understanding of spectral response patterns relative to sensor image bands and how changes such as insect defoliation would alter

Table 4. Remote sensing studies applied to insect defoliation*.

Insect	Study area	Species	Sensor[1]	Image data: Single vs. multidate	Analysis method[2]	Damage classification: class or continuous	Reference
Aspen defoliators	Alberta	Trembling aspen	Landsat MSS	Multi-date: June 6/1977, June 8/1988	No AC[1]	Class data	Hall et al. 1984
	Alberta	Trembling aspen	Landsat TM	July 21, 1999, July 19, 2001	AC, modeling of changes in LAI	Continuous	Hall et al. 2003
Gypsy moth	Michigan	Oak	Landsat TM, SPOT	June 29, 1988 June 27, 1988	No AC, supervised and unsupervised	Class data	Joria et al. 1991
	Virginia	Oak	SPOT HRV-XS SPOT HRV-XS	June 15, 1987 July 4, 1988	Principle components, image differencing, spectral temporal change classn., Post-classn. change detection	Class data	Muchoney and Haack 1994
	Ohio	Oak	Landsat TM, ETM+ Landsat ETM+	Early June, Late June, Late July	AC, Infrared simple ratio and image differencing	Class data	Hurley et al. 2004
	Maryland Pennsylvania	Oak		Aug. 4, 1999, Aug. 22, 2000, July 24, 2001	AC, Tasselled Cap transformation, change vector analysis	Continuous via frass deposition	Townsend et al. 2004
Spruce budworm	Newfoundland	Balsam fir	SPOT HRV MLA	Aug. 27, 1991	No AC, vegetation indices, discriminant function	Class data	Franklin and Raske 1994
	Quebec	Balsam fir White spruce	Landsat TM	July 22, 1986	AC, image segmentation	Class data	Chalifoux et al. 1998
Hemlock looper	Newfoundland	Balsam fir	SPOT HRV MLA	Aug. 29, 1987	No AC, supervised classification	Class data	Franklin 1989

	Newfoundland	Balsam fir	Landsat TM	Aug. 6, 1990	No AC, correlation and Discriminant analysis	Class data	Luther et al. 1991
	Quebec	Balsam fir, eastern hemlock	SPOT Vegetation	10-day composites: June 1-10 to 21-30	AC, multiple logistic regression	Class data	Fraser and Latifolic 2005
Jack pine budworm	Saskatchewan	Jack pine	Landsat TM	July 20, 1984, Aug. 11, 1986, Aug. 30, 1987	AC, unsupervised classification	Class data	Hall et al. 1995
	Northern Wisconsin	Jack pine	Landsat TM	June 14, 1987, May 10, 1992, Aug 1, 1993	AC, spectral mixture analysis	Continuous budworm population numbers	Radeloff et al. 1999

* Table adapted from Hall et al. 2006a

[1] Landsat MSS, Landsat Multispectral Scanner
Landsat TM, Landsat 4 or 5 Thematic Mapper
Landsat ETM^{+}, Landsat 7 Enhanced Thematic Mapper Plus
SPOT, Satellite Pour l'Observation de la Terre
SPOT HRV-XS, SPOT High Resolution Visible, Multispectral
SPOT HRV MLA, SPOT High Resolution Visible, Multispectral Linear Array

[2] AC, atmospheric correction procedures were employed

these patterns. As a result, a high requirement for analyst's experience and knowledge is required and applied within the context of interpretation elements that include tone, texture, size, shape and patterns (Lu et al. 2004). Further, despite the manual interpretation process being reportedly time-consuming and difficult to replicate (Gong and Xu 2003), it has been widely used (Desclée et al. 2006). This approach was employed by Hall et al. (1983) who displayed the near infrared (NIR) channel of the Landsat Multispectral Scanner image representing the Time-1 "before aspen defoliation" or healthy as red, and the same channel of the image at Time-2 "after defoliation" as green. Areas of no change have similar NIR reflectance on both dates and would appear yellow, with degrees of aspen defoliation appearing in hues of red. While this method is an effective tool for visual analysis, there is no automation for mapping, nor is there a definitive spectral basis from which to base class limits on the severity of defoliation. As a result, quantitative approaches for detecting differences in image spectral response are more frequently cited in the literature (Table 4).

4.4.2.2 Image algebra

Image algebra methods that have been applied to natural disturbance applications include image differencing, image ratioing, vegetation index differencing, image regression, and change vector analysis (CVA) (Lu et al. 2004; Table 4). Factors relevant toward using any of these methods include the selection of appropriate image bands or vegetation indices, and defining the degree of change that serve as thresholds to determine areas of change and the degree of change. Among these methods, the difference in spectral responses between two image dates is reportedly the most widely used method in change detection (Singh 1989; Coppin et al. 2004). Image differencing of SPOT data for example, has been used to identify gypsy moth (*Lymantria dispar* L.) defoliation in a hardwood forest in Virginia (Muchoney and Haack 1994). While image differencing of satellite image bands is a simple and direct means of determining the change in spectral response caused by disturbance, more often this approach is combined with a vegetation index computed by a ratio of image bands.

Image ratioing involves a pixel-by-pixel computation of a ratio of two image bands. Using the same image band over two dates result in decision rules that define the degree of change from values that are higher or lower than a value of one. More commonly, vegetation indices that consist of a ratio of two or more image bands are used as indicators of vegetative biomass (Tucker 1979; Elvidge and Zhikang 1995), from which differences in these indices at different dates become measures of change. This method has been applied to insect defoliation. Gypsy moth defoliation was considered more effectively detected with differencing of a vegetation index than from single image bands (Nelson 1983). Royle and Lathrop (1997) derived the difference in a vegetation index based on the infrared/red reflectance (infrared simple ratio) to map four classes of eastern hemlock (*Tsuga Canadensis* Carriere) defoliation caused mainly by the hemlock woolly adelgid (*Adelges tsugae* Annand). Similarly, differences in the infrared simple ratio over 3 dates were used in the detection of gypsy moth defoliation with Landsat TM data (Hurley et al. 2004). Jin and Sader (2005) employed the normalized difference moisture index, computed as the difference over sum ratio of the Landsat TM near infrared and short-wave infrared channels, in the detection of forest disturbances. Image ratios are often used as vegetation indices that can serve as predictors of leaf area index (Chen 1996), and this has been used to determine the change in leaf area attributable to insect defoliation (Hall et al. 2006a). These studies demonstrate that associating differences in vegetation indices to disturbances can be used to detect change caused by insect defoliation and forest disturbances directly, but they have also been used as input into statistical regression models for modeling change. According to

Rignot and van Zyl (1993), image ratioing is better adapted to the statistics of SAR images and therefore preferred over image differencing for the detection of backscatter change. In contrast to image differencing, image ratioing detects change independent of the backscatter level observed. Moreover, ratioing eliminates systematic radiometric inaccuracies that may be comprised in the applied image series.

Image regression results in an empirical model that relates the fit between two images at different dates over the same area (Singh 1989; Coppin et al. 2004). It is based on the implicit assumption that images of two dates over the same area are linearly related (Coppin et al. 2004). Within a natural disturbance context, the image dates selected would correspond to pre- and post-outbreak disturbance time frames. A key requirement for this approach to function is to define threshold values that provide the basis to identify pixels that have changed as a result of disturbance.

Image regression has also been used in describing the relationship between forest damage and vegetation indices. Mean shortwave infrared/near infrared ratio values were highly correlated to conifer forest damage with an r^2 value of 0.83 (Vogelmann 1990). Hall et al. (2006 a, b) applied a non-linear model that estimated the amount of defoliation in percent as a continuous function of the relative change in leaf area index (LAI) between two dates. Insect defoliation is considered a general stress response that is closely linked to changes in LAI (Solberg et al. 2007). By mapping changes in LAI and assigning threshold values that define the degree of defoliation as to light, moderate and severe, a map of defoliation severity can be produced.

Change vector analysis is a multivariate technique that processes the spectral and temporal image data concurrently to generate outputs that represent the magnitude and direction of change (Coppin et al. 2004). For a given image pixel, remote sensing data is represented as a vector whose elements contain the spectral band values associated with the imaging sensor being employed. A change vector is described as the magnitude of change between band values at two dates. The change vector is characterized by the vector length, computed as the Euclidean distance in multidimensional space, and an angle of change, represented by the direction cosines (Siwe and Koch 2008). Reference or ancillary information is necessary for interpreting the change vectors and to set the thresholds that define the degree of radiometric difference necessary to identify change (Nackaerts et al. 2005). Johnson and Kasischke (1998) reported CVA identifies the dynamic nature of change in an image, but an important consideration is that ancillary information was needed to identify the nature of what the change represented. CVA has been used to assess the degree of forest cover change in conifers (Cohen and Fiorella 1998), and to map changes from forest to clearcuts and from clearcuts to regenerating forest (Kontoes 2008).

4.4.2.3 Image transformations

Image transformations are designed to reduce the number of spectral bands that tend to increase significantly when analyzing multitemporal data sets (Singh 1989). Principal component analysis (PCA) and Tasseled Cap (Crist and Cicone 1984) transformations concentrate information along a smaller number of orthogonal components that are uncorrelated (Coppin et al. 2004), and these are among those that are most well-known (Franklin 2001). Gypsy moth defoliation was considered accurately detected from the application of PCA with multi-temporal SPOT data (Muchoney and Haack 1994). Areas of tree mortality were mapped from a PCA of a 3-date Landsat TM data set comprising 12 image bands. A stepwise regression procedure was required to determine which components were associated with mortality (Collins and Woodcock 1996). A wetness difference index based on a Tasseled Cap transformation of image bands has been applied to habitat change (Betts et al. 2003), mountain pine beetle red attack (*Dendroctonus ponderosae* Hopkins) (Skakun et al. 2003), partial cut harvesting (Franklin et al. 2002) and detection of forest disturbance from harvesting (Jin and Sader 2005). This approach provides the ability to process the near infrared and shortwave infrared image channels into image transformations that are responsive to differences in structure and moisture. Its use has become a viable approach for digital change detection of forest disturbances over a range of applications, and thus, it offers potential for insect defoliation and dieback application.

4.4.2.4 Classification

Classification techniques include the application of image classification algorithms to a combined set of image bands from a multi-temporal data set, and a post-classification of images that are classified independently at each image date. Collectively, the classification category includes methods such as post-classification comparison, spectral-temporal combined analysis, unsupervised change detection, and artificial neural networks (Lu et al. 2004). By classifying images representing before and after disturbance dates, a pixel-by-pixel comparison can be undertaken to identify changes (Coppin et al. 2004). Because each image date is classified independently, relative radiometric calibration is not a significant issue. The accuracy of such a change product, however, is highly dependent on the accuracy achieved with the classification representing each image date (Fuller et al. 2003). Serra et al. (2003) employed a post-classification process for land cover change detection with a high 85% classification accuracy when landscape fragmentation and image registration effects were accounted for by employing a one pixel buffer removal process during analysis. A limitation with the post-classification change process is that it employs a binary decision rule as either change or no change, and this can oversimplify the changes in land cover that may be more subtle or more dramatic (eg., degrees of defoliation severity vs. forest to clearcut) and for classes whose composition is heterogeneous. To address this problem, semantic metrics was employed to identify the different degrees of change in the 1992 to 2001 United States National Land Cover data over Chester Country, PA (Ahlqvist 2008).

4.4.2.5 GIS

The development and increasing availability of Geographic Information Systems (GIS) provides the opportunity to incorporate other spatial datasets into the detection of disturbance and land cover change (Lu et al. 2004). The integration of remote sensing and GIS is often viewed as a mechanism whereby remote sensing products are viewed as inputs into a GIS (Coppin et al. 2004). Remote sensing outputs in a GIS may be used to produce map products, and its integration with GIS datasets and models are conducive towards the assessment of disturbance impacts. GIS data, however, can be integrated with remote sensing datasets in at least three ways that include pre-classification stratification, post-classification sorting, and as direct inclusion into the classification and modeling exercise (Rogan and Miller 2006). Preclassification stratification is essentially a tool to create spatial masks from GIS data that can be used to remove areas that are not considered relevant to the disturbance problem being analyzed (Coppin et al. 2004). Post-classification sorting is a process to partition the mapped classes from remote sensing by ancillary data for description or labeling spectral classes generated from unsupervised processes (Rogan and Miller 2006). Direct inclusion is the use of GIS variables along with spectral data into the classification process (Coops et al. 2006).

4.4.2.6 Advanced models and new methods of change detection

Innovative time series approaches to pixel-based change detection are being developed as a result of the opening of the Landsat archive (Roy et al. 2014). Examples include new cloud and shadow masking methods, mosaicking, and temporal compositing approaches to generate the pixels of the highest quality for analysis (Roy et al. 2014; White et al. 2014). For example, the Continuous Monitoring of Forest Disturbance Algorithm (CMFDA; Zhu et al. 2012) estimates sigmoidal models for each pixel and spectral band of multi-year time series of satellite multispectral observations. Once fitted for every single pixel of the area of interest, CMFDA can accurately detect any non-seasonal change that deviates from model predictions after three consecutive clear observations, which may enable the early detection and tracking of insects outbreaks as new images become available. Testing of this approach for pest damage would be necessary to verify its application potential.

Two areas in change detection research that offer potential for forest pest application include object-based change detection and data fusion from multi-temporal images. Rather than using individual pixels as analysis units, object-based change detection uses image objects, i.e., a group of connected pixels that are more similar between themselves than when compared with their surroundings (Descleé et al. 2006, Chen et al. 2012). This is advantageous when the objects of interest (e.g., tree crowns) are much larger than the pixels, as is the case in imagery of sub-meter resolution, especially because information regarding the spatial context and mutual relations between image objects can be exploited in the analysis (Hussain et al. 2013). The second area, image fusion, involves the integration of multi- source, multi-resolution information to improve the change detection process (Zhang 2010; Du et al. 2013). Given that differences in insect damage severity can be subtle, incorporating other source data that identifies the host tree species and removing other areas not relevant to forest change could improve detection and mapping of pest damage. The absence of current studies of object-based change detection and image fusion suggest its application for assessing pest damage could be an area of future research.

5.0 Discussion

5.1 Application of Remote Sensing to Insect Defoliation and Dieback: Lessons Learned

Landsat TM, ETM+ and SPOT data have been most frequently employed in insect defoliation studies and more than half of the studies employed two or more dates of image data representing before- and after-defoliation time periods (Table 4). Timing of image acquisition coincident with when the manifestation of damage is most visually obvious remains the most important criteria for image selection. Some studies of insect pests that result in foliage color change such as spruce budworm and hemlock looper were reported with single date images. In terms of atmospheric pre-processing, more recent studies after 1998 tend to employ such procedures, and this is consistent with change detection studies that recommend image pre-processing procedures be performed prior to analysis (Lu et al. 2004).

Of the papers reviewed, there is no universal agreement as to which change detection algorithm and image dataset is best for change detection of natural disturbance (Table 4). Given the range of damage patterns from physical loss of foliage to a change in foliage color, the application of several methods in defoliation studies was expected. There are, however, some methods that appear more prevalent than others. Image band ratios, transformations such as principle components and Tasselled Cap, image differencing, and various image classification approaches are among those most frequently used for mapping defoliation. A study of 75 change detection methods on the North American Landscape Characterization (NALC) program using both visual and statistical procedures resulted in normalized image differencing and normalized difference vegetation index differencing outperforming most other change-detection methods (Yuan and Elvidge 1998). Other promising results were reported from discriminant analysis, multiple logistic regression and modelling changes in leaf area (Table 4). The type of information needed, however, was a driver for selection of method. In order to select the appropriate scale and image processing method, the user requires a clear understanding of the problem and the information needed in relation to the biology and damage caused by the forest pest.

Most of the change detection approaches presented by Singh (1989), Coppin et al. (2004), Lu et al. (2004) and Coops et al. (2006) that were summarized in this report operate at the pixel level. While several of the methods have been successfully applied to natural disturbance problems, an alternative more spatial approach is to detect change at the stand polygon level such as that applied to spruce budworm defoliation (Chalifoux et al. 1998). The rationale is that forest damage is influenced by stand and site characteristics (Brockhaus et al. 1992). It is clearly evident that a vast array of change detection methods and approaches are available and the selection of those considered most sensitive to the problem of insect defoliation and dieback can be challenging.

5.2 Prospects for an Operational System

Aerial surveys include the determination of the causal agent, which remains a difficult challenge for remote sensing because its focus is on spectral response changes that requires contextual and local knowledge for its identification.

Among the considerations for designing an operational forest insect defoliation and dieback monitoring system include what damage agents to monitor, temporal frequency and approach for image data acquisition, sensors to be employed, change detection methods to be used, data collection protocols and specifications for product definition. There are many insect pests in Canada that are characterized by their variable damage patterns, relatively small areas, and widely scattered locations from which they occur (Armstrong and Ives 1995; Brandt 1997; Hall et al. 1998). As a result, it would not be logistically possible, nor feasible to attempt to monitor them all from remote sensing. The five defoliators described in this study comprise the major defoliators from which yearly, operational monitoring would help to account for the major damage these pests cause (Table 1) in addition to monitoring of drought-related dieback.

Within the framework of the Canadian Wildland Fire Information System, coarse resolution satellite data are used to detect hot spots that identify areas of fire activity from which a sample of higher resolution imagery such as Landsat TM could be acquired for a more detailed characterization of the disturbance (DeGroot et al. 2007). As such, there is a need for a hot-spot analogy for insect and dieback-related disturbance. The integrated use of two data acquisition systems is recommended in this role. First, provinces routinely employ aerial sketch map surveys to track the broad aerial extent and location of pest disturbances in Canada (Simpson and Coy 1999; Alberta Sustainable Resource Development 2005). While these surveys tend to be focused on areas assigned to operational and commercial forestry interests, they are a valuable record that is compiled each year. Second, coarse resolution satellite data such as that employed by Change-

SAT, employs change metrics based on a combination of growing season SPOT Vegetation and NOAA AVHRR data that has proven successful in detecting large areas of disturbances such as insect defoliation (Fraser and Latifovic 2005, Fraser et al. 2005). Coarse resolution data offer the advantage of frequent coverage over large areas when compared to finer spatial scale sensors (Borak et al. 2000; Table 2). In addition, the advantage of using coarse resolution data on a yearly basis is the capability to monitor the evolving trend of a given disturbance or insect outbreak over large areas that has not been possible previously with fine resolution sensors such as Landsat or SPOT (Fraser and Latifovic 2005).

Achieving operational monitoring of insect defoliation conditions across Canada requires frequent coverage of the same area during outbreaks, and creating new monitoring sites when these outbreaks occur in other areas. No one sensor, coarse or fine resolution, would be capable of meeting these imaging demands. The opportunity to achieve operational monitoring can only be achieved through use of multiple sensors (Table 2, 3). Using multiple sensors results in data characterized by multiple resolutions (eg., spectral, spatial, radiometric; Section 4.1) and imaged under variable atmospheric conditions that need to be harmonized and synthesized to facilitate its use (Melesse et al. 2007). A challenge and research need is to develop the methods that ensure monitoring of disturbance conditions can be achieved within a multiple sensor framework.

6.0 Summary

Insect defoliation and climate-related dieback are major disturbances on Canada’s forests. While aerial and ground surveys comprise the primary methods by which these disturbances are assessed, they are limited by the geographic extent that is typically monitored and there is a need for finer levels of spatial precision. Remote sensing has been widely explored with variable results resulting in a need for a more comprehensive review of this problem.

This review focused on the five major defoliators that cause the greatest amount of damage to Canada’s forests. In addition to these defoliators, the problem of aspen dieback has been included because its damage patterns can resemble severe defoliation, and its distribution and magnitude in Canada appear to be increasing coincident with the effects of a changing climate. Successful use of remote sensing to detect and map the severity of these disturbances, relies on an understanding of information needs and the nature of the manifestation of damage. The nature of foliage loss or foliage color change raises challenges with respect to assessment of severity and the wide range of damage patterns that may occur. These varying damage patterns need to be translated into spectral, spatial, radiometric and temporal resolution terms that govern the framework of an operational remote sensing system that could be optimized for these types of disturbances.

Our review encompassed both optical and radar data sources and methods of change detection and exposed that the application of satellite optical data at medium spatial resolution predominates in the literature. Methods most frequently used in remote sensing detection tend to utilize reflectance information in the near infrared and shortwave infrared portions of the electromagnetic spectrum. Several issues for moving forward within the context of an operational system were identified as areas necessary for research. These issues include robust methods of image normalization, the development of image-field severity models, developing a “hot-spot” analogy for yearly monitoring, and the compilation of defoliation and dieback information from multiple data sources as a system for yearly monitoring. A combination of remote sensing, aerial survey and field assessment methods are recommended over a single system of any data source and assessment method alone.

Remote sensing approaches can complement aerial surveys and potentially provide more spatially precise information about insect defoliator and aspen dieback patterns, but it may be logistically difficult to undertake that role on a national basis alone. The combination and spatial integration of both remote sensing and aerial survey approaches are recommended within the framework of a system to derive information about insect defoliator and dieback disturbances at regional and national scales. New technologies regarding satellite sensors, airborne LiDAR, Unmanned Aerial Vehicles (UAVs), and methods of analysis will no doubt play a role in future forest health monitoring programs. While much of the knowledge and tools to develop a more integrated pest monitoring system are available today, technological innovation will continue to push the limits of what we can do tomorrow.

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