# Detection and Accuracy Assessment of Mountain Pine Beetle Infestations Using Landsat 8 OLI and WorldView02 Satellite Imagery

Lake Tahoe Basin-Nevada and California

by

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This thesis is dedicated to my parents Kris and Norman Nash Sr. I could not have completed this or any other goal in life without your support and love.

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# List of Abbreviations

| | |
|---|---|
| ADS | Aerial Detection Surveys |
| B | Blue |
| DEM | Digital Elevation Model |
| DN | Digital Number |
| ETM | Enhanced Thematic Mapper |
| EWDI | Enhanced Wetness Difference Index |
| G | Green |
| GIS | Geographic Information System(s) |
| GPS | Global Positioning System |
| LTB | Lake Tahoe Basin |
| LTBMU | Lake Tahoe Basin Management Unit |
| m | meter |
| MLSC | Maximum Likelihood Supervised Classification |
| MPB | Mountain Pine Beetle |
| NASA | National Aeronautics and Space Administration |
| NDF | Nevada Division of Forestry |
| NDMI | Normalized Difference Moisture Index |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Near Infrared |
| NPS | National Park Service |
| OBIA | Object Based Image Analysis |
| R | Red |

| | |
|---|---|
| RGI | Red Green Index |
| RMSE | Root Mean Square Error |
| RS | Remote Sensing |
| SWIR | Short Wave Infrared |
| TCT | Tasseled Cap Transformation |
| TM | Thematic Mapper |
| TOA | Top Of Atmosphere |
| TRPA | Tahoe Regional Planning Agency |
| USDA | United States Department of Agriculture |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |
| WV02 | WorldView-2 |

## Abstract

This work evaluates and reports the accuracy assessment of Maximum Likelihood Supervised Classification (MLSC) using the different stages of Mountain Pine Beetle (MPB) infestations outside the Lake Tahoe Basin Management Unit (LTBMU) using Landsat 8 OLI 30m and WorldView-02 (WV02) 2m (comparatively higher) spatial resolution imagery. Using ArcGIS 10.3, the accuracy of satellite imagery using MLSC and the Enhanced Wetness Difference Index (EWDI) provide a good comparison of the imagery at dissimilar spatial resolutions.

MPB infestations at epidemic population levels can cause economic losses and have detrimental effects ecologically in Lodgepole pine tree stands. Detecting endemic populations of MPB can prevent epidemic infestations, preventing economic and ecological losses. After pre-processing, using the different stages of the MPB infestations as a control points, MLSC and the calculation of Tasseled Cap Transformation (TCT) indices (e.g., to calculate EWDI) are used to assess the accuracy of each type of imagery. The overall accuracy results of MLSC of Landsat 8 OLI 30m (51.22%) supersede those of WV02 imagery (26.82%) and are shown in error matrices within this thesis. Accomplishments of this project include the advantage to using WV02 imagery to locate MPB infestations at their endemic stage rather than relying on annual ADS's. Improvements in positional accuracy of Global Positioning System (GPS) data collection devices and improved Remote Sensing (RS) software for image analysis may improve this analysis.

# Chapter 1 Introduction

The Mountain Pine Beetle (*Dendroctonus ponderosae*) exists among forested regions in western North America, primarily in lodgepole pine (*Pinus contorta*) forests. Mountain Pine Beetle (MPB) infestations are native to North America and therefore cannot be eradicated. Knowledge of the size and location of MPB populations can help forest management control the spread of endemic populations and prevent epidemic populations from occurring. Remote Sensing (RS) methods have been shown to be an efficient way of detecting and monitoring MPB infestations (Meddens et al. 2014; Wulder et al. 2006a; Wulder et al. 2006b; White et al. 2005). Knowledge of the accuracy of RS techniques per imagery type may improve the precision of future analyses of MPB infestations at varying scales/resolutions. Testing the accuracy of these methods can potentially provide forest management with reliable sources of imagery and suitable classification methods used to detect and monitor MPB infestations saving time and money.

## 1.1 Mountain Pine Beetle and Infestations

Although native to North America, the MPB has had detrimental impacts on lodgepole pine tree stands, their primary hosts. The MPB range spans from Mexico to Canada and can be found at elevations from sea level up to 11,000 feet (NPS 2015). It is normal for the MPB to kill off trees in their native biological range. From northern New Mexico spreading north to British Colombia, the MPB has killed off more than 60 million acres of forest since the early 1990’s (Rosner 2015). MPB infestations rely on dead timber and weak dying trees. The effects of the increasing temperatures and severe drought throughout the Rockies and the Western United States has weakened pine forests, expanding the endemic population to epidemic population levels beyond their natural biological range. Weakened trees, from influences such as the drought, have provided the MPB with plenty of food, helping them thrive and reproduce at epidemic rates. Without mitigation techniques to maintain endemic populations, epidemic populations occur, resulting in negative effects ecologically and economically. The extent of ecological and economic impacts from the MPB infestations can vary depending upon forest management objectives.

Economically, tree loss can be viewed as a detriment to local economy in regards to tourism and timber production. Where the production of timber from logging is dependent on mature lodgepole pine trees, MPB infestations can have detrimental impacts on the economy (Amman and Schmitz 1988). Aside from direct negative economic influences due to MPB infestations, the cost of maintaining forests due to dead tree removal in forests that are visited by tourists increases (Amman and Schmitz 1988).

Ecologically, MPB infestations affect the overall tree cover, reducing the natural habitat for both large and small mammals, indirectly affecting fisheries. Loss of vegetation that naturally intercepts and absorbs water provides stability to soil. With the loss of trees, water runoff increases which leads to erosion and sedimentation in drainages where aquatic life persists. Detecting areas of MPB infestations at epidemic levels using RS may assist forest managers in mapping out future mitigation techniques, which can slow the spread of infestations reducing ecological and economic losses.

## 1.2 Region 5 Forest Service Management Objectives

According to the 2010 USDA Forest Service Management Guide for the MPB, the main objective is to prevent economic impacts resulting from tree mortality.

Mitigation efforts of the USDA Forest Service include preventive and direct control, focusing on forests and not specifically the MPB (USDA 2010).

Although it is expensive, preventive management strategies keep the population of the MPB below epidemic levels by limiting the food supply which includes; (1) partial cutting (stands experiencing a new attack), (2) clear cutting (already infested trees), (3) prescribed cutting, and (4) species discrimination (cutting larger host trees in order to prevent MPB population growth) (USDA 2010). Preventative management is applied in stands that are already infested or that are nearby an infestation. These methods of preventive control reduce the density of healthy host trees (larger diameter lodgepole), thus reducing the rate of population growth.

Methods of direct control, used to control MPB population growth include; (1) semiochemicals (baiting with a pheromone that attracts the MPB in order to contain the population in one area), (2) spot baiting (used to eliminate small infestations of ~30 trees or less), (3) mop-up baiting (used in previously treated areas), and (4) grid baiting (containing infestations that are ~50 acres in size) (USDA 2010).

Mitigation efforts and strategies of forest management are dependent upon forest management objectives. Depending on the scale (endemic, incipient epidemic or epidemic) of MPB population, 30m and 2m spatial resolution imagery can both be used in the detection and mapping of infestations. Epidemic populations that span larger areas (>30m$^2$) are visible using Landsat 8 OLI imagery, whereas endemic populations that are intermittent throughout the forest that cover smaller areas (>2m$^2$) can be detected using a comparatively higher spatial resolution such as WV02 imagery. Forest management objectives define the level of control applied to MPB infestations.

According to the forest management objectives of USDA Forest Service Region 5, in the LTBMU, forest health and undesirable changes (cause and extent) amongst are of concern (USDA 2013). Once a MPB infestation is located (normally through ADS) forest management objectives of the LTBMU attempt to maintain an endemic population, preventing incipient-epidemic and epidemic populations from developing. Mitigation efforts (thinning) have prevented epidemic populations from developing in the LTBMU, preserving the aesthetic of the forest.

Tourists frequent the LTBMU year-round. Objectives of the LTBMU, aside from aesthetics, are to reduce fire risk. Tree mortality (caused by MPB infestations) impact the wildlife, plant succession, recreation, and increase fire hazards (Safranyik 1982). Fuel reduction requires field crews to remove dead timber, which is time consuming and expensive, directly impacting the annual budget allotted for forest management. Detecting MPB populations using modern day satellite imagery can assist forest management in reaching their objectives and provide a means of locating endemic, incipient epidemic and epidemic populations so preventive and direct control can be applied.

## 1.3 Role of Remote Sensing in MPB Detection and Monitoring

MPB infestations can be detected in aerial photography, verified through field methods and mapped over a multiple years using RS imagery. Many of the areas that MPB infestations occur are in remote regions that are steep and inaccessible by foot. The areas of infestation are expansive and estimating tree mortality caused by MPB infestations can be difficult or impossible to gather using ground crews (Wulder et al. 2006). Manual field data collection and aerial detection surveys (ADS) conducted using aircraft and aerial photography are time consuming and expensive. RS imagery allows easy seasonal/annual acquisition and has been used in estimating MPB cause tree mortality that would normally not be possible using ground-based survey methods (Wulder et al. 2006). Although RS imagery cannot completely replace all traditional data collection methods, it compliments these methods with greater detail, assisting in addressing the objectives of forest management (Wulder et al. 2006).

RS imagery has been used in the field of environmental science for monitoring vegetation and the physical changes/phases that occur. The lodgepole pine tree goes through different mortality phases when attacked (Coops et al. 2006). These mortality phases are evident in RS imagery bands that are visible to the human eye. Enhanced detection using computer technology enables analysts to capture multiple spectral bands of the color spectrum including the near infrared band (NIR) of the color spectrum using modern satellite imagery sensors.

In this, multispectral imagery (a type of RS imagery with multiple bands), allows analysts to delineate different stages of the MPB infestation based on reflectance values of the bands. This imagery contains the red (R), green (G), blue (B) and Near Infrared (NIR) bands, which allows analysts to delineate different phases of the MPB infestation, not apparent to the human eye. The multiple band reflectance values all serve a purpose in the visual separation of the different colored stages of the pine needles that are characteristic of MPB infestation stages. The Normalized Difference Vegetation Index (NDVI), Tasseled Cap Transformation (TCT), and Enhanced Wetness Difference Index

(EWDI) are a few indices used in delineating healthy from unhealthy vegetation.  Both TCT and EWDI indices will be used in this research and are explained later in the methods section of this project.

Using RS methods to map and detect MPB infestations, this study informs forest managers of the capabilities and accuracies of MLSC of imagery to accurately detect and measure the intensity of infestations using 30m and 2m spatial resolution multi-spectral imagery.  Using TCT and EWDI indices over a multi-date period (2014 and 2015), the accuracy of detecting red attack MPB infestations was assessed.  Based on the accuracy of this analysis, locational and temporal characteristics of MPB infestations within the study area were detected and accuracy was assessed over a two-year period using ground truthed validation points.  Locating the infested stands using RS imagery and integrating Geographic Information Systems (GIS) to produce accurate maps of these areas may be an efficient and cost effective management tool in locating MPB infestations. Calculating the TCT Wetness index for 2014 and 2015 assists in calculating the EWDI. EWDI is not directly related to the amount of precipitation or drought condition of each respective year used in calculating the index, nor is it directly related to the classification process of MPB infestations.  This project tests the accuracy of classification methods based on the resolution of the imagery available.

## 1.4 Research Questions

The MPB, biology, infestations, and impacts caused by these native beetles have been studied for over a century.  Information regarding the dynamics of the MPB in central British Columbia date back to 1910, giving researchers data on the trends of infestations throughout a long period of time (Lundquist and Reich 2014).  Studies conducted in the past include the detection of MPB infestations using RS imagery at varying spatial resolutions. The spatial resolution of the imagery required is dependent upon forest management objectives. Different population stages of MPB infestations can be detected at varying spatial resolutions. Studies related to this thesis similarly involve the use of many different types of RS imagery, the differing accuracies based on the spatial resolution of the imagery, and the scale used for such analyses.

This project compares the accuracy of MLSC using both Landsat 8 OLI 30m and WorldView-02 (WV02) 2m spatial resolution satellite imagery. The result of accuracy assessment of 30m and 2m spatial resolution imagery suggests which type of imagery best suits management objectives, depending upon the population stage and scale of infestation. High spatial resolution (2m) satellite imagery is normally costly ($126.50/25km^2$) (Digital Globe 2015) and therefore accuracy assessment of lower spatial resolution (30m) imagery that is readily available to the public (at no cost) may be valuable to forest management. 30m-spatial resolution satellite imagery is readily available on a consistent basis whereas ADS are scheduled annually, normally more expensive, and not up-to-date. Calculating the accuracy of MLSC methods using two types of RS imagery offers forest management with reliable options (rather than ADS) for detecting and monitoring MPB infestations.

Testing the accuracy of MLSC using MPB infestations and their different stages answers a few main questions throughout this thesis project. Questions involved in this thesis include; (1) Will ground truthed validation points of red attack stage MPB infestations help in establishing training areas in the supervised classification process for both 30m and 2m spatial resolution imagery?; (2) What type of imagery (30m and 2m) results in a higher overall accuracy using supervised classification?; and (3) Using 2014 and 2015 Landsat 8 OLI 30m spatial resolution satellite imagery to calculate the TCT Wetness Index, is there a relationship between the wetness difference from 2014 to 2015 (EWDI) where red attack and dead attack stage MPB infestation ground truthed validation points existed?

## 1.5 Thesis Outline

With the purpose of this project now established, four chapters follow that address: (2) related work; (3) data and project methodologies; (4) results; and (5) discussion and recommendations.

Chapter 2 includes the description of the habitat of the lodgepole pine tree and why it serves as the primary host for the MPB. The MPB lifecycle, population size and symptoms associated with an infestation of the lodgepole pine tree are also clarified. Following this, RS applications used for the detection of MPB infestations are explained through studies similar to this thesis project that have been conducted by others in the past. These studies include the detection of MPB infestations using multi-date Landsat TM and ETM+ 30m resolution imagery and the calculation of the TCT and EWDI. One study mentioned in this chapter explains how unsupervised classification method can be used to detect MPB infestations using high spatial resolution (2m) imagery. Acknowledging the observation of unsupervised classification, the following chapters (3-5) will explain how supervised classification and EWDI can improve on these previous methods.

Chapter 3 includes the data and methodology used to complete this project. This project utilizes multiple different data types including: raster 30m and 2m-spatial resolution imagery, vector ADS sketch maps, vector boundary data, vector vegetation classification maps, and vector ground truthed validation points. Descriptions of the multiple bands of the imagery used and their applications offer an introductory understanding of each band. ADS sketch maps are used to locate potential MPB infestations to assist in locating the manually collected ground truthed validation points in the field. The different types of data and their uses in this project are explained. MLSC, leveraging unsupervised classification, methods and accuracy assessment while using an error matrix to calculate the errors of commission, errors of omission, and overall accuracy are explained as well.

Chapter 4 includes the results from using ground truthed validated points to establish training areas used in the MLSC method. The accuracy assessment results from this, are discovered in this project. Maps are presented based on the type of imagery (30m or 2m spatial resolution), classification method (MLSC), and the calculation of the EWDI.

Finally, Chapter 5 discusses conclusions and recommendations of this project, articulating how these methods may be adopted and/or abandoned based on forest management objectives. Scale, resolution and mitigation efforts are discussed within this chapter. Technological improvements, RS processing techniques, and improved spatial resolution of imagery used in the detection and mapping of the MPB are progressive and need acknowledgement.

# Chapter 2 Related Work

Remote Sensing and aerial photography provide analysts with an accurate and efficient means of detecting, assessing, and monitoring the damage of MPB infestations throughout North America. From New Mexico, northwest to British Columbia, ecological and economic impacts have occurred due to the MPB infestations. The extent of ecological and economic impacts caused by MPB infestations varies depending upon forest management objectives and mitigation efforts. Detecting areas of MPB infestations using RS imagery have and continue to assist forest managers in mapping out future mitigation techniques, slowing the spread of infestations, and, thus reducing ecological and economic losses.

## 2.1 Lodgepole Pine Tree

The MPB, although native to North America, has had detrimental impacts on pine forests, mostly in the lodgepole pine tree stands throughout parts of western North America. The primary host for the MPB is the lodgepole pine tree, which suffers extensive mortality shortly after an initial infestation (Coops et al. 2006). Not all trees in a lodgepole pine stand are directly affected by MPB infestations. The MPB selects trees based on the diameter, phloem thickness, habitat type, and elevation (Roe and Amman 1970, Cole and Amman 1980).

Phloem thickness is of the depth of the inner bark of the lodgepole pine tree. An older tree that has a larger diameter tends to have a larger phloem thickness, which is conducive to successful brood productions of the MPB. The lodgepole pine tree increases in size and diameter in an ideal habitat type. A study conducted by Phister et al. in 1977 in the Gallatin canyon, just southwest of Bozeman Montana, concluded that tree mortality was more prevalent in lodgepole pine trees than other types of trees such as Douglas-fir (*Pseudotsuga menziesii*), Subalpine-fir (*Abies lasiocarpa*) and Spruce tree (*Picea*) types which prevail in higher elevations (Cole and Amman 1980). The MPB has been known to cause diebacks in lodgepole pine, Sugar pine (*Pinus lambertiana*), and Whitebark pine (*Pinus albicaulis*) tree stands. Other insects such as the Jeffrey pine beetle (*Dendroctonus jeffreyi*) and the Fir engraver (*Scolytus ventralis*) cause tree mortality in mixed conifer forests, also prevalent in the LTB (Van Gunst 2012).

In higher elevations, above 8,000 feet, where the lodgepole pine tree is not as prevalent, the MPB may require more than one year to complete its life cycle. These higher elevations experience colder and often freezing temperatures, characteristic of fall and winter. Successful brood production is dependent upon moderate temperatures and therefore the reproduction cycle at higher elevations is curtailed due to freezing temperatures. Consequently, the mortality of lodgepole pine trees caused by MPB infestations is linked to elevation (Cole and Amman 1980).

## 2.2 Mountain Pine Beetle

The one-year lifecycle of a MPB goes through four stages of development: egg, larva, pupa, and adult. The majority of the MPB's lifespan is spent feeding on the tree the inner phloem, beneath the bark. Once the MPB is mature, the adult emerges from beneath the bark and migrates to other trees to attack (Amman et al. 1990). The MPB usually feed on healthy lodgepole pine trees that are larger in diameter because of the increased thickness of the inner phloem. Natural causes, such as wind assist the migration of the MPB, normally within close proximity from the primary host trees

(Carroll 2007). Densely populated lodgepole pine tree stands contain a greater amount of weakened trees, providing plenty of food and are more susceptible to MPB infestations. An abundance of host trees provide the MPB not only a place to migrate, but to thrive and reproduce at rates that create epidemic populations.

### *2.2.1. Mountain Pine Beetle population groups*

MPB infestations are divided into four different population categories: endemic, incipient epidemic, epidemic and post-epidemic. All of these are defined by the ratio of the MPB population to the availability of host trees (Safranyik and Wilson 2007). Endemic populations exist in healthy forests but naturally kill off small patches of host trees. Incipient-epidemic populations occur between the endemic and epidemic stage (outbreak phase) where the MPB population grows in size and concentrates into larger infested patches of trees, surrounded by individual trees that bound the edge of a large infestation (British Columbia Ministry of Forests 2003). Declining populations of the MPB are referred to as the post-epidemic phase (after infestation).

Indigenous to North America, the MPB has spread outside of its normal biological range into new areas, creating epidemic population levels. At the endemic population stage, the MPB populations are relatively low and the size/density of infestations (~1 tree per acre) are harder to detect than epidemic populations (Lundquist and Reich 2014). Once the MPB infestations reach an epidemic stage, the population increases rapidly, causing extensive damage to lodgepole pine tree stands, increasingly in densely affected tree stands. As detailed earlier, therefore, detecting the extent and severity of MPB infestations is crucial in forest management and mitigation planning.

### *2.2.2. Mountain Pine Beetle infestation symptoms*

The MPB infests trees and the effects of these infestations occur in four different color phases. During an infestation, the pigments in the pine needles break down and chlorophyll is lost, causing the needles to change color (Hill et al. 1967). These four phases include the green attack phase, yellow/green phase, red attack phase, and the grey attack phase. The green attack phase is the initial infestation, usually occurring from mid-July through August. Following this initial attack, the needles of the tree turn a yellow/green (faders), which indicates the transition from green to red. The pine needles' pigment gradually breaks down from a green to yellow, losing chlorophyll, and turn to red at an advanced stage of infestation (Hill et al. 1967). During the red attack phase the needles turn a reddish-brown about a year later (red attack phase). The grey attack (dead attack) phase occurs two or more years after the green attack phase during which the trees lose most of their foliage (Krause 2006). These four transitional color phases of the pine needles are visible in RS imagery and can assist in the identification of the phases and severity of MPB infestations. These physical changes are evident in the different reflectance values found in RS imagery. These four-color phases are useful in identifying the stages and severity of the MPB infestation using RS imagery and GIS classification techniques.

In recent studies, loss of pigment in foliage has aided in classifying pixels as MPB red attack stage in RS imagery. The symptoms related to MPB infestations have also helped in establishing training areas that are used in supervised classification methods of RS imagery. Changes in foliage color are evident in ADS data, which is used to positively identify MPB infestation stages that can be classified in RS imagery (Meddens

2012; Wulder et al. 2006; Wulder et al. 2008; White et al. 2004; Franklin et al. 2003; Wulder et al. 2009; Sharma 2007). The pigmentation (color) change in trees due to MPB infestations can be seen clearly from an aerial photograph (Figure 1).

Figure 1 Color stages of a MPB infestation. *Photo credit*: Dezene Huber, University of Northern British Columbia

With knowledge of the symptoms characteristic of MPB infestations, these infestations are positively identified on the ground during field data collection. Symptoms besides pigment loss in foliage include bore holes in the bark, dust at the base of the tree from the bore holes, pitch tubes that form at the entrance of the bore holes, and crevice like formations beneath the bark where the MPB lays its eggs. Once the MPB is mature, it exits from beneath the bark and moves to another host tree leaving, a small exit hole in the bark (Safranyik and Wilson 2007) (Figure 2).

Figure 2  Ground-based evidence of MPB infestation; *above left*, pitch tubes present from MPB entrance; *above middle,* bark loss during winter months from birds preying on larvae; *above right,* exit holes from mature MPB leaving host tree. *Source*: Nash 2015

## 2.3 Scale and Detection using RS Imagery

The Lake Tahoe Basin (LTB) is a national forest with almost 80% of the land in the basin being managed by the United States Department of Agriculture (USDA) Forest Service. The objectives of forest management and their mitigation efforts are the deciding factor as to the methods used (ADS or supervised classification of RS imagery) in detecting and monitoring MPB infestations.  Mitigation efforts are dependent upon the stage and size of the MPB infestation.  Both high (2m) and comparatively lower (30m) spatial resolution multi-spectral imagery has been used in detecting and mapping MPB infestations.  The magnitude of infestation (endemic or epidemic), at which MPB infestations occur determines which type of imagery (30m or 2m) to use.  Epidemic population clusters can be detected using both types of imagery.  Endemic population clusters require a higher (2m) spatial resolution to detect and monitor.

## 2.4 Regional, Landscape and Local Scale

The management of forests in North America occurs on three different scales: regional, landscape and local.  Regional scale includes provinces, states, and forest service regions. Landscape scale is smaller and includes forest districts and national forests. Local scale focuses on new sites where the MPB has infested experiencing minimal effects (British Columbia Ministry of Forests 2003). For example, local scale requires imagery with a comparatively higher spatial resolution that has multiple spectral bands. This higher spatial resolution imagery can be used to detect smaller (endemic and incipient-epidemic) infestations ($2m^2$ in diameter) for object-based analysis of newly infested trees. Larger infestations (greater than $30m^2$ in diameter) can be detected using multi spectral imagery that has a much lower spatial resolution (30m).

Detecting the extent and severity of MPB infestations at different scales is crucial in forest management and inventory. The mapping of MPB infestations has been ongoing since the 1960s. The advent of improved RS satellite instruments and quality of images/processing has increased the capabilities of detecting and mapping MPB infestations (Wulder et al. 2006). Technological advancements of sensors have resulted in higher spatial resolution images with a shorter turn-around time. This facilitates the production of imagery that is up-to-date and available without copyright restrictions (Wulder and Franklin 2012). The technological capabilities of monitoring forests have increased the demand for improved precision of data collection at different scales, which is now possible using RS imagery. Improved methods of data collection using RS imagery combined with traditional methods (ADS and field data collection) meeting this demand. The latest version of ArcGIS 10.3 allows a range of data sets at varying spatial resolutions to be processed together using a multitude of tools, resulting in enhanced precision of monitoring forest health (Wulder and Franklin 2012).

## 2.5 Remote Sensing and MPB Infestations

RS is the activity of measuring, observing and monitoring phenomena that occurs on the Earth's surface without physically touching the phenomena (NASA 1998). Measuring, observing, and monitoring these phenomena is possible by capturing images using sensors that are, most often, onboard spacecraft or aircraft. In this thesis, RS imagery includes aerial photographs, Landsat 8 Operational Land Imager (OLI) 30m spatial resolution and WV02 2m spatial resolution imagery. Landsat 8 OLI and WV02 imagery are satellite collections that have multiple bands, where each band, or a combination of bands is used for specific purposes in the classification of pixels representing objects on earth (Table 1).

Table 1 Bands, wavelengths and applications

| Index | Equation | Application |
|---|---|---|
| SWIR/NIR | Band 5/Band 4 | Indicates health, water stress and drought |
| NDMI | (Band 4-Band 5) / (Band 4+Band 5) | Detection of water content in vegetation and indicates vegetation health |
| NDVI | (Band4-Band3) / (Band4+Band3) | Detection of healthy vegetation by the greenness of the tree tops |
| RGI | Band3 /Band2 | When the red value increases, the index value does. Value is used in detecting dead trees and red attack damaged trees. |
| TCT(brightness) | Equation is based on image band values | Image brightness |
| TCT(Wetness) | Equation is based on image band values | Image greenness similar to NDVI |
| TCT(Greenness) | Equation is based on image band values | Vegetation wetness, density, dead trees based on wetness value |
| EWDI | T1-T2 (T2=recent image, T1=older image) | Calculates wetness values by year for comparison |

### *2.5.1 Indices used for MPB detection*

There are multiple indices used in monitoring and detecting vegetation for evaluating forest health. These indices include: Short Wave Infrared/Near Infrared (SWIR/NIR), Normalized Difference Moisture Index (NDMI), Normalized Difference Vegetation Index (NDVI), Red Green Index (RGI), Enhanced Wetness Difference Index (EWDI), and Tasseled Cap Transformation (TCT). Relevant to this project, TCT and EWDI indices are used in the detection of MPB infestations using RS imagery (White et al. 2005; Wulder et al. 2006; Meddens et al. 2014). The calculation of the aforementioned indices and their applications can be viewed in (Table 2).

Table 2 Band combinations used to create indices. *Source*: Gillis 2012

| **Index** | **Equation** | **Application** |
|---|---|---|
| SWIR/NIR | Band 5/Band 4 | Indicates health, water stress and drought |
| NDMI | (Band 4-Band 5) / (Band 4+Band 5) | Detection of water content in vegetation and indicates vegetation health |
| NDVI | (Band4-Band3) / (Band4+Band3) | Detection of healthy vegetation by the greenness of the tree tops |
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| TCT(Wetness) | Equation is based on image band values | Image greenness similar to NDVI |
| TCT(Greenness) | Equation is based on image band values | Vegetation wetness, density, dead trees based on wetness value |
| EWDI | T1-T2 (T2=recent image, T1=older image) | Calculates wetness values by year for comparison |

*2.5.2. MPB detection using Multi-date Landsat TM and ETM+ imagery*

There are currently no studies conducted in the LTB assessing the accuracy of multi-date 30m vs. 2m-spatial resolution imagery. One study was recently conducted in north central Colorado and southern Wyoming (similar in climate and vegetation patterns found in the LTB), using multi-date RS imagery from 1996 to 2011 that included mixed conifer forests at high elevations, Lodgepole Pine and Aspen at middle elevations, and Ponderosa Pine and Douglas Fir at lower elevations. In 2008, an aerial survey completed by the USDA Forest Service estimated 1.15 million hectares (~4500 square miles) MPB caused tree mortality in Colorado and estimated the cost of mitigation in 2010 close to $30 million (Meddens et al. 2014). This particular study documented the percent change and spatial patterns of red attack tree mortality caused by the MPB. Detecting a pattern in epidemic MPB populations assisted in mitigating the problem by reducing the economic costs related to MPB infestations.

Meddens et al. 2014 used bands 1-5 and 7 from Landsat TM and ETM+ multi-spectral imagery to calculate the TCT brightness/wetness/greenness indices as control variables, as well as the NDVI in order to monitor the rate at which MPB infestations spread using multi-date imagery. Multi-date classification of red attack pixels, calculated from SWIR/NIR, was provided from previous research by Meddens et al. 2013. A regression model with a Root Mean Square Error (RMSE) of 13.7 was applied to predict the percent red attack pixels within the 30m spatial resolution pixels across the entire Landsat scene and results were compared to ADS to assess accuracy of predictions (Meddens et al. 2014). The results from using Landsat 30m spatial resolution imagery delivered an average MPB mortality rate of 29.4% in primarily lodgepole pine areas at mid elevations (2500m-3000m).  Elevations where Ponderosa pine, Douglas-fir, and Aspen were prevalent at lower elevations (2000m-2500m) resulted in a 5.2% mortality rate, followed by mixed fir and lodgepole pine at high elevations (3000m-3500m) with a 16% mortality rate (Meddens et al. 2014) (Figure 3).

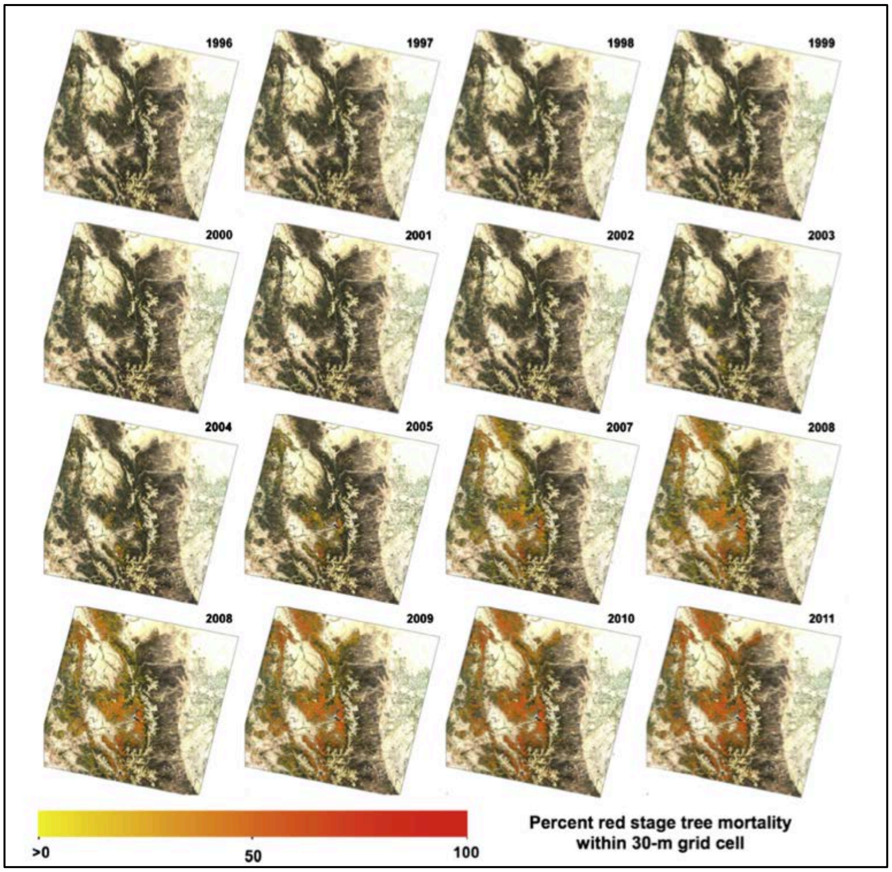


Figure 3  Percent red attack stage from 1996-2011. *Source*: Meddens et al. 2014

The coupling of the SWIR/NIR indicator of forest health and NDVI has shown that red attack stage MPB infestations can be detected using the bands available in Landsat 30m spatial resolution more accurately and completely using multi-date imagery rather than using single date imagery.

### *2.5.3. Multi-date analysis using Landsat Imagery and EWDI*

Another study was conducted by Wulder et al. 2006 describing the procedures for using multi-date Landsat TM and ETM+ imagery to detect the location and severity of MPB infestations in the red attack stage in southern British Columbia using the EWDI (Wulder et al. 2006). The MPB had reached epidemic population levels in many parts of British Columbia and caused extensive damage and mortality to forests (164,000 ha in 1999 to 8.5 million ha in 2005), especially the lodgepole pine tree (the primary host) due to its size and density amongst other species of trees (Wulder et al. 2006). Measuring the magnitude of infestations required sources beyond human means. Ground crews, helicopter surveys, ADS and other traditional methods of data collection were not timely or suitable for the detection and mapping of the epidemic populations of the MPB. RS imagery proved more efficient and less expensive than previously mentioned methods used for detecting MPB infestations at both landscape and provincial scales.

The use of multi-date imagery has proven to be more reliable in change-detection than single date imagery due to the nature at which the foliage changed in color following an infestation (green to red). The use of multi-date imagery also assists in the detection of MPB infestations due to their progressive changes in the landscape (pre/post infestation symptoms). For example, if a tree was attacked by the MPB in 2000, the red attack phase would not be obvious until the following year (2001) due to the one year lifecycle of the MPB and its noteworthy effects on trees. One year following a red attack stage, the foliage dissipated and no existing foliage was apparent (grey attack stage). As the tree loses pigmentation, it is deprived of the essential nutrients for survival, therefore losing moisture.  EWDI measures the wetness (moisture) difference between multi-date imagery and is therefore a great indicator of forest health between years of RS imagery.

Imagery used in the study by Wulder et al. in their 2006 study included Landsat imagery from 2002-2004 during the months of July, August and September.  These months were ideal for imagery acquisition as the MPB had completed its brood cycle and migrated to the next host tree.  Pre-processing methods (geometric correction, radiometric correction) were applied by using ground control points, referencing the imagery shortly after acquisition to ensure the accurate representation of objects upon the landscape.  The images from 2002-2004 were normalized, excluding; burn scars, clear cuts, snow, clouds, roads, lakes and other phenomena using an exclusionary mask.  This mask reduced the chances of false positives occurring in the classification process by excluding objects that were not intended for use in the analysis, ensuring that only target phenomena were included in the classification.  This process was commonly used when utilizing indices to detect infestations and monitor forest health in RS imagery.

After pre-processing and normalization, the TCT wetness indices were calculated by year (multiplying each band by a constant that is specific to the satellite sensor).  This process involved the conversion of the original bands to a set of bands (TCT wetness) that were useful in calculating the EWDI, commonly used in vegetation monitoring (ESRI ND) (Figure 4).  This method was used to show the moisture difference in vegetation from 2002 to 2004.  MPB infestations caused moderate moisture loss in the vegetation, whereas healthy vegetation did not (Wulder et al. 2006).

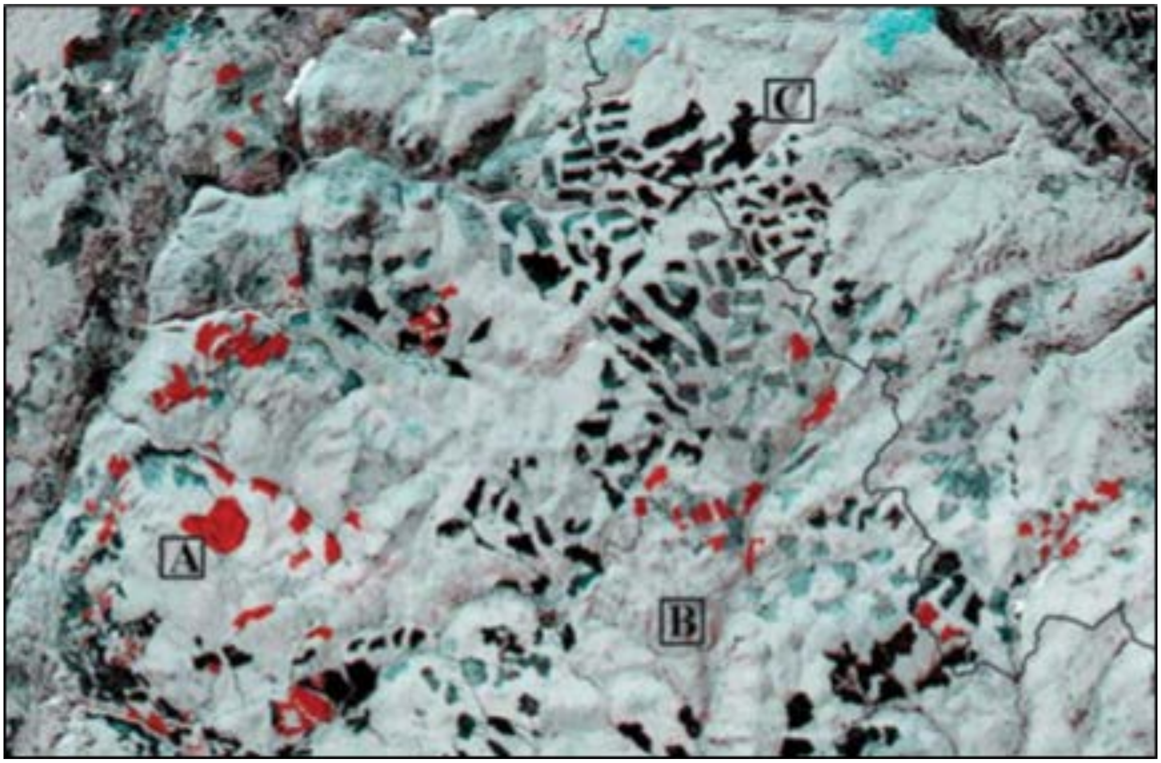


Figure 4 *Section A*, an area that was clear-cut with an obvious lack of moisture; *section B*, MPB infestation where trees are losing moisture; *section C*, moisture increase in this image. *Source*: Wulder et al. 2006

### *2.5.4. Accuracy assessment of EWDI and supervised classification*

Accuracy of EWDI classification methods in Wulder et al. 2006 study consisted of gathering 100 ground validated points of non-attack trees and another 100 ground validated points of attacked trees. The overall accuracy of classification using the EWDI was assessed by using an error matrix by calculating the cumulative of the correctly classified sample points of each class and dividing this number by the total number of sample points (e.g., 193/200=96.5%) (Wulder et al. 2006). The producer's accuracy, or percent of reference points collected that were classified using RS methods, equaled 96% (96% of the attacked trees were identified by the RS method) (Wulder et al. 2006). User's accuracy showed 97% of the trees being correctly identified with an error of commission of 3% (i.e., trees being erroneously included in the RS data) (Table 3).

Table 3 User’s, Producer’s and Overall accuracy assessment of RS methods. *Source*: Wulder et al. 2006

| | **Ground Truthed non-attack trees** | **Ground Truthed attacked trees** | **Sum** | **User’s Accuracy** |
|---|---|---|---|---|
| **RS non-attack trees** | 96 | 4 | 100 | 96% |
| **RS attack trees** | 3 | 97 | 100 | 97% |
| **Sum** | 99 | 101 | 200 | Overall accuracy 96.5% |
| **Producer’s accuracy** | 96.9% | 96% | Null | Null |

EWDI proved to be an accurate method in the classification of red attack trees that have been infested by the MPB. This method, applied in this thesis project was similar to the method used by Wulder et al. 2006. Table 4 shows an example of accuracy assessment using supervised classification in a 1991 study by Congalton. In Table 4, the producer’s accuracy represents is the ratio of the number of correctly classified ground truthed MPB(R) to the total number of MPB(R) ground truthed points. In this example, 65 out of 75 (65/75=87%) MPB(R) ground truth points were correctly classified by the computer. The user’s accuracy represents the probability that a MPB(R) ground truth point is classified as MPB(R), or in this example, 65 of the ground truth MPB(R) points out of 115 classified points is MPB(R), the probability that the MPB(R) ground truthed points are classified by the computer is (65/115), or 57%. The overall accuracy is calculated by dividing the total number of objects correctly classified in RS imagery by the total number of samples, or in this example, (65 MPB(R)+81 MPB(G)+85 MPB(D)+90 Healthy(NI)/434 Total Points)=74%. The error matrix used to calculate the accuracy assessment for MPB(G), MPB(D), and Healthy(NI) trees can also be seen in (Table 4).

Table 4 Error matrix used for accuracy assessment of supervised classification. *Source*: Congalton 1991

| | **MPB(R)** | **MPB(G)** | **MPB(D)** | **Healthy(NI)** | **Row total** |
|---|---|---|---|---|---|
| **MPB(R)** | 65 | 4 | 22 | 24 | 115 |
| **MPB(G)** | 6 | 81 | 5 | 8 | 100 |
| **MPB(D)** | 0 | 11 | 85 | 19 | 115 |
| **Healthy(NI)** | 4 | 7 | 3 | 90 | 104 |
| **Column Total** | 75 | 103 | 115 | 141 | 434 |

*Tree Categories*
MPB(R)=Red attack MPB infestation
MPB(G)=Green attack MPB infestation
MPB(D)=Dead from MPB
Healthy(NI)=Healthy No MPB infestation

*Producer's Accuracy*
MPB(R)=65/75=87%
MPB(G)=81/103=79%
MPB(D)=85/115=74%
Healthy(NI)=90/141=64%

*User's Accuracy*
MPB(R)=65/115=57%
MPB(G)=81/100=81%
MPB(D)=85/115=74%
Healthy(NI)=90/104=87%

*Overall Accuracy*
MPB(R) [65]+MPB(G) [81]+MPB(D) [85]+Healthy(NI) [90]=321
Row total + Column Total=434
321/434=74%

### *2.5.5. RS unsupervised classification of IKONOS imagery*

Unlike the classification of imagery using indices, unsupervised classification techniques are dependent upon the computer, without supervision and guidance of the user. High-resolution imagery has a spatial resolution of 2m or less. Objects can be detected more clearly and with less distortion than 30m spatial resolution imagery such as Landsat 30m satellite imagery. High-resolution imagery allows the detection and mapping of MPB infestations at a local scale, which includes smaller plots of infested tree stands (2m$^2$ or greater). MPB infestations can be localized before incipient-epidemic populations occur. Forest management may utilize local scale analysis to detect small infestations so that field crews can remove the problem before it persists. High resolution RS imagery is available commercially and can assist in the detection of MPB infestations accurately, consistently and efficiently while providing coverage at local to landscape scales (White et al. 2005). The downfall to using high-resolution imagery is the associated costs as well as the coverage of certain phenomena, such as MPB infested trees, over time. Digital Globe offers high-resolution (2m) imagery for ~$106 per 25km$^2$ (3 July 2015) unless acquired through an educational imagery grant, in which 1000km$^2$ may be granted per individual.

A study was conducted by White et al. 2005 near Prince George, British Colombia using high resolution multi-spectral imagery testing the accuracy of IKONOS multispectral imagery in the detection of MPB infestations during their low and medium attack stages. Concerns regarding accuracy, consistency and timeliness of satellite imagery were brought forth by White et al. 2005 regarding data acquisition. The questions asked by White et al. 2005 were: (1) Is the imagery going to be accurate enough for the analysis so the detection method is replicated? and (2) Is it possible to acquire imagery at a high resolution per the study area in a timely manner? (White et al. 2005). These questions should pertain to all forest management regarding MPB infestations and the use of RS imagery for detection.

Between 2002 and 2003, the MPB infestation had doubled from 2.0 to 4.2 million hectares with projected estimates as high as 7 million hectares in 2004 near Prince George, B.C. (White et al. 2005). Rather than trying to control the epidemic population growth, management and mitigation efforts have shifted to focus on the source of the problem, trying to control future epidemic populations of the MPB. This shift in management resulted in detecting smaller incipient-epidemic populations using high-resolution RS imagery, followed by mitigation efforts, preventing incipient-epidemic populations from progressing into epidemic populations.

A combination of ground validated red attack trees recorded with a handheld GPS receiver (with a positional accuracy of 15m), ortho-rectified aerial photography, and georeferenced IKONOS 4m spatial resolution imagery (captured the same day as the aerial photography) were used in the detection and mapping of incipient epidemic MPB infestations (White et al. 2005). Following this process, White et al. 2005 applied an exclusionary image mask, including; burned areas, clear cuts, water bodies, roads, buildings and other cultural objects (acquired from an existing vector GIS database). This mask excluded all objects that could possibly be misconstrued as vegetation considering the spectral variability, characteristic of the progression of MPB infestations (Figure 5).

Figure 5 Exclusionary mask of burn scars, roads, clear cuts, water bodies and other cultural phenomena. *Source*: White et al. 2005

Included in the accuracy assessment by White et al. 2005 was the comparison of ground truthed locations (aerial GPS point data collected by helicopter) of moderate red attack phase MPB infestations to the unsupervised classification results of IKONOS 4m high-resolution imagery. True positive accuracy (red attack trees identified in aerial photography that fall within the IKONOS classified pixels), errors of omission (red attack trees that fall outside IKONOS imagery pixels), and errors of commission (pixels that contain no red attack trees) were calculated using an error matrix, assessing the accuracy of unsupervised classification of IKONOS imagery (Figure 6).

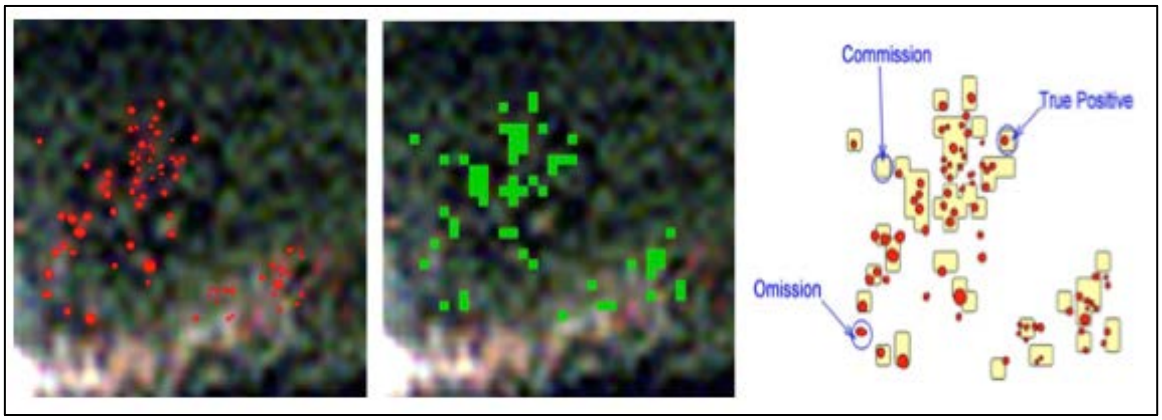


Figure 6 *Above left,* red attack tree crowns delineated from ADS; *above middle,* IKONOS pixels representing red attack tree crowns delineated from unsupervised classification methods; *above right,* example of errors of commission, omission and true positive results. *Source*: White et al. 2005

IKONOS imagery spatial resolution differs from the spatial resolution of aerial photography, therefore, a 4m buffer was applied to the ground control points to match IKONOS 4m spatial resolution imagery. Based on the values of ground control points in Figure 6, the true positive, errors of commission and errors of omission were calculated (Table 5). Table 5 shows the total number of red attack ground control points and total number of red attack points classified in IKONOS imagery that were used to assess the accuracy of unsupervised classification. True positive results of moderate red attack damage MPB infestations using a 4m buffer on IKONOS imagery showed ~92% accuracy, omission results at ~8% and commission at ~2% (White et al. 2005). The accuracy assessment of using high-resolution multi-spectral IKONOS imagery proved to be an efficient approach to detecting moderate red attack MPB infestations in this particular study.

Table 5 Accuracy assessment results of unsupervised classification methods of IKONOS 4m spatial resolution imagery using medium-density attack sites. *Source*: White et al. 2005

| Buffer Size | 1m | 2m | 3m | 4m |
|---|---|---|---|---|
| Total red attack trees (air photos) | 510 | 510 | 510 | 510 |
| Total red attack pixels (IKONOS) | 389 | 389 | 389 | 389 |
| True positive (pixel count) | 398 | 439 | 457 | 471 |
| True positive (%)[a] | 78.04 | 86.08 | 89.61 | 92.35 |
| Lower 95% confidence interval (%) | 70.45 | 79.67 | 83.91 | 87.33 |
| Upper 95% confidence interval (%) | 85.63 | 92.49 | 95.31 | 97.37 |
| Omission (tree count) | 112 | 71 | 53 | 39 |
| Omission (%)[b] | 21.96 | 13.92 | 10.39 | 7.65 |
| Lower 95% confidence interval (%) | 14.37 | 7.51 | 4.69 | 2.63 |
| Upper 95% confidence interval (%) | 29.55 | 20.33 | 16.09 | 12.67 |
| Commission (buffer count) | 25 | 16 | 13 | 8 |
| Commission (%)[c] | 6.43 | 4.11 | 3.34 | 2.06 |
| Lower 95% confidence interval (%) | 3.86 | 2.01 | 1.43 | 0.52 |
| Upper 95% confidence interval (%) | 9 | 6.21 | 5.25 | 3.6 |

Forest management objectives determine the urgency and level of accuracy necessary to detect and mitigate infested tree stands. As mentioned earlier, epidemic MPB populations can have detrimental impacts both ecologically and economically. Prevention of the progression of incipient-epidemic to epidemic MPB populations requires a higher level of classification accuracy and higher spatial resolution imagery. White et al. 2005 objective was to locate individual trees in order to quickly mitigate the problem. The chosen IKONOS 4m spatial resolution imagery by White et al. 2005 proved to be an efficient way of completing this task. Accuracy assessment in this study confirmed the quality of unsupervised classification techniques using IKONOS imagery. MLSC, using ADS data and ground truthed validation points of healthy and MPB infested trees in the LTBMU and surrounding areas may improve the classification accuracy. Combining these data sources will help in establishing training areas from known MPB infested sites, assisting in supervised classification methods of 30m and 2m spatial resolution imagery. White et al. 2005 study showed that IKONOS 4m spatial resolution multi-spectral imagery can be used in the accurate detection of incipient-epidemic MPB infestations.

Both 30m and 4m spatial resolution RS imagery can be used for accurately detecting MPB infestations at regional, landscape and local scales. The stage of MPB population (endemic, incipient-epidemic, or epidemic) and forest management objectives (i.e., control an incipient epidemic MPB population or prevent epidemic MPB population from spreading) combined play a role in the required level of precision and accuracy of classification needed to efficiently plan mitigation efforts. Both high and lower spatial resolution imagery can be used as a cost effective data source to detect infestations at the endemic, incipient-epidemic and epidemic population levels of the MPB. Results from previous studies (Meddens et al. 2014; Wulder et al. 2006; White et al. 2005) show that improved RS methods can be incorporated with traditional data acquisition methods in the detection and monitoring of MPB infestations, improving the accuracy of detection of MPB infestations.

## 2.6 Applications of Previous Studies

Previous studies by Meddens et al. 2014; Wulder et al. 2006; and White et al. 2005 have concluded that the accuracy of MPB detection using high and lower spatial resolutions from multiple different satellite sensors can be tested using many different methods (EWDI, supervised classification and unsupervised classification). In all three studies, ground truthed validation points are used to test the accuracy of each method. The combination of MLSC techniques (to establish training areas) and testing the accuracy using ground truthed validation points for the detection and monitoring of MPB infestations has proved to be the best way to assess the accuracy of classification methods using either high or lower spatial resolution imagery.

Rather than relying on a single ADS, WV02 2m spatial resolution imagery is used to locate areas of tree mortality in this thesis project. The quality of the image allows analysts to detect areas of tree mortality without reliance on aerial surveys. Not all stands of MPB infested trees were recorded in ADS sketch maps, seen throughout this thesis project. The areas where MPB infestations were located, outside the LTBMU are included in Region 5. These trees, recorded in this project were not recorded as lodgepole pine tree mortality caused by the MPB in 2015 ADS. Using higher spatial resolution imagery to locate lodgepole pine tree mortality, previously mentioned classification techniques and known accuracy assessment methods, these previous studies can be elaborated. Previous studies have focused on incipient-epidemic and epidemic MPB population groups. This particular study focuses on the detection of endemic MPB population clusters using the aforementioned classification and accuracy assessment methods.

# Chapter 3 Data and Methodology

In the previous chapter, methods and results from studies by Meddens et al. 2014, Wulder et al. 2006, and White et al. 2005 were discussed. The data and methodology used to detect MPB infestations and assess the accuracy of MLSC using Landsat 8 OLI 30m and WV02 2m spatial resolution satellite imagery for this project is similar to the aforementioned studies.

This chapter describes the study region and the different types of data, along with the methodology used to test the accuracy of MLSC. The study area describes the background of the region chosen for this analysis. The data section provides detailed information about each type of imagery used in this analysis. Images from Landsat 8 OLI (30m) and WV02 (2m) comprise the low and high spatial resolution RS imagery. Vector data provided from ADS, along with field collected waypoints of known MPB infested trees were used as ground truthed validation data (control points) in the accuracy assessment process. The data and methodology section describes the classification methods and different types of indices used to conduct this analysis. The methodology section of this chapter provides a detailed account of how to conduct this analysis so that others may replicate these steps in order to conduct studies similar to this thesis project. Results show the assessment of accuracy of 30m and 2m spatial resolution imagery using MPB as the subject of matter.

## 3.1 Study Area

After speaking with Jeffrey Moore (vegetation analyst for USDA Forest Service Region 5), he stated that there was little to no MPB caused tree mortality or infestations in lodgepole pine stands within the LTBMU. From this information, the study area lies 3 miles (~5000m) just outside the LTBMU in the Northeast section of the LTBMU where the elevation and vegetation is similar to that within the basin. The LTB itself lies between the Sierra Nevada mountain range to the west and the Carson Mountain Range to the east, overlapping the state line that separates California and Nevada (Figure 7).


Figure 7 Location of study region. Red Bounding box represents the location of sections A, B, and C. *Source*: Nash 2015

Mountains surrounding the lake (elev. 6225 ft.) rise up to elevations of over 10,000 ft. and consist of mixed forests and vegetation (USGS 2012). Nearly 80% (150,000+ acres) of the land in the LTB is public and managed by the USDA Forest

Service making up the Lake Tahoe Basin Management Unit (LTBMU) (USDA 2015a). The lodgepole pine tree (primary host to the MPB) exists among the Jeffrey Pine, Red Fir, White Fir and mixed coniferous trees in the LTB. During a recent phone conversation in September 2015 with Jeffery Moore mentioned that when MPB infestations occur, the LTBMU is proactive in their mitigation procedures. The MPB infestations in the LTB have been controlled using a mitigation technique known as thinning, reducing the density of lodgepole pine trees, and preventing epidemic populations from occurring. The red bounding box in Figure 7 is the boundary of three small sections (A, B and C) of endemic clusters of MPB infestations, located ~3 miles Northeast of the Northeast portion of the LTBMU boundary, that are included in this analysis. In these three sections: MPB red attack, dead attack and healthy lodgepole pine trees existed that were positively identified and recorded as ground truthed validation points with a handheld Garmin GPS device.

## 3.2 Data

Data used in these analyses included raster WV02 2m (high spatial resolution) and Landsat 8 OLI 30m (comparatively lower spatial resolution) satellite imagery, ADS data (vector format), GPS ground collected data (vector format), study region boundary (vector format) and vegetation classification data (vector format). Satellite imagery was used in this project to classify MPB infestations using the MLSC method while the ancillary data from ADS and ground truthed validation points of MPB infestations were used to test the accuracy of this classification method. Because 30m spatial resolution imagery has a lower spatial resolution than 2m, both types of imagery are used to determine how the accuracy of MLSC varies between 30m and 2m spatial resolution imagery.

### *3.2.1. Types of data*

The level of precision in classification methods required is dependent upon the population stage of the MPB (endemic, incipient-epidemic, or epidemic) and the mitigation objectives of forest management. By comparing the accuracy of classification using two different spatial resolutions (2m and 30m), forest management personnel may choose the type of imagery with a suitable spatial resolution that assists mitigation objectives effectively. Mitigation efforts are decided based on the stage of the MPB infestation and dependent upon the population stage of the MPB. Known areas of MPB infestations in lodgepole pine stands were used to define the study areas. Since the LTB is a well-managed area, ADS sketch maps within and outside the LTBMU were considered for use as ground validation points of recorded lodgepole pine tree stands that were infested by the MPB. The data used for this analysis is summarized in (Table 6).

Table 6 Datasets used in this project

| **Data** | **Type** | **Dates** | **Source** |
|---|---|---|---|
| Landsat 8 OLI 30m resolution imagery | Raster | 2014, 2015 | USGS |
| WV02 2m resolution imagery | Raster | 2014, 2015 | Digital Globe Foundation |
| ADS Sketch Maps | Vector | 2014, 2015 | USDA |
| Ground Truthed Validation GPS waypoints | Vector | July, August, September, October 2015 | Author |
| Vegetation Classification Map | Vector | 2009 | USDA |

*3.2.2. Landsat 8 OLI 30m spatial resolution imagery*

Landsat 8 OLI imagery was selected and downloaded for the months of July 2014 and August 2015 from the USGS Global Visualization Viewer at http://glovis.usgs.gov. The months of the imagery vary across 2014 and 2015 due to the amount of cloud coverage existing over the study region at the time of image acquisition. For example, the cloud coverage for Landsat 8 OLI for August 2014 was 4% (mainly over the study region) so the month of July was used. These months are ideal for image acquisition since the effects of MPB infestations (green attack phase turns to red attack phase) occur during this time of year, one year after the initial infestation. As mentioned previously, the MPB lifecycle is one year so the effects from an infestation are not apparent to the human eye until the summer after the initial attack (Wulder et al. 2006).

Shortly after Landsat 5 was decommissioned, Landsat 8 OLI was launched on 11 February 2013 (NASA 2016). Landsat 8 OLI has 11 spectral bands and the band uses are similar to Landsat 5 TM due to having similar resolutions and spectral character capture. Bands used in this analysis are summarized in (Table 7). Landsat imagery with a spatial resolution of 30m allows analysts to accurately detect tree mortality (Meddens et al. 2014). A study conducted in British Columbia by Franklin et al. 2003 concluded that using Landsat TM ETM+ imagery and supervised classification methods resulted in a 73% accuracy in the detection of red attack stage MPB infested trees (Franklin et al. 2003). Although the use of 30m imagery has been shown to be fairly accurate, using satellite imagery that has a higher spatial resolution (2m) may increase the accuracy results of supervised classification.

Table 7 Landsat 8 OLI band characteristics and applications. *Source*: USGS 2014

| **Band number/color** | **Wavelength (um)** | **Resolution (meters)** | **Application** |
|---|---|---|---|
| Band 1/Coastal aerosol | .43-.45 | 30 | Coastal and aerosol studies, dust and cloud detection in atmosphere |
| Band 2/Blue | .45-.51 | 30 | Soil from vegetation delineation |
| Band 3/Green | .53-.59 | 30 | Plant vigor and health |
| Band 4/Red | .64-.67 | 30 | Vegetation slopes |
| Band 5/Near Infrared (NIR) | .85-.88 | 30 | Shorelines |
| Band 6/Short Wave Infrared 1(SWIR 1) | 1.57-1.65 | 30 | Moisture content of soil and vegetation. Used in EWDI |
| Band 7/SWIR 2 | 2.11-2.29 | 30 | Soil and vegetation classification |
| Band 8/Panchromatic | .50-.68 | 15 | High resolution band |

### *3.2.3. WorldView02 2m spatial resolution imagery*

WV02 imagery was selected and downloaded from the Digital Globe FTP server after an imagery grant was approved. Imagery captured by WV02 satellite during July 2014 and August 2015 covered mainly the eastern portion of the LTBMU (Figure 8). WV02 is the first high-resolution 8-band multispectral satellite commercially available since IKONOS was decommissioned in 2013 (Digital Globe 2015). As previously mentioned, the months of July and August are ideal months for image acquisition due to the nature of the MPB infestation and progression of tree mortality that follows the initial infestation from the prior year.

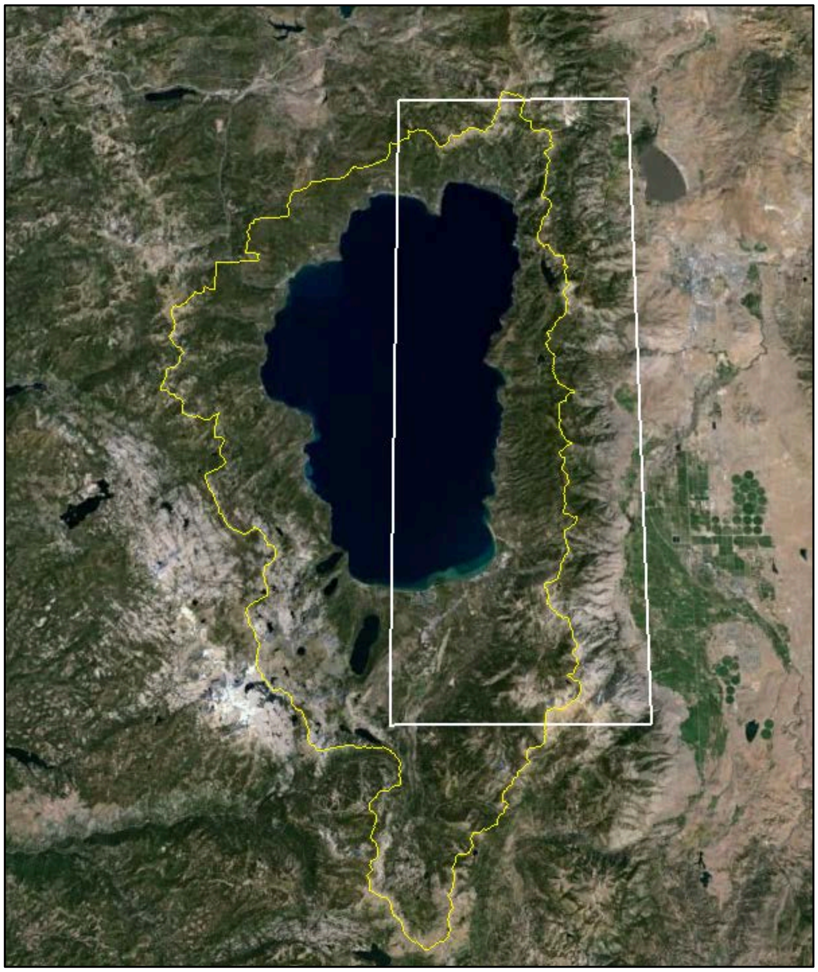

Figure 8 Bounding box represents the coverage of WV02 2m spatial resolution imagery for July 2014 and August 2015. *Source*: USGS 2012

WV02 was launched on 8 October 2009 with an expected mission life of 10-12 years. Table 8 shows WV02 band characteristics and applications. WV02 has one panchromatic band (pan-sharpened capable of producing 1.85m spatial resolution) and eight multispectral bands (capable of producing imagery with an average of 2.07m spatial resolution) (DigitalGlobe 2015). A comparatively higher spatial resolution to Landsat 8 OLI 30m, WV02 2m gives the analyst greater detail, allowing the analysis of smaller patches (~2m$^2$) of red attack phase MPB infested trees. With a spatial resolution of 2m, objects that cover 2m$^2$ can be viewed with WV02 imagery.

Table 8 WV02 Band characteristics and applications. *Source*: DigitalGlobe 2010

| Band number/color | Wavelength (um) | Resolution (meters) | Application |
|---|---|---|---|
| Band 7/Coastal | .40-.45 | 1.84 | Atmospheric correction |
| Band 4/Blue | .45-.51 | 1.84 | Absorbed by chlorophyll and penetration of water |
| Band 3/Green | .51-.58 | 1.85 | Reflectance of healthy vegetation and delineating healthy from unhealthy plants |
| Band 6/Yellow | .585-.625 | 1.84 | Detection of "yellowness" of plants on land and in water |
| Band 2/Red | .63-.69 | 1.84 | Discrimination of vegetation due to the absorption of red light, characteristic of healthy plants. Classification of bare soil, roads and other dark features. |
| Band 5/Red Edge | .705-.745 | 1.84 | Measuring plant health and vegetation classification |
| Band 1/Near Infrared 1(NIR1) | .77-.895 | .46 | Estimation of moisture, vegetation types and soil types |
| Near Infrared 2/ (NIR 2) | .86-1.04 | .46 | Overlaps NIR1 and enables broader biomass studies |

### 3.2.4. *Aerial Detection Survey Sketch Maps*

Every year, the USDA Forest Service conducts one ADS to sketch map trees that have been either damaged or killed. The sketch map attributes include the damage type, number of trees affected, and the tree species that were affected (USDA 2015b). Normally, the sketch maps are validated using field crews and the data is fairly reliable. The numbers of trees affected in each polygon, representing a sketch of the infested area are estimated per acre. Areas containing less than one affected tree per acre are considered a normal level of mortality (endemic MPB population), and therefore not recorded on the sketch map (USDA 2015b).

WV02 imagery was used to detect these small patches of trees not recorded in ADS. WV02 has a spatial resolution of 2m, therefore smaller patches of trees that are infested by the MPB can be detected using the imagery rather than by aircraft, whereas, ADS are used primarily for detection of infested stands for planning and allocating mitigation procedures (British Columbia Ministry of Forests 2003; White et al. 2005). Since ADS is not used to detect endemic (<1 tree per acre) populations, WV02 is useful. ADS sketch maps can be used as a source of ground validation to establish training areas, as well as to assess the accuracy of MLSC methods using RS imagery. ADS sketch mapping is also useful in establishing an inventory of affected trees and detecting MPB infestations at a provincial scale (White et al. 2005). ADS from 2005-present are provided by the USDA Forest Service and are downloadable free of charge.

### 3.2.5. *Ground Truthed Validation Points*

Ground truthed validation points were collected in the field during August, September, and October 2015 with a handheld GPSMAP© 62sc GPS recreational GPS receiver. The positional accuracy of most recreational GPS devices is on average about 9 feet. These waypoints were used to establish training areas to create signature files, later used in MLSC function in ArcGIS 10.3. The ground truthed validation points were used to assess the accuracy of MLSC of both 30m and 2m spatial resolution imagery of 2015 Landsat 8 OLI 30m and WV02 2m spatial resolution imagery.

Single-tree coordinates were collected in locations that included healthy, red attack and dead attack lodgepole pine trees in dense stands as well as single infested trees. The collected ground truthed validation points served the same purpose as ADS sketch maps, however, the total amount of infested trees could be recorded more precisely when single trees were recorded and immediately documented. This procedure was used to record smaller endemic patches of MPB infested trees that were not recorded in the Region 5 ADS sketch maps.

According to Jeffrey Moore, infestations that are less than one tree per acre (endemic) were not recorded in the sketch maps. Human errors occur when attempting to define smaller patches of tree mortality/infestation during ADS, therefore, ground validation points were used to establish training areas that were used in the MLSC method.

## 3.3 Procedures and Analysis

This section of this paper describes the processes that occur after image acquisition. These processes include pre-processing (completed by Glovis and DigitalGlobe), creating natural color composite images, collection of ground truth validation points, vegetation classification map used to establish training areas, MLSC, accuracy assessment of MLSC per imagery resolution (30m and 2m) and comparison of results. The calculation of TCT wetness indices for Landsat 8 OLI 30m spatial resolution imagery for 2014 and 2015 were also included in the processes used to calculate the EWDI (Figure 9).

### *3.3.1. Pre-processing*

Glovis and Digital Globe completed orthorectification prior to image acquisition. Orthorectification is the process of correcting the geometry of an image to reduce distortion caused by terrain, sun angles, and the angle at which the image was taken from the satellite sensor (ESRI n.d.). These corrections were completed by comparing the imagery with ground control points (known landmarks) and resampled so the exact location of a single pixel is located in the correct location on earth (ESRI n.d.). Without orthorectification and geometric correction, the imagery can misrepresent pixels resulting in a misalignment of the imagery, thus creating inaccuracies in the analyses. These pre-processing steps ensured that a single pixel in the image correctly represented the precise location on earth.

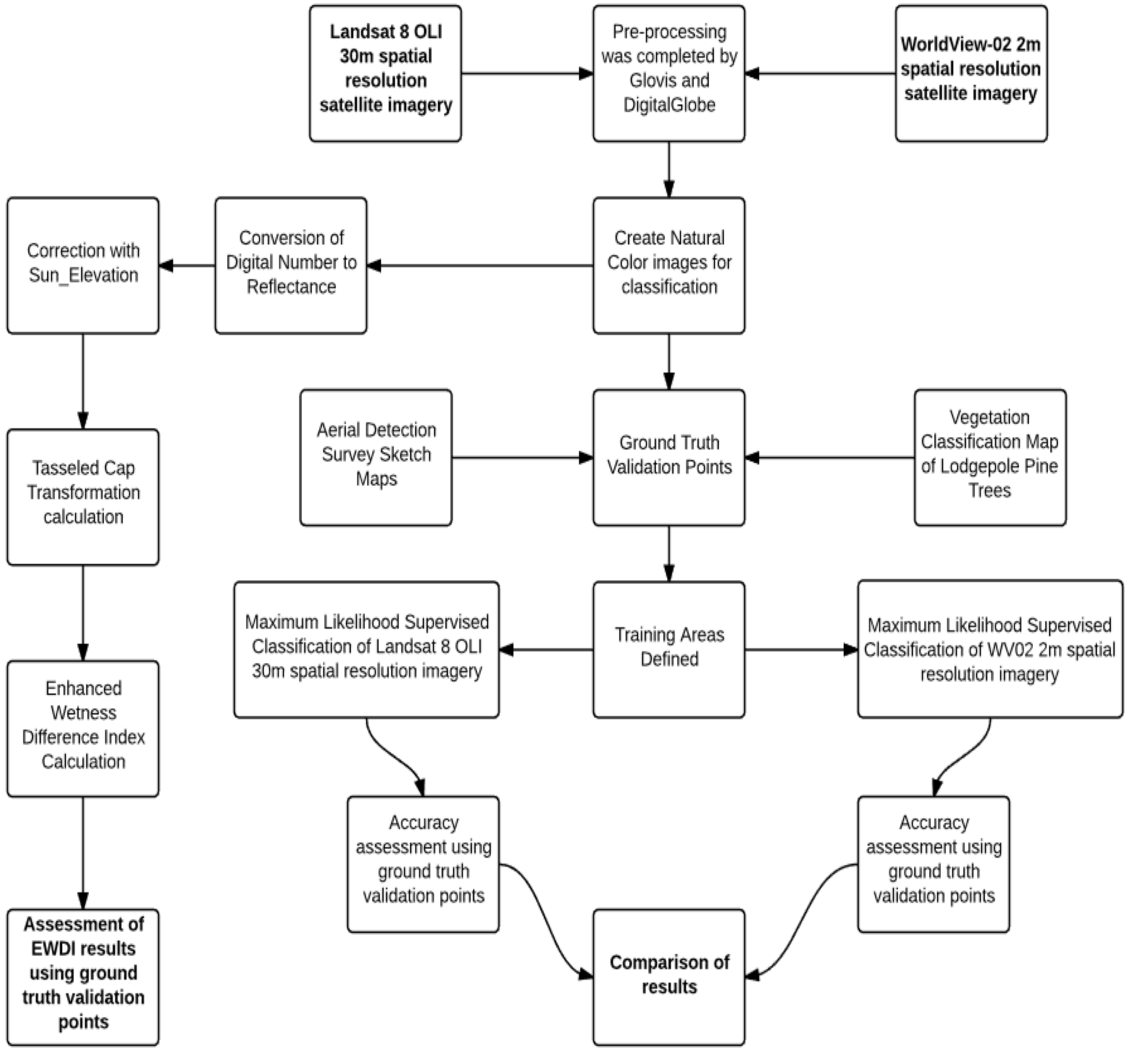


Figure 9 Workflow diagram. *Source*: Nash 2015

### *3.3.2. Maximum Likelihood Supervised classification*

Maximum Likelihood Supervised Classification is the process of classifying objects in an image based on the guidance of the analyst. After natural color composite images were created, training areas (based on the vegetation classification map and ground truthed validation points) were established and used in the MLSC process using the spatial analyst tool in ArcGIS 10.3. A MLSC algorithm was used to classify cells that were similar to specified pixels that represented an object based on classification confidence. Different classes were assigned based on the level of certainty after the

MLSC process was executed. For example, if a signature file was created for a red attack stage tree, a maximum likelihood classification process was executed and other pixels in the image that match the digital number of chosen pixel (with the most certainty) was reclassified in the image as red attack stage. Ground truthed validated points of healthy, red attack and dead attack lodgepole pine trees assisted in creating classes and control variables used for the MLSC.

### *3.3.3. Vegetation Classification Map*

Insect infestations of other types, existing vegetation other than the lodgepole pine trees and other phenomena exist that can affect the accuracy of the classification of MPB red attack stage. These other phenomena, that affect the visual signature of the landscape, include water bodies, clear cuts, fire scars, other vegetation, and urban development. These phenomena must be excluded to ensure accuracy of the results. Other types of trees/vegetation exist amongst lodgepole pine in the LTB, which may affect the classification MPB in lodgepole pine tree stands. White et al. 2005 used an exclusionary mask of logged areas, water bodies and cloud cover present at the time of image acquisition. The purpose of this mask was to reduce the spectral variations that are characteristic of a mixed forest (White et al. 2005). Minimizing the spectral variations before executing supervised classification improved the accuracy of the results.

Dependent upon the size and location of infestations located using ground truthing, a vegetation classification map can be helpful in creating a mask; it would be similar to White's exclusionary mask that excludes other types of trees and phenomena (water bodies, clear cuts, fire scars, other vegetation and trees, and urban development) besides the lodgepole pine tree. The vegetation classification map is available to the public via the USDA Forest Service and was downloaded free of charge. Existing lodgepole pine tree stands were queried from this data and created into a vector polygon layer. The vegetation classification map included: (1) scrub, (2) forests and (3) developed areas. Lodgepole pine forests were queried from the forest category and then used to create training areas, utilized in creating signature files that were relevant to running the MLSC algorithm in ArcGIS 10.3.

#### *3.3.4. Accuracy Assessment Methods Using Ground Truthed Data*

Data used in the accuracy assessment of MLSC included the vegetation classification map (only lodgepole pine trees) and ground truthed validation points of lodgepole green (LPG) and lodgepole red (LPR) trees. The overall accuracy, errors of commission and errors of omission were calculated based on these layers. GPS waypoints were collected in the sections A, B and C and later used in the MLSC of objects in RS imagery.

ADS mapping (mentioned later) is a type of ground truth data collected over a large area by aircraft. The purpose of using GPS waypoints as ground truth data was to precisely locate points/areas in both 30m and 2m spatial resolution imagery, associating a ground control point with a pixel of the image that occurs relatively close in time to the acquisition of imagery, ensuring the most accurate data used in the accuracy assessment of 2015 imagery. Ground truthed validation data acquired during the months of July, August, September and October (approximately the same time of year as the RS imagery acquisition) provided a sample amount of points, within pixels, that were assigned to a particular category (LPG or LPR).  These points represented objects with locations on earth and assigned a Digital Number (DN), which was represented one pixel of the image.

After all ground truthed validation points were collected from the field, they were uploaded into ArcGIS 10.3 and overlaid upon Landsat 8 OLI and WV02 imagery post MLSC.  In order to assess the accuracy of classification, the ground truthed validation points were assigned values (DN's) based on their location and underlying class (5 user-defined classes).  This step was completed using the Spatial Analyst Extract Values to Points tool in ArcGIS 10.3.

This sample data was then inputted into an error matrix, which is a square array of numbers (sample units) in rows and columns and assessed for accuracy (Congalton 1991).  The error matrix allows analysts to assess the accuracy of classification methods by comparing the location and class of ground truthed validation points to the location and class of the imagery.  Producer's accuracy is the total number of correct pixels classified using supervised classification in RS imagery by the total number of reference (ground truth) pixels.  User's accuracy is calculated by the total number of correct pixels classified by the total number of pixels classified in the RS imagery using supervised classification.

Using this error matrix (Table 9)., the overall accuracy, errors of commission (misclassified as MPB(R)) and errors of omission (objects left out that are included in sample) were calculated.  The overall accuracy was calculated by dividing the total number of objects correctly classified by the total number of samples of supervised classification, which equaled 74% (Table 9). The goal of this project was to calculate and compare the overall accuracy of supervised classification using 30m and 2m spatial resolution imagery, which was achieved by using an error matrix similar to that of Congalton 1991.

Table 9 Example of an error matrix. Columns represent ground truth data and rows represent the results from supervised classification of RS imagery. *Source*: Congalton 1991

| | MPB(R) | MPB(G) | MPB(D) | Healthy(NI) | Row total |
|---|---|---|---|---|---|
| **MPB(R)** | 65 | 4 | 22 | 24 | 115 |
| **MPB(G)** | 6 | 81 | 5 | 8 | 100 |
| **MPB(D)** | 0 | 11 | 85 | 19 | 115 |
| **Healthy(NI)** | 4 | 7 | 3 | 90 | 104 |
| **Column total** | 75 | 103 | 115 | 141 | 434 |

*Tree Categories*
MPB(R)=Red attack MPB infestation
MPB(G)=Green attack MPB infestation
MPB(D)=Dead from MPB
Healthy(NI)=Healthy No MPB infestation

*Producer's Accuracy*
MPB(R)=65/75=87%
MPB(G)=81/103=79%
MPB(D)=85/115=74%
Healthy(NI)=90/141=64%

*User's Accuracy*
MPB(R)=65/115=57%
MPB(G)=81/100=81%
MPB(D)=85/115=74%
Healthy(NI)=90/104=87%

*Overall Accuracy*
MPB(R) [65]+MPB(G) [81]+MPB(D) [85]+Healthy(NI) [90]=321
Row total + Column Total=434
321/434=74%

It is possible to use an error matrix (similar to that of Congalton 1991), in this project with estimates of MPB infested lodgepole pine trees recorded in the attribute data from the ADS, however, the attribute information included in the ADS data is only an estimate and does not represent the true number of trees infested and false results would occur. The results from using ADS attribute data may be subjective, therefore, using ground truthed validation points is a more precise method of recording MPB infested trees, later used to calculate the overall classification accuracy, errors of commission and errors of omission of 2015 Landsat 8 OLI 30m and WV02 2m spatial resolution imagery using an error matrix.

### *3.3.5. Tasseled Cap Transformation Wetness Index and Enhanced Wetness Difference Index Calculation*

EWDI enables analysts to measure the change in wetness over time using multi-date imagery. Landsat 8 OLI data was used to measure the change in wetness from 2014 to 2015. Loss of moisture in the canopy of lodgepole pine trees is characteristic of MPB infestations. In order to calculate the wetness difference (EWDI) between multi-date imagery (2014 and 2015), the TCT wetness index must be calculated for each year. The TCT wetness index exhibits the wetness for 2014 and 2015. Once the TCT wetness index is calculated, the EWDI measures the change in moisture from one year to the other. When a MPB infestation occurs, the foliage loses moisture and changes from green attack to red attack, one year after the initial infestation. EWDI has proven to be an effective tool in detecting areas of red attack MPB infestations (Wulder et al. 2006).

The calculation of the EWDI includes five steps: (1) DN values converted to reflectance, (2) Bands 2 through 7 SUN_ELEVATION converted to radians, (3) bands 2 through 7 corrected with the SUN_ELEVATION (post conversion to radians), (4) TCT wetness index calculation using corrected bands 2 through 7 and current Landsat 8 OLI coefficients, and (5) EWDI calculation.

The first step (1), DN values were converted to reflectance using Equation 1 (USGS 2014) and is as follows:

$$\rho\lambda' = M_\rho Q_{cal} + A_\rho \quad (1)$$

where $\rho\lambda'$ = the Top of atmosphere reflectance (TOA), $M_\rho$ = the RADIANCE_MULT_BAND_x (located in metadata of imagery where *x* is the band number), $Q_{cal}$ = DN values (located in metadata), and $A_\rho$ = RADIANCE_ADD_BAND_x (located in metadata where *x* is the band number).

Following step 1, step (2) is calculated where each individual band (2 thru 7) was corrected with the sun elevation after the SUN_ELEVATION (located in the metadata) was converted to radians from degrees using the following equation (2):

$$\text{radians} = (\text{degrees} * \pi)/180° \quad (2)$$

where *degrees* = SUN_ELEVATION (located in the metadata) that is specific to each image at the time of acquisition. The SUN_ELEVATION changes throughout the year due to the north-south position of the sun in relation to the earth (NASA 2011). Post conversion of the SUN_ELEVATION from degrees to radians, each band is corrected to be used in the TCT wetness calculation. Equation 3 was used to correct each band and is as follows:

$$\rho\lambda = \rho\lambda' / \sin(\theta_{SE}) \quad (3)$$

where $\rho\lambda$ = TOA Corrected reflectance, $\rho\lambda'$ = uncorrected TOA reflectance (calculated using Equation 1), and $\sin(\theta_{SE})$ = sun elevation in radians.

After bands 2 through 7 were corrected, (step 3), the TCT wetness index was calculated using the latest Landsat 8 OLI coefficients (Table 10) (Baig et al. 2014). The

TCT wetness index was calculated using the same equation that Wulder et al. used in their 2006 study when they calculated the EWDI using Landsat 7 ETM+ satellite sensor.

Table 10 TCT coefficients for Landsat 8 OLI. *Source*: Baig et al. 2014 *Note*: Band 1(coastal and aerosol) and Band 8 (panchromatic) were not used in calculating the TCT wetness index

| Index | Band2 (Blue) | Band 3 (Green) | Band 4 (Red) | Band 5 (NIR) | Band 6 (SWIR1) | Band 7 (SWIR2) |
|---|---|---|---|---|---|---|
| Wetness | 0.1511 | 0.1973 | 0.3283 | 0.3407 | -0.7117 | -0.4559 |

Using the raster calculator in ArcGIS 10.3, Equation 4 was applied to step (4) and used to calculate the TCT wetness index based on the current Landsat 8 OLI band coefficients. This equation is applied for bands 2 through 7 for both 2014 and 2015 Landsat 8 OLI satellite imagery and is as follows:

$$TCW\_x = (0.1511*(Band2\_corrected))+(0.1973*(Band3\_corrected))+(0.3283*(Band4\_corrected))+(0.3407*(Band5\_corrected))+(-0.7117*(Band6\_corrected))+(-0.4559*(Band7\_corrected)) \quad (4)$$

where $TCW\_x$ = the Tasseled Cap Wetness and $x$ is the year (2014 or 2015).

Finally, after the TCT wetness index was calculated, the EWDI was calculated using Equation 5 as follows:

$$EWDI=TCW1-TCW2 \quad (5)$$

where *EWDI* = the Enhanced Wetness Difference Index, *TCW1* = the Tasseled Cap Wetness Index for 2014, and *TCW2* = the Tasseled Cap Wetness Index for 2015.

Ground truthed validation points of healthy, red attack and dead attack stage MPB infested lodgepole pine trees assist in detecting the wetness changes from 2014 to 2015. If the value of a single $30m^2$ pixel decreased from 2014 to 2015 where known red attack and dead attack stage lodgepole pine trees existed, the EWDI calculation will prove to be another means of detecting MPB caused tree mortality by recording the wetness difference of infested stands and correlating these observations to the stages of the MPB infestations.

## 3.4 Overview of Methods

The aforementioned methods include the use of ground validation points used to test the accuracy of MLSC for Landsat 8 OLI 30m and WV02 2m spatial resolution satellite imagery. Normally, the computer can classify certain phenomena based on a DN, however, ground truthed validation points are used to test the accuracy of classification based on a user's guidance (supervised classification). Each cluster of red attack, grey attack and healthy lodgepole pine tree were recorded. Based on these ground truthed validated points on earth (~9 feet positional accuracy), the accuracy of MLSC was assessed. In addition to this method, TCT wetness for 2014 and 2015 was calculated and used in the calculation of the EWDI in order to detect the change in wetness of locations where the MPB red attack and dead attack trees existed.

# Chapter 4 Results

Using RS imagery (Landsat 8 OLI and WV02) to find a better option than ADS in order to cost efficiently detect MPB infestations of lodgepole pine trees in the LTBMU did not meet my expectations. However, WV02 imagery and USDA Region 5 Forest Service vegetation classification maps helped in locating red attack trees amongst stands of healthy lodgepole pine trees, invaluable for this study. These resources (pre-existing and new) resulted in the documentation of endemic populations of red attack stage MPB infestations outside the intended study region (LTBMU) that have yet to be recorded or detected within Region 5 USDA Forest Service ADS.

In previous studies, incipient-epidemic and epidemic populations have been detected using Landsat 30m spatial resolution imagery (30m$^2$ or greater, or one pixel of Landsat 8 OLI imagery). MPB infestations were located although they did not cover 30m$^2$. Using WV02 2m spatial resolution imagery, I was able to locate endemic populations of red attack stage MPB infestations outside the LTBMU in Region 5, without the use of ADS 2015 sketch maps. Based on the ADS, observations of WV02 imagery and field investigations, only endemic populations of the MPB existed outside the LTBMU.

The MPB infestations located in this project were much smaller than 30m$^2$, sometimes, only spanning 2m$^2$ in diameter (endemic stage), and in clusters of only 2 to 20 trees. Ground truthed validation points of healthy, red attack and dead attack stage lodgepole pine tree MPB infestations were recorded. Considering the positional accuracy of the collection device (~3m), the coordinate of each tree in this study was within 3m of its actual location.

ADS data provided no assistance in locating endemic populations of the MPB in the LTBMU based on investigations of the ADS sketch maps, however, WV02 assisted in locating stands of red attack stage MPB infested trees, later confirmed as endemic red attack stage MPB infestations just outside the LTBMU in Region 5. Although USDA Forest Service sketch maps provided an estimation of tree mortality, they were not beneficial in detecting endemic populations that were specific to the MPB and lodgepole pine tree, which is imperative to mitigating an incipient-epidemic MPB population before epidemic populations occur. As a result, combining WV02 imagery and vegetation classification maps provided data sources that were useful in the detection of MPB infestations within lodgepole pine tree stands.

MLSC of Landsat 8 OLI 30m and WV02 2m imagery was not as accurate as I presumed. On the other hand, improved spatial resolution of WV02 satellite imagery assisted in locating three small endemic clusters (A, B and C) of MPB populations consisting of dead attack, red attack and healthy lodgepole pine trees. Section A contained healthy, red attack and dead attack MPB infested lodgepole pine trees while sections B and C contained only red attack MPB infested lodgepole pine trees.

This chapter is broken into five sections. In Section 4.1, the reliability of ADS data is discussed. Section 4.2, ground truthed validation points and the positional accuracy are explained. Section 4.3 reports the accuracy assessment results of MLSC of Landsat 8 OLI 30m spatial resolution imagery, while Section 4.4 reports the accuracy assessment results of MLSC of WV02 2m spatial resolution imagery. Finally, Section 4.5 exhibits the results from using TCT and EWDI in the detection of red and dead attack stages of MPB infestations between 2014 and 2015 using Landsat 8 OLI imagery.

## 4.1 Aerial Detection Survey Data

After querying out MPB-caused (USDA Forest Service Region 5 ADS code 11006) mortality in lodgepole pine trees (USDA Forest Service Region 5 ADS code 108) from the ADS sketch map attribute table, only a couple smaller areas on the western edge of the LTBMU were identified. Based on local knowledge from hiking in this particular area, I concluded that these two smaller areas would be very difficult to access in steep terrain. Before taking this risk, extra time and not knowing the situation from the air, I conducted a limited investigation as to the reliability of the ADS sketch maps and their attributes. I chose an aerial sketch location south of the extended study region (Figure 10). Coordinates of this location were derived from a KMZ file created in ArcGIS 10.3 and imported into Google Earth Pro. The hike was nearly 12 miles round-trip south of Tragedy Springs, located just off Highway 88, southwest of Silver Lake California (Figure 10).

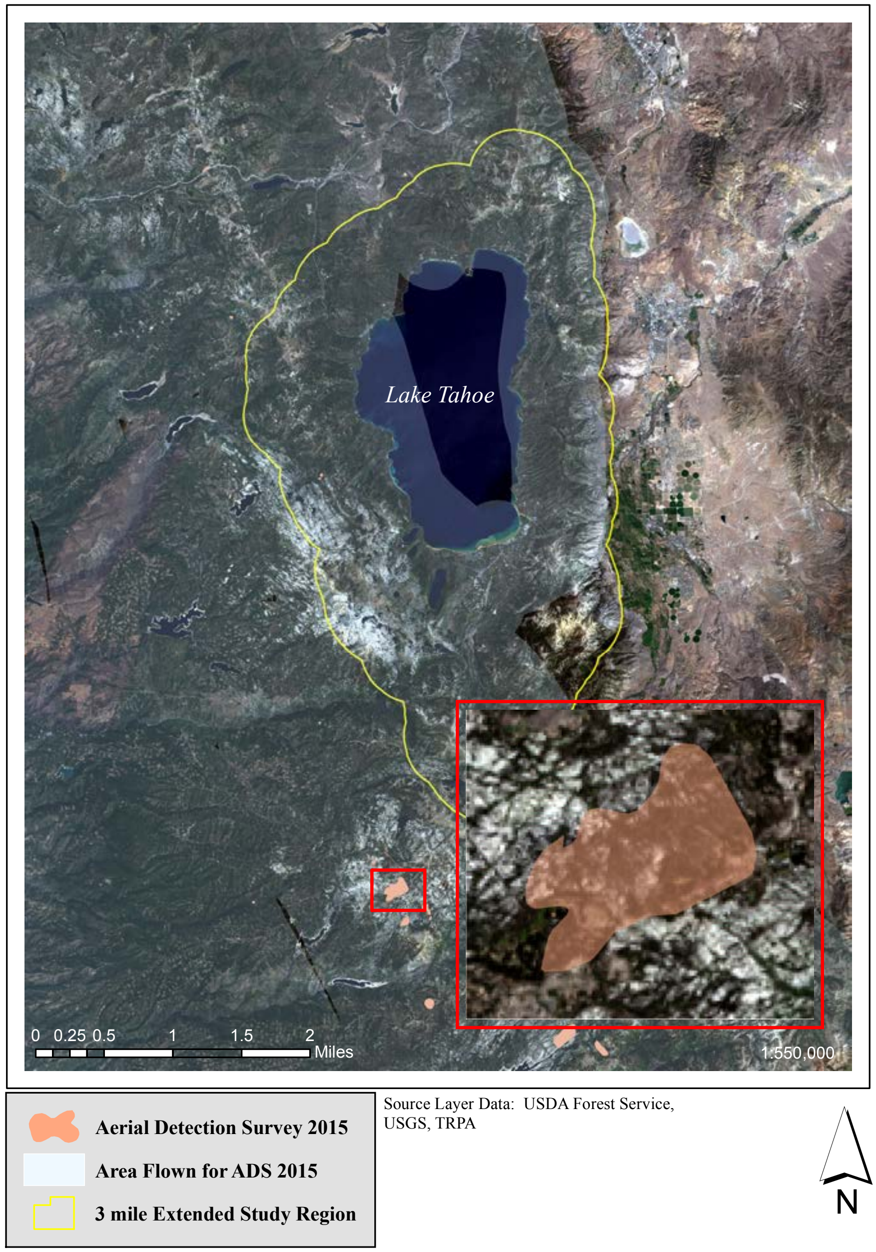


Figure 10 Area flown by USDA Forest Service Region 5 ADS during August 2015 *Note*: inset map shows a larger scale of a southern section of Region 5 ADS sketch map section ONLY used as an example to test reliability of ADS data. *Source*: Nash 2015

An elevated side view photo of the area used to test the reliability of the ADS data and attributes associated with this polygon can be seen in (Figure 11), showing there was a lack of red attack stage MPB infestation.  Using knowledge of the symptoms associated with MPB infested lodgepole pine trees, ground truthed validation concluded there was no MPB infestation in lodgepole pine trees in this particular ADS sketch map site.  Tree mortality occurred sporadically (about 1 tree per acre) in different types of trees other than the lodgepole pine tree (Figure 12).

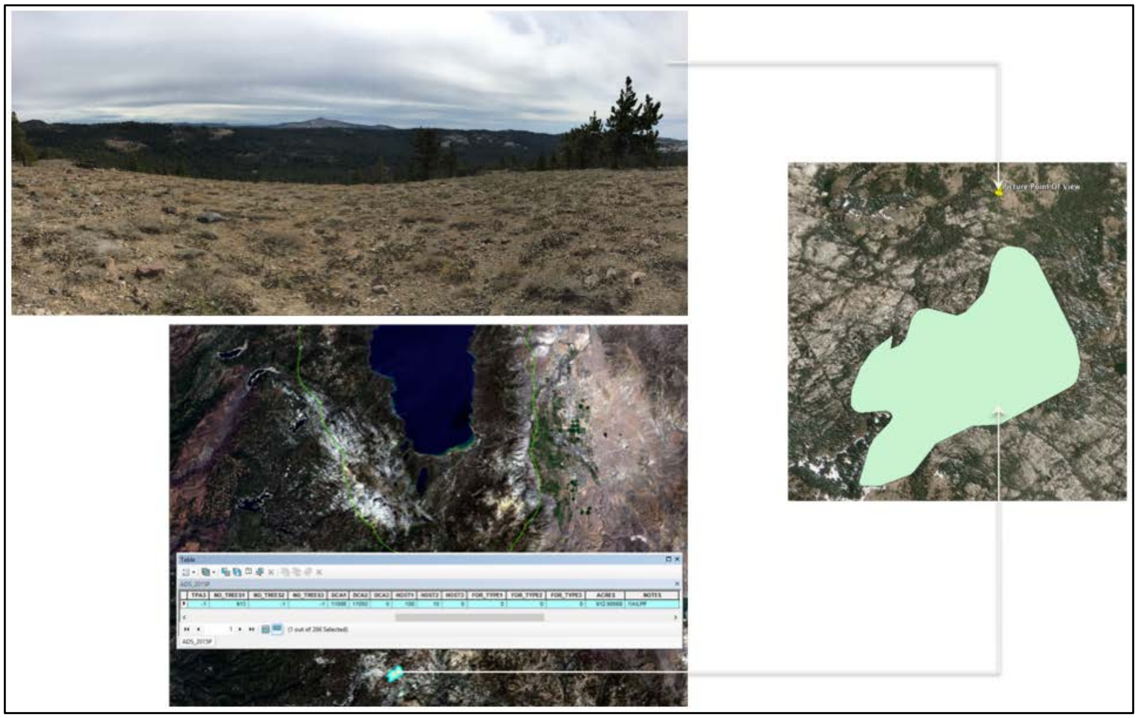

Figure 11 *Above left*, Side view photograph of ADS site; *bottom left*, attribute information of the ADS sketch site; *right*, ADS sketch map. *Source*: USDA 2015

Figure 12 *Above left*, healthy lodgepole pine tree amongst Whitebark pine infested trees; *above right*, beetle damage causing sporadic tree mortality of Whitebark pine trees located in ADS Figure 11. *Source*: Nash 2015

In September 2015, Jeffrey Moore stated in a recent phone conversation that ADS sketch maps illustrate the extent of tree mortality and infestations where at least one tree per acre that was affected (as illustrated in the attribute table in Figure 11). He also explained that clusters are not necessarily recorded and the attribute data is not completely accurate because the observations are recorded from an airplane and human errors occur. According to Jeffrey Moore, based on knowledge of infestations and what lodgepole tree stands look like from the air, this specific aerial sketch site was labeled as MPB caused mortality in a lodgepole pine tree stand.

From this information and visiting an ADS sketch site to validate the attributes, I abandoned treks to the smaller ADS sketch sites on the west side of the LTBMU (basing this decision on reliability of ADS data and safety). ADS sketch sites were not used as ground truth data for 2015 Landsat 8 OLI 30m and WV02 2m spatial resolution imagery. According to Jeffrey Moore, when epidemic infestations occur within the LTBMU, field crews visit these sites and thin susceptible trees to maintain endemic populations. Based on this information, it was best to extend the LTBMU study area boundary using a 3-mile (5000m) buffer. Here, I was successful in locating endemic clusters of the MPB in lodgepole pine tree stands near the intended study region, the LTBMU.

## 4.2 Ground Truthed Validation Points

Nearly 3 miles outside the LTBMU in the northeastern portion of the extended study region, three separate areas of MPB infested lodgepole pine trees were located. These ground truthed validation points were used for Landsat 8 OLI 30m (Figure 13) and WV02 2m (Figure 14) spatial resolution satellite imagery.

The ground validation points recorded in these three stands (A, B, and C) represent healthy lodgepole, red attack stage, and dead attack stage MPB infested trees. The image was divided into three different sections: (1) A, (2) B, and (3) C. Section A consisted of 69 waypoints representing locations of healthy lodgepole and red attack stage MPB infested lodgepole. Section B consisted of 6 red attack stage MPB infested lodgepole and section C consisted of 7 red attack stage MPB infested lodgepole pine trees. Together, (A, B and C) 82 total ground truthed validation points were collected and used in the accuracy assessment of MLSC for Landsat 8 OLI and WV02 imagery.

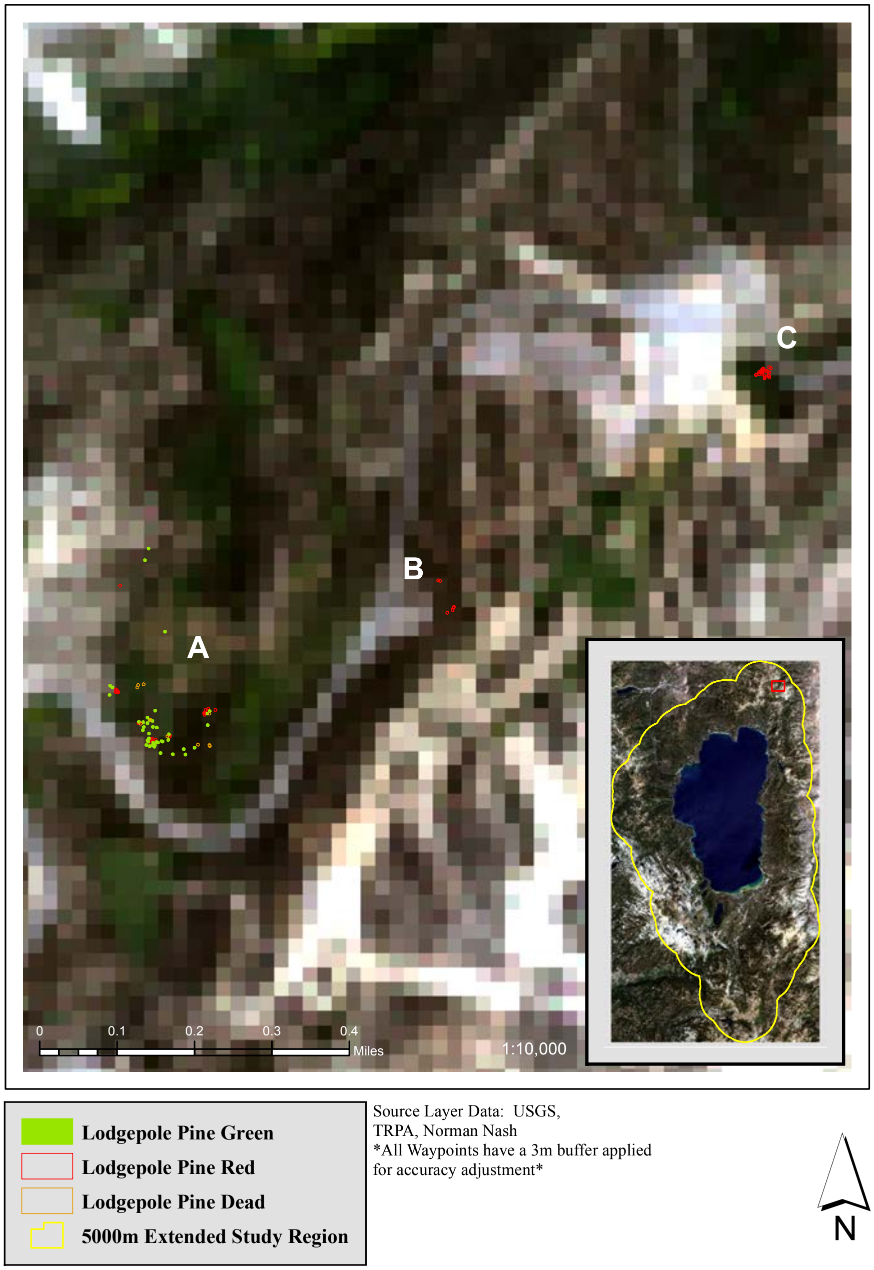


Figure 13 Landsat 8 OLI 30m spatial resolution satellite imagery ground validation point map. *Source*: Nash 2015

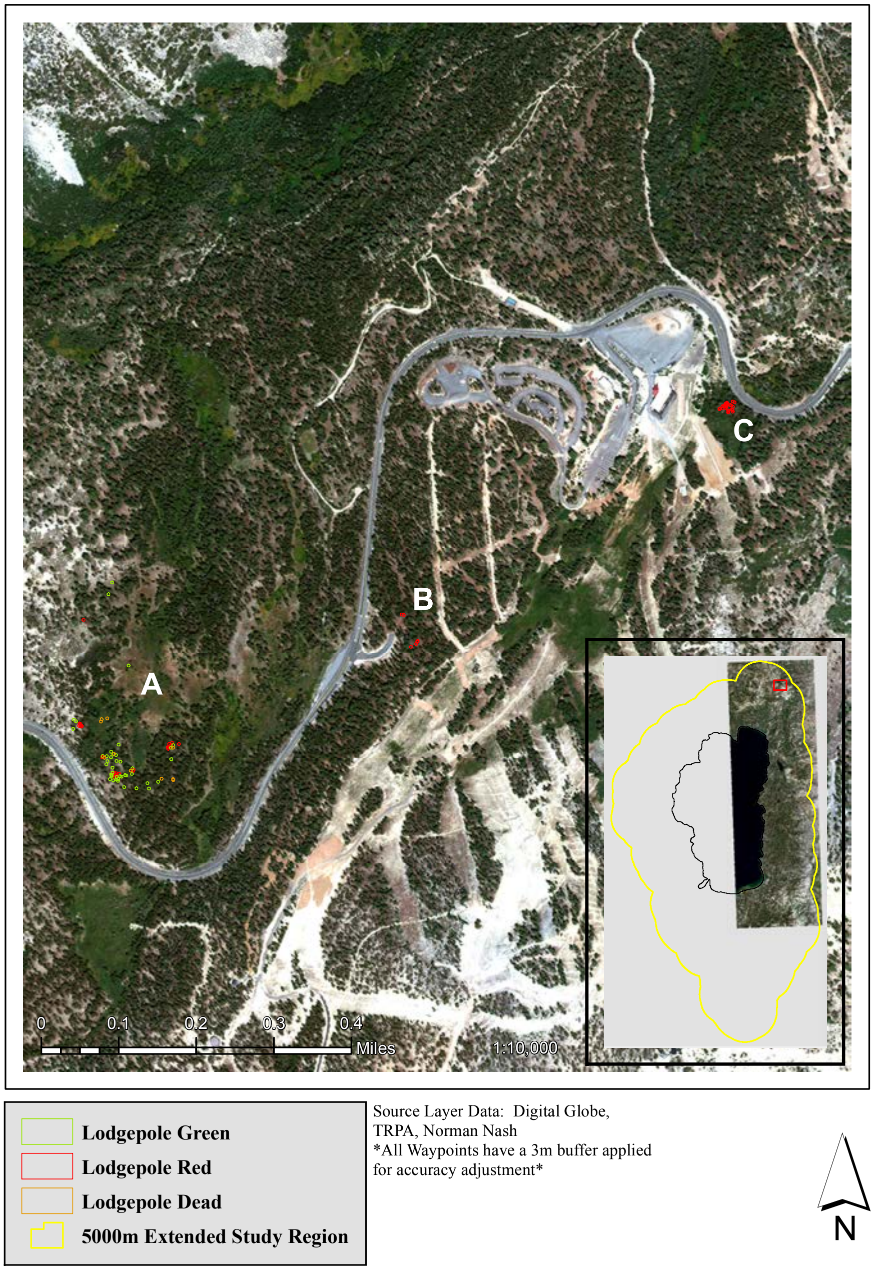


Figure 14 WV02 2m spatial resolution satellite imagery ground validation point map.
*Source*: Nash 2015

Aforementioned, a Garmin GPSMAP 62sc© recreational GPS device was used to collect all points with an accuracy of about 9 feet. With an accuracy of about 9 feet, this meant that the true point could be within 9 feet in any direction from the center of where it was collected. This positional accuracy discrepancy affects the results when conducting an accuracy assessment using 30m and 2m spatial resolution RS imagery. A 3m buffer was applied to compensate for the lack of positional accuracy of the Garmin GPSMap 62sc and used in the accuracy assessment of MLSC.

### 4.3 Maximum Likelihood Supervised Classification Landsat 8 OLI 30m Spatial Resolution Satellite Imagery

MLSC allows the user to define classes based on ground validation points and local knowledge of the area to determine which pixels and associated DN's represent certain phenomena on the earth. Using this method, 5 classes were defined based on the DN of each class prior to classifying the image (Figure 15).

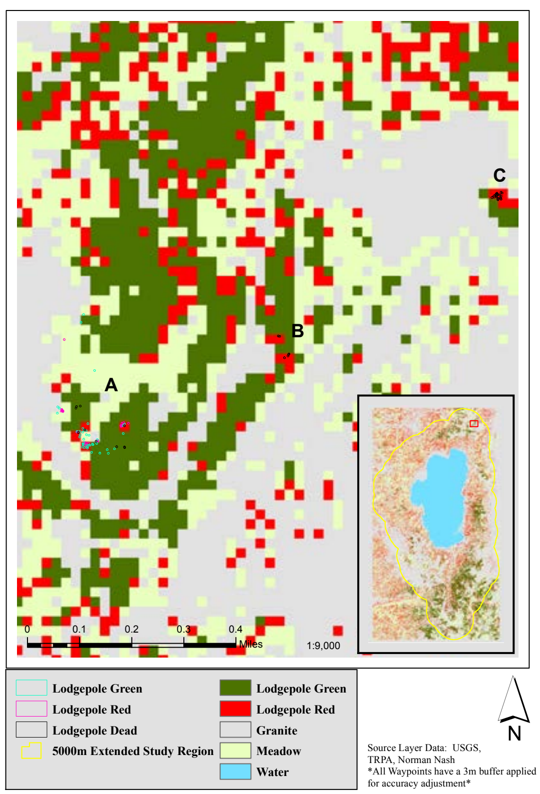


Figure 15 Landsat 8 OLI 30m spatial resolution satellite imagery Maximum Likelihood Supervised Classification with 5 user-defined classes. *Source*: Nash 2015

The five user-defined classes were based on smaller training areas that contained a higher density of red attack stage, healthy lodgepole pine trees, and known vegetation/soil conditions of the area. Using local knowledge, classes were defined based on the prevalence of known soil and vegetation type in the area and also cross-referenced with Google Earth Pro imagery. The three sections (A, B and C) can be viewed at a larger scale in (Figure 16).

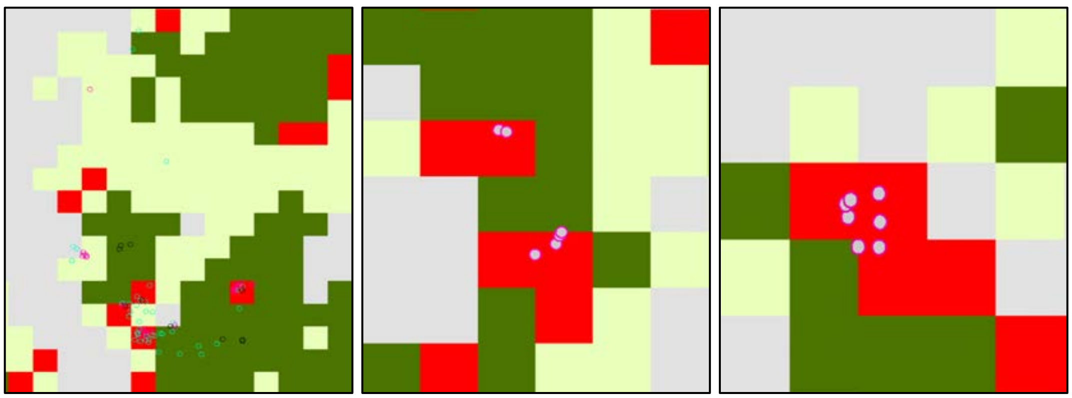

Figure 16 *Above left*, section A; *upper middle*, section B; *upper right*, section C Landsat 8 OLI 30m spatial resolution satellite imagery Maximum Likelihood Supervised Classification *Note*: Refer to the 5 user defined classes in the legend of Figure 19 Sections B and C have a light grey fill applied for visual enhancement. *Source*: Nash 2015

The values of the 5 user defined classes were extracted using the "Extract Values to Points" method mentioned earlier in this chapter. The classes for Landsat 8 OLI are; Lodgepole Green (Value 1), Lodgepole Red (Value 6), Granite (Value 10), Meadow (Value 12), and Water (Value 14). The ground validation points' values were extracted and assigned to each user-defined class using the "Extract Values to Points" tool located in the "Extraction" tools in ArcToolbox (Table 11). This table shows the error matrix used for accuracy assessment of the MLSC of Landsat 8 OLI 30m spatial resolution imagery using ground truthed validation points in sections A, B, and C where all three sections were combined into one error matrix.

Table 11 Error Matrix for 2015 Landsat 8 OLI 30m spatial resolution imagery of sections A, B, and C. *Columns*, represent ground truthed validations points; *rows*, Maximum Likelihood Supervised Classification based on 5 user-defined classes. *Source*: Nash 2015

| Predicted Sections A, B, and C | LPG (Value 1) | LPR (Value 6) | Granite (Value 10) | Meadow (Value 12) | Water (Value 14) | Row Total |
|---|---|---|---|---|---|---|
| LPG | 12 | 2 | 0 | 0 | 0 | 14 |
| LPR | 20 | 30 | 0 | 0 | 0 | 50 |
| Granite | 3 | 1 | 0 | 0 | 0 | 4 |
| Meadow | 7 | 7 | 0 | 0 | 0 | 14 |
| Water | 0 | 0 | 0 | 0 | 0 | 0 |
| Column Total | 42 | 40 | 0 | 0 | 0 | 82 |

The error matrix in Table 11 was used to calculate the overall accuracy, errors of commission and errors of omission. The location and class of each ground truthed validation point and the location and class of each Landsat 8 OLI 30m pixel were compared, allowing the accuracy assessment of MLSC using ArcGIS 10.3.

The overall accuracy (ratio of the total number of ground truthed validation points correctly classified to the total number of ground truthed validation points) of MLSC of Landsat 8 OLI 30m spatial resolution imagery, using LPG and LPR as ground validation control points was (12+30/82) or 51.22%. LPG errors of commission (ratio of the number of pixels incorrectly classified by the total number of pixels classified in the LPG class) was (2/14) or 14.3% of pixels were classified as LPG that do not belong in the LPG class. LPG errors of omission (ratio of the number of incorrectly classified LPG ground truthed validation by the total number of total LPG ground truthed validation points) was (30/42) or 71.4% of LPG ground truthed validation points that belong in the LPG class were not classified as LPG.  Based on the descriptions of errors of commission and omission, the LPR errors of commission was (20/50) or 40% of pixels were classified as LPR that do not belong in the LPR class.  LPR errors of omission was (10/40) or 25% of LPR ground truthed validation points that belong in the LPR class were not classified as LPR.

## 4.4 Maximum Likelihood Supervised Classification WV02 2m Spatial Resolution Satellite Imagery

With higher resolution imagery, endemic clusters of lodgepole pine red attack stage MPB infestations were visible, allowing analysts to create more precise training areas.  The use of five user-defined classes based on training sites resulted in a more detailed and precise classification of WV02 imagery due to the comparatively higher spatial resolution than Landsat 8 OLI.  A MLSC map of WV02 2m spatial resolution satellite imagery was created with five user-defined classes.  These classes were based on training sites created from ground truthed validation points and local knowledge of the soil type and vegetation type within the imagery (Figure 17).

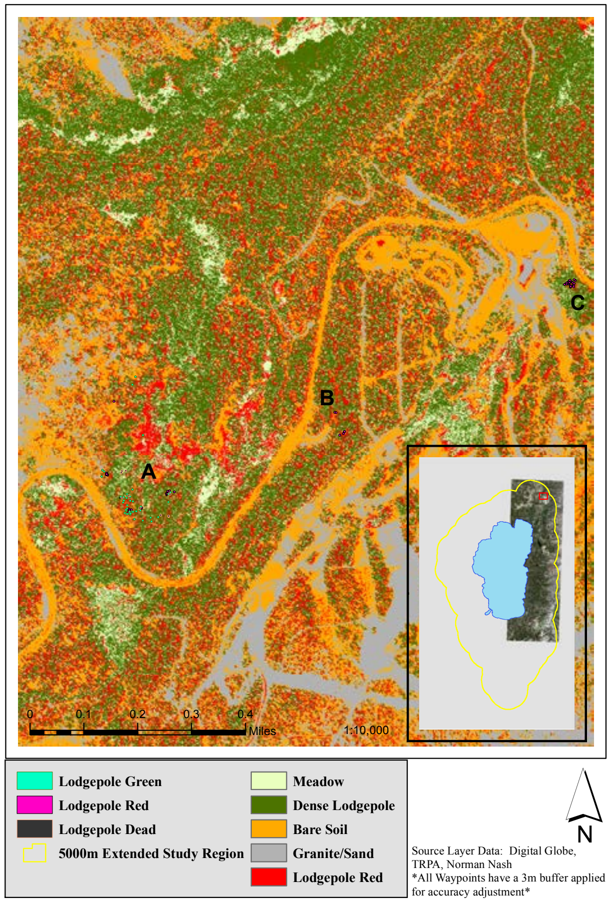


Figure 17 Maximum Likelihood Supervised Classification WV02 2m spatial resolution satellite imagery with 5 user-defined classes. *Source*: Nash 2015

A larger scale of sections A, B, and C can be viewed in (Figure 18). Following this figure, (Table 12) exhibits an error matrix, including ground truthed validation points from sections A, B, and C, that were used to conduct and accuracy assessment of the MLSC method for 2015 WV02 2m spatial resolution satellite imagery.

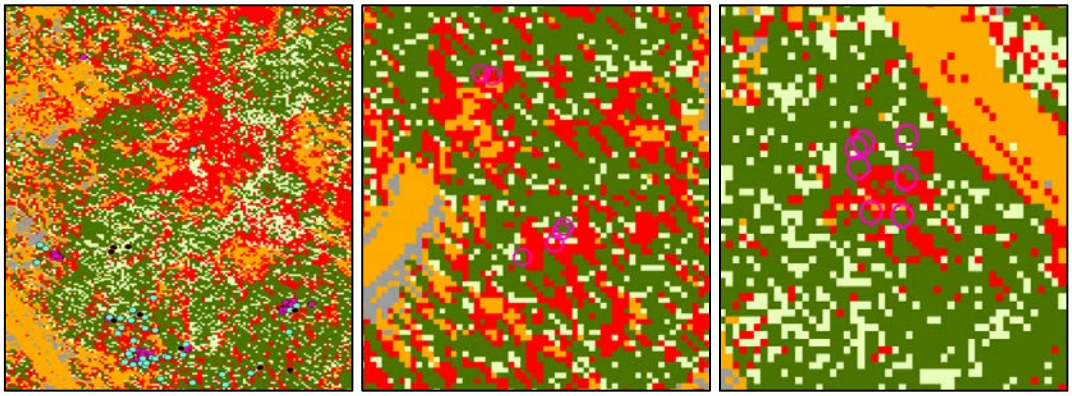

Figure 18 *Above left*, section A; *above middle*, section B; *above right*, section C Maximum Likelihood Supervised Classification *Note*:  Refer to the 5 user defined classes in the legend of Figure 24. *Source*: Nash 2015

The values of the 5 user-defined classes of WV02 were extracted using the same method applied to Landsat 8 OLI imagery.  The classes for WV02 were; Dense Lodgepole or LPG (Value 3), Lodgepole Red (Value 12), Bare Soil (Value 5), Granite/Sand (Value 8), and Meadow (Value 1).  The ground validation points' values were extracted and assigned to each user-defined class using the same method as Landsat 8 OLI.  LPR and LPG ground truthed validation points, along with the 5 user-defined classes, were used in an error matrix (Table 12) to assess the accuracy.

Table 12 Error Matrix for 2015 WV02 2m spatial resolution satellite imagery of sections A, B, and C. *Columns*, ground truthed validations points; *rows*, Maximum Likelihood Supervised Classification based on 5 user-defined classes. *Source*: Nash 2015

| Predicted Sections A, B, and C | LPG (Value 3) | LPR (Value 12) | Bare Soil (Value 5) | Granite/Sand (Value 8) | Meadow (Value 1) | Row Total |
|---|---|---|---|---|---|---|
| LPG | 13 | 18 | 0 | 0 | 0 | 31 |
| LPR | 16 | 9 | 0 | 0 | 0 | 25 |
| Bare Soil | 4 | 5 | 0 | 0 | 0 | 9 |
| Granite/Sand | 2 | 2 | 0 | 0 | 0 | 4 |
| Meadow | 7 | 6 | 0 | 0 | 0 | 13 |
| Column Total | 42 | 40 | 0 | 0 | 0 | 82 |

The error matrix in Table 12 was used to calculate the overall accuracy, errors of commission and errors of omission. The location and class of each ground truthed validation point and the location and class of each WV02 2m pixel were compared, allowing the accuracy of MLSC to be assessed using ArcGIS 10.3.

The overall accuracy (ratio of the total number of ground truthed validation points correctly classified to the total number of ground truthed validation points) of MLSC of WV02 2m spatial resolution imagery, using LPG and LPR as ground validation control points was (13+9/82) or 26.82%. LPG errors of commission (ratio of the number of pixels incorrectly classified by the total number of pixels classified in the LPG class) was (18/31) or 58.1% of pixels were classified as LPG did not belong in the LPG class. LPG errors of omission (ratio of the number of incorrectly classified LPG ground truthed validation by the total number of total LPG ground truthed validation points) was (29/42) or 69% of LPG ground truthed validation points that belonged in the LPG class were not classified as LPG. Based on the descriptions of errors of commission and omission, the LPR errors of commission was (16/25) or 64% of pixels were classified as LPR did not belong in the LPR class. LPR errors of omission was (31/40) or 77.5% of LPR ground truthed validation points that belonged in the LPR class were not classified as LPR.

## 4.5 Enhanced Wetness Difference Index for Landsat 8 OLI 30m Spatial Resolution Satellite Imagery using imagery from 2014 and 2015

In order to calculate the EWDI for 2014 and 2015, the TCT calculations were completed (Section 3.3.5). The EWDI is an index that shows the wetness difference between 2014 and 2015 Landsat 8 OLI imagery (Figure 19).

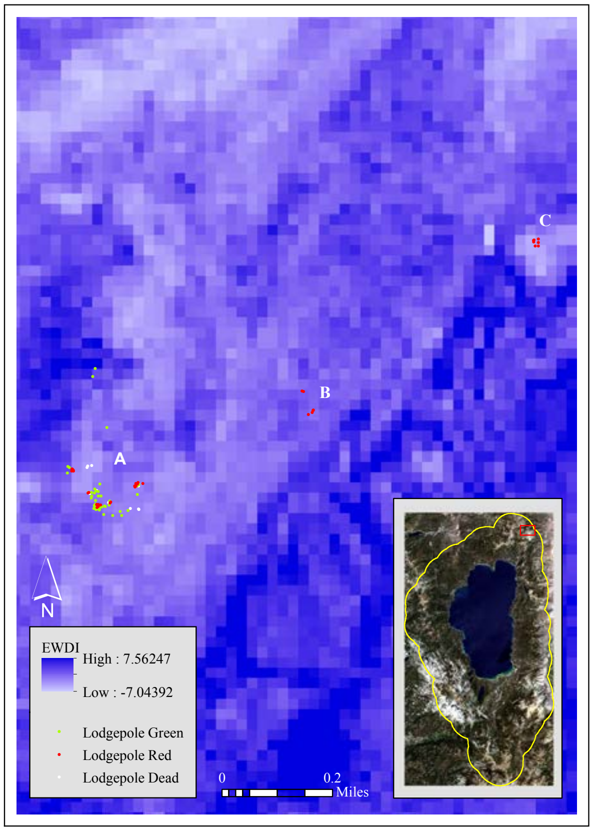


Figure 19 EWDI calculated using the TCT wetness 2014 and TCT wetness 2015 of Landsat 8 OLI 30m spatial resolution imagery. *Source*: Nash 2015

EWDI was calculated using the TCT wetness values for 2014 and 2015 Landsat 8 OLI 30m spatial resolution imagery. The following figures (Figure 20-Figure 23) show the TCT wetness and the EWDI between 2014 and 2015 in sections A, B and C of the study area for Landsat 8 OLI 30m spatial resolution satellite imagery. Ground truthed validation points collected for both lodgepole red attack and lodgepole dead attack trees were included and separated by section according to the TCT wetness of each year (2014 and 2015), and the resulting EWDI.

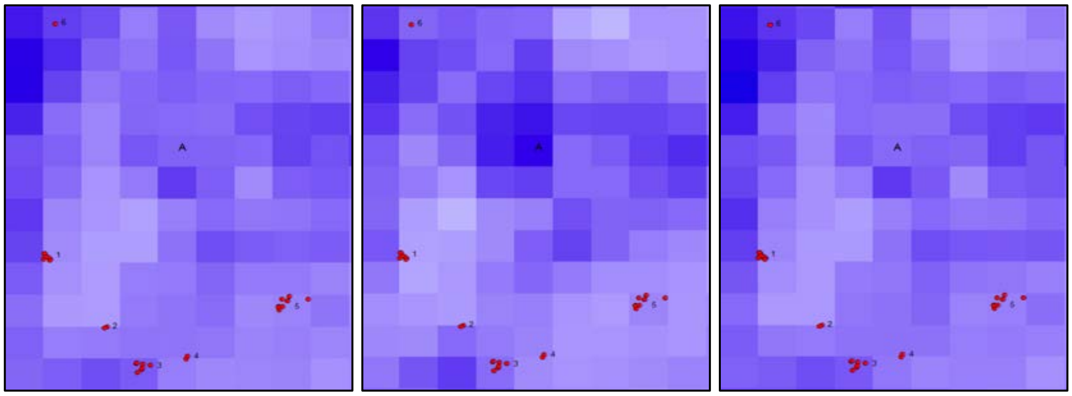

Figure 20 Landsat 8 OLI 30m TCT wetness index and EWDI in section A LPR ground truthed validation points. *Above left*, 2014 TCT wetness; *above middle*, 2015 TCT wetness; *above right*, EWDI. *Source*: Nash 2015

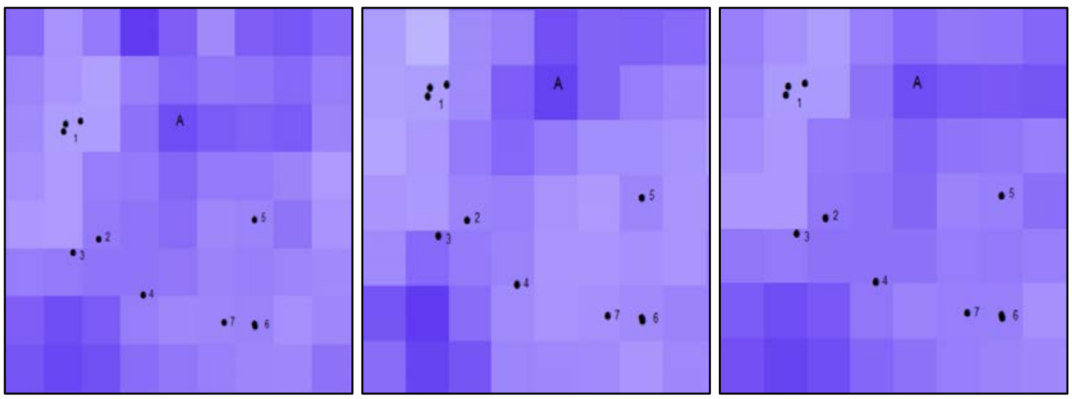

Figure 21 Landsat 8 OLI 30m TCT wetness index and EWDI in section A LPD ground truthed validation points. *Above left*, 2014 TCT wetness; *above middle*, 2015 TCT wetness; *above right*, EWDI. *Source*: Nash 2015

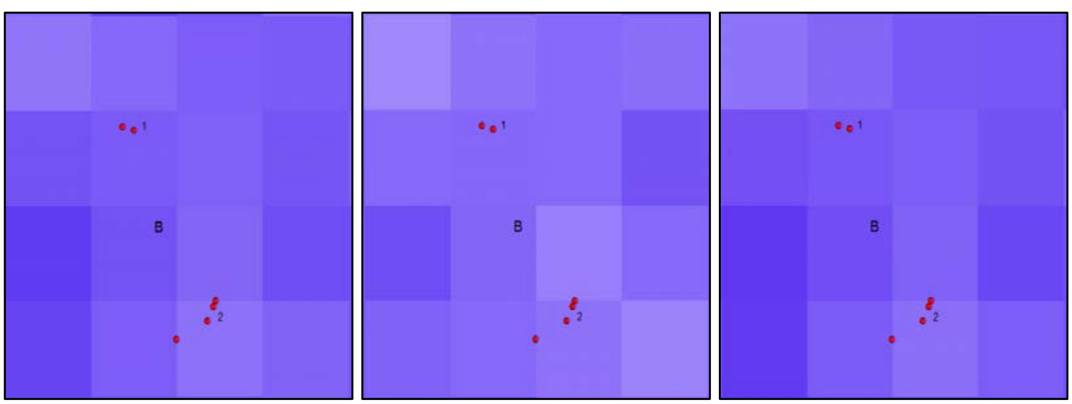

Figure 22 Landsat 8 OLI 30m TCT wetness index and EWDI in section B LPR ground truthed validation points. *Above left*, 2014 TCT wetness; *above middle*, 2015 TCT wetness; *above right*, EWDI. *Source*: Nash 2015

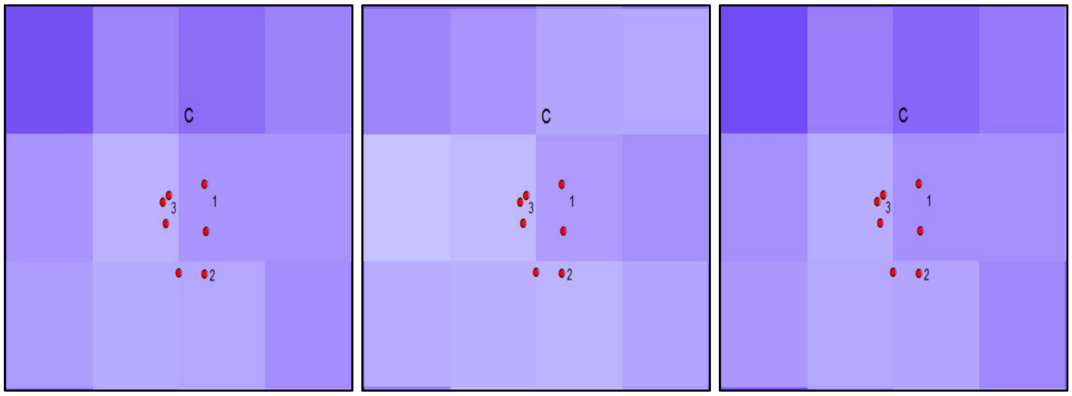


Figure 23 Landsat 8 OLI 30m TCT wetness index and EWDI in section C LPR ground truthed validation points. *Above left*, 2014 TCT wetness; *above middle*, 2015 TCT wetness; *above right*, EWDI. *Source*: Nash 2015

The values of each LPR and LPD attack ground truthed validation point were clustered based on location within each pixel. Each cluster of ground truthed validation points that lies in a single pixel ($30m^2$) were associated to a number (1-7), which displays the TCT wetness and EWDI value per pixel for 2014 and 2015 (Table 13). The EWDI scale is between (-7.04392 to 7.56247) shown previously in the legend of Figure 19.

Table 13 2014 and 2015 TCT wetness and EWDI pixel values of ground truthed validation points per $30m^2$ pixel. (🡅), represents an increase in wetness from 2014 to 2015; (🡇), indicates a wetness loss from 2014 to 2015. *Source*: Nash 2015

| **Section A Lodgepole Red** | **2014 TCT Wetness Pixel Value** | **2015 TCT Wetness Pixel Value** | **EWDI Value** |
|---|---|---|---|
| (1) | -0.008176 | 0.007907 | -0.016083 🡅 |
| (2) | -0.021351 | -0.040020 | 0.018669 🡇 |
| (3) | -0.048578 | -0.037942 | -0.010636 🡅 |
| (4) | -0.026604 | -0.017879 | -0.008725 🡅 |
| (5) | -0.015521 | -0.016065 | 0.000544 🡇 |
| (6) | -0.076063 | -0.043578 | -0.032485 🡅 |

| **Section A Lodgepole Dead** | **2014 TCT Wetness Pixel Value** | **2015 TCT Wetness Pixel Value** | **EWDI** |
|---|---|---|---|
| (1) | 0.008532 | 0.005571 | 0.002960 🡇 |
| (2) | -0.022056 | -0.017385 | -0.004671 🡅 |
| (3) | -0.021351 | -0.040020 | 0.018669 🡇 |
| (4) | -0.026604 | -0.017879 | -0.008725 🡅 |
| (5) | -0.015521 | -0.016065 | 0.000544 🡇 |

| | | | |
|---|---|---|---|
| (6) | -0.015570 | -0.011545 | -0.004025 ↑ |
| (7) | -0.013238 | -0.004617 | -0.008622 ↑ |

| **Section B Lodgepole Red** | **2014 TCT Wetness Pixel Value** | **2015 TCT Wetness Pixel Value** | **EWDI** |
|---|---|---|---|
| (1) | -0.050812 | -0.042007 | -0.008805 ↑ |
| (2) | -0.030524 | -0.033019 | 0.002495 ↓ |

| **Section C Lodgepole Red** | **2014 TCT Wetness Pixel Value** | **2015 TCT Wetness Pixel Value** | **EWDI** |
|---|---|---|---|
| (1) | -0.003867 | -0.002140 | -0.001727 ↑ |
| (2) | -0.159249 | -0.022355 | -0.136894 ↑ |
| (3) | -0.237038 | -0.027283 | -0.209755 ↑ |

According to the pixel values derived from the 2014 and 2015 TCT wetness index, a positive EWDI number represents a loss of moisture (↓) and a negative number represents a moisture increase (↑). Using the ground truth validation points as reference, 12 out of 18 pixels in this study region exhibited a wetness increase. MPB infested trees decrease in moisture as pigmentation was lost with the progression of infestations. In Table 13 EWDI was calculated using Landsat 8 OLI 30m spatial resolution imagery and with MPB infestations at the endemic stage, $30m^2$ coverage was not likely, yet the change in moisture from 2014 to 2015 per pixel was still affected due to MPB infestations

EWDI, an index, averages the reflectance value of the phenomena within the pixel. The DN represents the average of an entire pixel, like an index. If the majority of a pixel is green, the red will not be strong enough to create an average. Red attack and dead attack trees decrease in moisture as the progression of MPB infestations occur. Therefore, red attack trees will be red in a natural color image an dead attack will be grey. An explanation for the results of EWDI for 2014 and 2015 is that the density and population stage of the red attack and dead attack MPB infested trees were not high enough to affect the overall reflectance (DN), resulting in a decrease in the wetness of the entire pixel. The results from EWDI showed that 3 out of 11 or 27.3% of Landsat 8 OLI 30m pixels containing LPR MPB infested trees decreased in wetness from 2014 to 2015. 3 out of 7 or 42.8% of the pixels included in the analysis containing LPD MPB infested trees decreased in wetness from 2014 to 2015. An average lodgepole pine tree spans nearly 2m in diameter. Considering the area covered per pixel, the diameter of lodgepole pine trees and lack of number of trees prevented a viable accuracy assessment using EWDI could not be properly performed in this analysis (not a bad thing). According to the results of the EWDI, there is not enough ground truthed validation points (LPR and LPD) to create a reliable relationship between wetness decrease/increase associated with MPB infestations due to a lack of sufficient sample points considering the 30m spatial resolution.

Originally, I was expecting a lot higher accuracy assessment results of MLSC of MPB stages using Landsat 8 OLI and WV02 imagery. Using ArcGIS 10.3's MLSC method, accuracy assessment results using the different stages of the MPB infestations as control points was 50% accurate using imagery that cannot be used to visibly locate infestations, therefore cannot be used to detect endemic stages of the MPB. In order to prevent epidemic population levels of the MPB, endemic clusters must be detected first. WV02 can be used aside ADS to detect endemic infestations, yet comes with a price. The accuracy assessment results of Landsat 8 OLI 30m, WV02 2m and EWDI of Landsat 8 OLI showed that endemic stages of MPB can accurately be detected less than 50% of the time using MLSC techniques with ArcGIS 10.3.

# Chapter 5 Discussion and Recommendations

The main focus of this project was to test the accuracy of MLSC of MPB red attack stage infestations in the LTBMU using both Landsat 8 OLI 30m and WV02 2m spatial resolution imagery; however, there was a scarcity of both endemic and epidemic MPB populations in the LTBMU. This resulted in a smaller study region within close proximity of the LTBMU where endemic clusters of MPB infestations occurred. This area was thoroughly hiked and the stages of MPB infestations documented. With an absence of MPB infestations located in the ADS sketch survey maps, WV02 (comparatively higher spatial resolution than Landsat 8 OLI) assisted in locating endemic clusters of MPB infestations that were used in this thesis project.

## 5.1 Understanding Remote Sensing and the Mountain Pine Beetle

Throughout this thesis, like White et al. 2005, I have found that high resolution RS imagery is available commercially and can assist in the detection of MPB infestations without the use of ADS. Although this thesis did not prove the classification methods to be accurate according to the error matrix, the consistency of WV02 imagery supersedes ADS due to the availability of imagery throughout the year. Forest management can use WV02 high-resolution imagery to detect tree mortality rather than relying on ADS. Rather than trying to control the epidemic population growth, management and mitigation efforts have shifted to focus on the source of the problem, trying to control incipient-epidemic populations of the MPB. One of the objectives of Region 5 Forest Service is to maintain the aesthetics of forest that are frequented by tourists. Being able to address an endemic MPB population fulfills this objective through mitigation efforts like thinning (mentioned in Chapter 1). This shift in management resulted in detecting smaller incipient-epidemic populations using high-resolution RS imagery, followed by mitigation efforts to prevent these incipient-epidemic populations from progressing into epidemic populations. Forest management may utilize local scale analysis to detect small infestations so that field crews can remove the problem before it persists.

## 5.2 Accomplishments of Thesis Project

ADS are conducted annually. According to Jeffrey Moore (who is in charge of the ADS), the budget for this service is $100,000 annually (does not include the salary of employees who process the aerial photography). Landsat 8 OLI 30m satellite imagery is available for download at no cost whereas, WV02 2m satellite imagery costs $\$126.50/25km^2$. This imagery would need to be purchased annually to map MPB and other beetle-caused infestations. The LTBMU covers nearly 832 $km^2$ (not including the area of Lake Tahoe itself). Therefore, the cost of WV02 2m spatial resolution satellite imagery would amount to just over $4,200. Compared to ADS at $100,000/yr., it is evident that WV02 2m-satellite imagery serves a purpose for the price. Throughout this thesis project, WV02 has assisted in locating endemic population clusters of MPB that were not recorded in ADS of 2015. The ground truthed validation points collected, that did not exist in the ADS database, may easily be added to the 2015 ADS database for future research and records.

WV02 accuracy assessment results using MLSC, although inferior to Landsat 8 OLI imagery, has its benefits. Sketch maps defining the areas of tree mortality, whether endemic or epidemic, can be drawn from using a combination of vegetation classification maps and WV02 imagery rather than having to gather this information from a plane. It would be beneficial to forest management to purchase WV02 imagery, covering their intended study region, to be referenced with ADS data collected per year.

## 5.3 Limitations of Thesis Project

Problems occur with accuracy assessment when trying to classify a $30m^2$ pixel when only a few objects (red attack stage lodgepole pine tree) existed within a single pixel, especially if the infested trees were amongst healthy lodgepole pine trees in that pixel. The DN was calculated as an average of all objects within that $30m^2$. Object Based Image Analysis (OBIA) is another method used to detect single objects and segment these objects into relatively homogenous groups of pixels (Blaschke 2009). This method allows the analyst to segment WV02 (or imagery with a similar spatial resolution) imagery into "like" pixels that have relatively similar DN's. While most clusters of red attack stage MPB infested lodgepole pine trees were found in clusters of 2-20 trees and were scattered amongst a primarily healthy lodgepole pine tree stand, this method would improve the classification of MPB infestation stages (red, yellow or grey). The LTBMU is well managed so the population of the MPB population is kept at an endemic level. MLSC techniques have proven to be more useful in detecting epidemic MPB populations that cover large areas (1 acre or more), using 30m spatial resolution imagery. MLSC can be used with both 30m and 2m spatial resolution imagery depending on the MPB population (endemic, incipient-epidemic, or epidemic), while OBIA is reserved more for 2m or less (high) spatial resolution imagery.

## 5.4 Recommendations for Future Work

A few recommendation for completing a project similar to this include: (1) Using WV02 2m spatial resolution imagery rather than ADS to locate tree mortality, (2) Using a GPS data collection device with the highest positional accuracy, (3) Exploring the newest RS software programs to process and analyze the imagery, (4) Defining more classes would increase the spectral variability and therefore segment the image into more pixels that represent other phenomena amongst MPB infested Lodgepole pine trees, and (5) Considering the forest management objectives to decide which population stage of MPB infestations need to be studied.

As mentioned earlier in the results chapter, a lot of time was spent assessing the reliability of ADS sketch maps. WV02 2m spatial resolution and vegetation classification maps proved to be reliable sources to locate tree mortality in lodgepole pine tree stands. Errors occur while collecting data, and are more likely to happen in an airplane. This study was not intended to discount ADS sketch surveys, rather to find a more efficient and reliable way to survey tree mortality (specifically MPB caused tree mortality).

A GPS device that has sub-meter accuracy, rather than a recreational GPS device (roughly 3m positional accuracy at best), would improve the accuracy of this thesis project. I found that using a Garmin GPSMap 62sc created issues with positional accuracy when creating training sites for the WV02 high-resolution imagery classification. A 3m buffer applied to ground truth points included 1.5 pixels, 360 degrees around the center of the waypoint. With this, a healthy lodgepole pine tree adjacent to a red attack stage lodgepole pine tree was included in the 3m buffers, which was applied for positional accuracy and slightly degraded the accuracy assessment process.

ArcGIS 10.3 has been commonly used to perform MLSC, however, there are other programs that are easier to use and more efficient. A few known RS software programs such as ERDAS (Earth Resources Data Analysis System) Imagine, eCognition, ENVI (Environment for Visualizing Images), and TerrSet (formally IDRISI), can be used for projects similar to this thesis. As of August 3, 2015, the Office of Surface Mining Reclamation and Enforcement mentioned on its website (http://www.tips.osmre.gov), ERDAS Imagine is used for classification, modeling, image analysis, multispectral classification and map production. Software features and benefits of Trimble's ECognition 2016 show the possibilities of OBIA and extracting groups of pixels for classification, commonly used for change detection and tree classification in forestry (http://www.ecognition.com). ENVI is also used for classification of images and compatible with ArcGIS (used for map production). Finally, according to Clark Labs in 2015, TerrSet is commonly used for surface analysis, change detection in vegetation and time series analysis (https://clarklabs.org/terrset/). These aforementioned software programs can be used for the detection and monitoring of MPB infestations, some more applicable than others depending on the population stage of the MPB infestation.

This work defined five classes that represented the five most prevalent types of soil and vegetation in the generalized study area sections A, B, and C. Gathering ground truthed validation points of different types of vegetation and soil types would allow the an increasingly amount of classes, creating a more segmented image (similar to OBIA mentioned earlier) so the red attack stage MPB infestations may be more visible.

Forest management objectives can be located through the USDA website and should be thoroughly read prior to study design. In forests experiencing epidemic MPB infestations, management objectives are likely focused on slowing the progression of MPB infestations by locating incipient-epidemic populations surrounding the infested areas and applying mitigation efforts. Locating smaller endemic and incipient epidemic MPB infestations requires the use of high-resolution imagery (2m or less) to detect smaller patches of trees that are newly infested. On the other hand, forest management mitigation efforts to control an epidemic MPB population can use Landsat 30m spatial resolution imagery to detect larger MPB infestations spanning more than $30m^2$.

Above are the main recommendations that I would suggest when approaching a project similar to this. Forest management objectives and mitigation efforts are dependent upon the population stage of the MPB infestation (endemic, incipient-epidemic, or epidemic), which determines the spatial resolution of the RS imagery needed for detection and monitoring of MPB infestations.

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