Detecting Mountain Pine Beetle Attack and Assessing Overall Forest Stand Health in Uinta-Cache-Wasatch National Forest

By Alex McComb

University of Utah Geography Department

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Introduction

Tree stands in the Uinta-Wasatch-Cache National Forest have been devastated by multiple bark beetle species, covering 407,300 acres of the 2.1 million acres, and is beginning to proceed to surrounding stands (U.S. Forest Service). The infestation is concentrated mostly on the Northern slope of the Uinta Mountains, where activity has reached epidemic levels. This surge of infestation coincides with increasing average temperatures, lower than normal precipitation, and fire suppression management (U.S. Forest Service; Breshears et al. 2005). Changes in the climatological cycle has shortened winters which controls beetle population, as beetle eggs and larvae are killed by the cold temperatures. Moreover, prolonged drought in the area has weakened trees, making them more susceptible to infestation. Mountain pine beetle (*Dendroctonus ponderosae*), douglas-fir beetle (*Dendroctonus pseudotsugae*), spruce beetle (*Dendroctonus* rufipennis) and fir engraver beetle (*Scolytus ventralis)*, are the four main types of beetle infesting this area, with the majority of the infestation by the mountain pine beetle.

Attack from this species, predominately infesting lodgepole pine (*Pinus contorta),* has been ongoing since 2003 in the Uinta-Wasatch-Cache National Forest, with total loss up to 90 percent for infected stands. In 2012, tree mortality dropped 60 percent, encompassing 26,000 acres (U.S. Forest Service; Munson et al. 2013). In 2013, mountain pine beetle induced tree mortality in lodgepole pine stands increased to around 29,000 acres, up nearly 40 percent. In 2014, this total decreased by over 79 percent, likely due to the majority of tress susceptible to mountain pine beetle being killed off

(Keyes 2016). Overall, in Summit County where the study area is located, mortality dropped to about 80 percent in 2012, and even though this represents a significant percentage decrease, more than 74,00 trees spanning 12,653 acres were lost (Munson et al. 2013). In 2013, this number increased to 14,053 acres and 111,994 trees, then in 2014 decreased to 539 acres and 1,168 trees (Keyes 2016), also likely due to susceptible trees being killed off, leaving more healthy and less vulnerable trees to live. On the east side of the National Park, in Daggett County, lodgepole pine mortality is also expansive, ranging from 1-tree/acre to 440-trees/acre. Infestation has been observed spreading to surrounding lodgepole pine stands on the far east sides of Ogden, Logan, and Heber Ranger Districts, and increasingly in the Salt Lake Ranger District (U.S. Forest Service). Mortality has decreased overall in the recent years, especially in certain areas near the study site, such as along Mirror Lake Highway running through Uinta-Cache-Wasatch National Forest (Keyes 2016).

Because of their small size, bark beetles work in concert to thin tree stands, sending out members to search for weakened and less vigorous trees, generally greater than 4” in diameter. When susceptible trees are found, the wood is converted into a chemical that attracts other members to the suitable tree. This has to be done quickly as resin from pine trees can deflect beetle attacks. Once inside the tree, mating, or nuptial chambers are created and the tree is then further hollowed to allow for eggs to be laid. Once hatched, the larvae begin to work their way out by means of a feeding path. As the phloem layer degrades within the tree, nutrient transport halts and the tree eventually dies. Moreover, mountain pine beetle carry a fungus that stains the inner wood a bluish color which plugs water vessels, impeding water transport, also contributing to its death (Davis 2012). Epidemic level die-off events convert forested landcover to grass and shrub ecosystems for a period of ten to twelve years, which has a large impact on other wildlife species, water yield and fuel capacity (Merzlyak 1999; Keyes).

Infestation is initially spotted by fading tree crowns, where needles turn yellow or orange, and finally red just before they drop to the ground. This discoloration usually occurs within one year of infestation. Moreover, sawdust like material, or frass, is usually found in the cracks of the bark at the trunk along with pitch tubes or resin deposits that are released from the tree in an attempt to defend itself. Other signs such as exit holes and galleries are commonly used to identify infestation (Merzlyak 1999; Keyes).

Fading of foliage after an initial attack follows three stages. The first is the green stage, where the host is under attack, but foliage remains green and signs of attack are not visible. Next comes the red stage, which occurs about twelve months after the initial attack, where over 90 percent of the trees killed will have red needles. Finally the gray attack stage, where around the three year mark, a majority of the trees will loose all needles (B.C. Ministry of Forests 1995). Wulder 2004 found that during the first year of mountain pine beetle attack the trees remained in the green attack stage (Wulder et al. 2004). Following the attack after the first year, some remained in the green attack stage while others had moved onto the red attack stage. A similar trend took place during the red and gray attack stage, where they co-occurred upon reviewing their status during the second and third summers after the initial attack. This change has also been supported by other studies (Wulder et al. 2004).

Remote sensing is used by the United States Forest Service for Aerial Detection Surveys to give an estimate on damage location, damage amount and relative size of insect population. This is done on a broad-scale, where the minimum mapping unit is 5 ha of selected National Forest land. However, the limitations of these surveys include fairly high cost for data collection and low agreement on aerial survey data and in-situ data, where there is only 68 percent agreement with a 50 m spatial tolerance (Johnson & Ross 2008). However, this does not hold true for all studies done using remote sensing methods to detect pine beetle outbreak, as there is not a widely used detection method which yields varying results. This, coupled with the increasing threat of sprawling pine beetle infestation, comes a higher demand for remote sensing methods that allow for a higher volume of studies and more accurate assessments of pine beetle outbreak.

Multispectral, as well as hyper spectral, imagery have been used to find the differences in the near-infrared (NIR) and shortwave infrared (SWIR) spectral regions to detect pine beetle induced tree mortality (Skakun et al. 2003; Pontilus et al. 2005; White et al. 2007). Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) multispectral imagery is commonly used in pine beetle remote sensing studies, as it has shown to be particularly useful when it comes to multi-date studies. This is because of its ability to determine disturbance to a forest at regular intervals as a result of a sun-synchronous orbit that covers the earth every sixteen days (for the two newer Landsat missions, 7 and 8). This is beneficial in the case of remote sensing of pine beetle infestation, which allows us to know when the initial infestation occurs, the extent and rate, and how the forest recovers after these events. Moreover, the global scale of Landsat missions allows infestation of a forest in any area to be mapped.

Multiple studies have shown that hyper spectral instruments are pertinent to successfully observe detailed changes to vegetation conditions before they are noticeable visibly. Moreover, narrow spectral bands are required for many vegetation health assessment applications (Treitz & Howarth 1999). Bands responsive to certain reflectance values are used to create ratios of wavelengths, also known as indices, that are able to pull out features while correcting geometrical inaccuracies and background effects (Bartet & Guyot 1991). These indices are the main means of determining conditions of vegetation. Observing vegetation stress by means of remote sensing methods is based on the presumption that photosynthesis is hindered by stress factors, altering the absorption of light and ultimately the spectral signature of the vegetation (Riley 1989)(Pinter et al. 2003). The narrow bands of hyper spectral imagery allow for a more detailed inspection of the Red and NIR spectrum that mark the total photosynthetic qualification and quality, as well as the overall moisture content of the vegetation (Bartet & Guyot 1991).

The purpose of the study was to use hyper spectral imagery to assess mountain pine beetle attack in a commonly infested area for a recent date, and to determine the efficacy of using this type of imagery for detecting pine beetle outbreak. This will help determine if infestation is prevalent in this area, and if it is, at what stage this attack is at (green, red or gray). Furthermore, this will determine if outbreak has spread from the northern part of the Uinta-Cache-Wasatch National Forest, where epidemic outbreak levels have recently occurred and the general health of trees in the study area.

Study Area

The study site is located on the mountain side east of Oakley, Utah in Summit County, centered at 40.68 N and -111.23 W (Figure 1A). The primary land cover in this area is lodgepole pine, the main tree infested by mountain pine beetle. This area was chosen as it is near an area of epidemic level mountain pine beetle attack (north side of Uinta-Cache-Wasatch National Forest) and was the only area available that was covered by the EO-1 Hyperion Sensor.

Data

EO-1 Hyperion Data was acquired from the USGS Center for Earth Resources Observation and Science (EROS) website on 23 March 2017, for the single date of 16 August 2016. The EO-1 is a NASA New Millennium Program sensor, created to sub-stantiate creation of future technologies for remote sensing (Ungar et al. 2003). The hyper spectral sensor is comprised of two push-broom imaging spectrometers, capable of detecting areas of the visible near-infrared (VNIR) and short wave infrared (SWIR) regions of the electromagnetic spectrum (Pearlman et al. 2003). Hyperion collects data at a 30 meter spatial resolution and a 10 nanometer spectral resolution, with a range from 0.43 to 2.4 μm. A Level 1R (radiometrically corrected) image was chosen, which is

Study Area

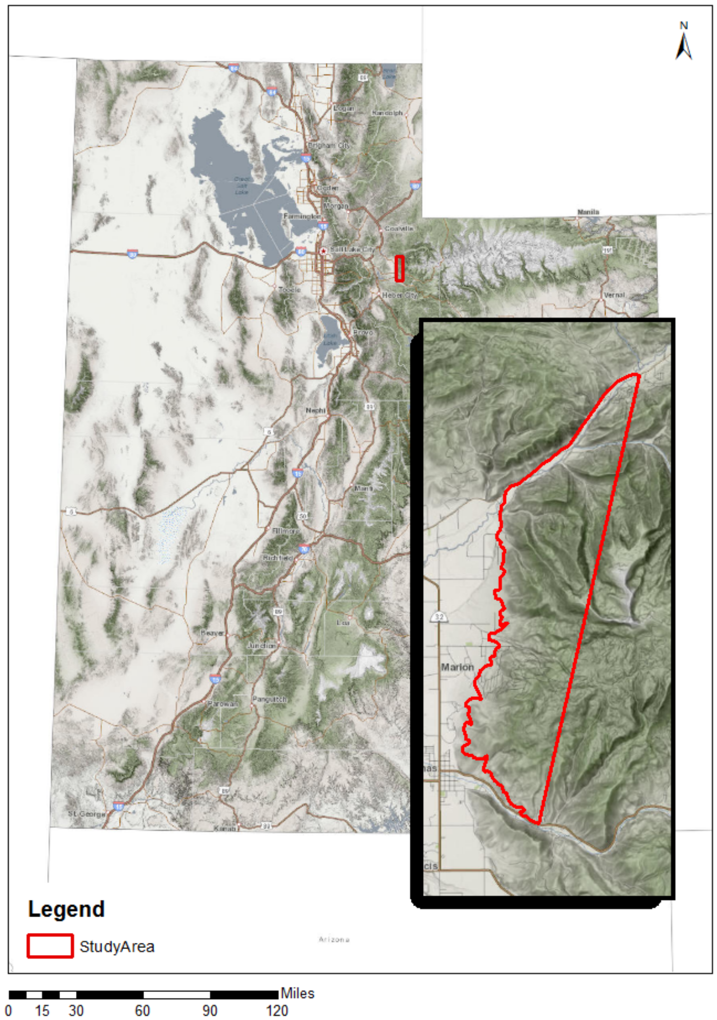


Figure 1

the lowest level of processing where the user can make their own corrections to the image such as atmospheric and geometric. This level was chosen to better understand image processing and observe how it affects the image and how to preform corrections.

Methods

The data was processed using ENvironment for Visualizing Images (ENVI) version 5.3, and a large part of the methods process was based on a tutorial provided by Exelis Visual Information Solutions, Inc. (Harris). A spatial subset was made of the study area, and was then geometrically corrected using seven ground control points based on a projected image of the area. Bands that are generally removed due to having values set to zero or because of acute noise related to water vapor absorption were also removed for this study, being bands: 121-126, 167-180, and 222-224. The data was then atmospherically corrected using the Fair Line-of-sight Atmospheric Analysis of Spectral Hypercubes FLAASH(R). This calibrates the image to surface reflectance, removes disturbances to the atmosphere from water vapor, carbon dioxide and other factors that can influence the reflectance of the image, as well as it being suitable for hyper spectral imagery (Harris). The value set for the Aerosol Model within the FLAASH tool was Rural, since this location is not largely affected by urban or industrial aerosols. Processing the data involved using multiple different indices and the ENVI Forest Health Tool to asses accuracy of these indices and to give a better overall picture for the study.

Indices Overview

Enhanced Wetness Difference Index (EWDI) has been successful in setting apart red attack stage trees from unaffected ones (Skakun et al. 2003; White et al. 2007). EWDI uses a Tasseled Cap Transformation (TCT), which has shown to aid in picking out damaged trees where brightness, greenness and wetness are easily discernible, which are also key features of infested trees (Sharma & Murtha 2001). This has been done often with high precision as Skakun et al. 2003 reached 81% accuracy in large patches where there where thirty to fifty trees at the red attack stage in a 900 square meter study area (Skakun et al. 2003). The high accuracy using EWDI is a result of its ability to discern changes in the SWIR portion of the spectrum, where an increase in reflectance in this region is an outcome of a decrease in water absorption.

Another study using EO-1 Hyperion data showed that moisture indices, such as the Moisture Stress Index (MSI), were significantly correlated to amount of damage ($r2$=0.51; p=0.0001), where both the shortwave infrared and near infrared were used together to determine levels of attack (White et al. 2007). The MSI relies on the hypothesis of the EDWI, where a decrease in foliage water content is correlated to pine beetle attack. A reflectance measurement is garnered to determine the overall leaf water content, where the amount of absorption increases around 1599 nanometers coinciding with increased foliage moisture. At 819 nm, absorption is wholly unchanged by varying water content, so it is used as the reference wavelength where $MSI = \rho 1599 / \rho 819$. The range of this index is from 0 to greater than 3, where the usual range for vegetation is between 0.4 and 2, and where higher values indicate higher moisture stress (Hunt and Rock 1989). Furthermore, White et al. 2007 found the sensitivity of the high spectral resolution to be able to pick out about fifteen or fewer infested trees at red attack stage in a study area of 900 square meters, suggesting that hyper spectral imagery has the ability to discern damaged trees in low densities compared to the overall study area, which can also lend support to earlier detection of outbreaks (White et al. 2007). Because of its success in previous use, the MSI was chosen as one of the indices for this study.

To further highlight the affect of pine beetle infestation the Plant Senescence Reflectance Index (PSRI) was used to determine increased canopy stress. This relies on the expectation that as plants senescence or die-off, chlorophyll degrades and pigment is brightened (in this case reddened). A ratio can be made to determine canopy senescence using reflectance values near 680 and 500 nm, as they have shown to be sensitive to changes in carotenoids pigment and chlorophyll, where $PSRI = \rho 680 - \rho 500 / \rho 750$ (Merzlyak 1999). The normal range of this index is from -1 to 1, with the general range for green vegetation ranging between -0.1 and 0.2, where a higher value indicates increased canopy stress. Although this has not been used in prior studies observing the effects of mountain pine beetle infestation, it likely can be applied as a change in pigmentation is highly related to mountain pine beetle induced tree mortality and give us an understanding as to the health of the area.

The Forest Health Vegetation Analysis Tool (FHVAT) in ENVI was also implemented to show general health of the study area. It is able to observe pest and blight conditions, where distribution of green vegetation is pulled out of the image using broadband and narrowband greens. It determines stress using leaf pigments, or the concentration of carotenoids and anthocyanin, and also light use efficiency, where tree stand growth rate can be detected. For the index, lower values indicate poor overall health, and higher values indicate better health (Harris).

The Modified Red Edge Normalized Difference Vegetation Index (MRENDVI) was selected for the FHVAT tool, as well as a standalone index to determine its influence on the FHVAT assessment. MRENDVI is used to highlight plant senescence, foliage content and gap fraction, or canopy structure, based on small changes of the red edge. The red edge is the area of spectral signatures (690 nm to 740 nm) that is a result of the change from chlorophyll absorption to NIR leaf scattering, and is defined by a steep line separating between these two wavelengths where *MRENDVI =* $\rho 750 - \rho 705 / \rho 750 + \rho 705 - 2 * \rho 445$ (Sims & Gamon 2002). The index ranges from -1 to 1, where the common range is between 0.2 and 0.7, with lower values indicating stressed vegetation. Minute changes in this region are easily detected by hyper spectral imagery which distinguishes it from other indices. Smaller Carotenoid Reflectance Index 2 (CRI2) was selected for the Leaf Pigment Index of the FHVAT, as it is useful for areas of high carotenoid concentration, where a higher value indicates high carotenoid concentration in compassion to chlorophyll and *CRI2 = 1 /* $\rho 510 - 1 / \rho 700$. The ratio uses wavelengths in the visible spectrum that allow for detecting spectral signatures which indicate stress-related pigments (Gitelson et al. 2002). For the Light Use Efficiency Index, Structure Insensitive Pigment Index (SIPI) was selected and is used to emphasize the correlation of carotenoid and chlorophyll, while decreasing the effect from canopy structure, such as leaf area index and mesophyll structure, where a higher value indicates stressed vegetation and *SIPI =* $\rho 800 - \rho 445 / \rho 800 - \rho 680$ (Penuelas et al. 1995). It should be noted that these indices are not useful for gray attack stage, as there are no leaves to determine reflectance values which these indices rely upon.

Results

Overall, the indices indicated that the area is in fairly good health, with a few minor areas that may be experiencing stress (Figure 2). The moisture stress index indicated that there were not areas experiencing high moisture stress, as none of the values were above 1. The average for the study area was 0.47, with a *sd* = .38, which is at the lower end of the spectrum indicating very low moisture stress (FIG1) as the average for green vegetation is between 0.4 and 2. This also tells us that it is unlikely the area is experiencing red attack stage. Next, the Plant Senescence Reflectance Index also indicated low plant senescence, as the average for the area was 0.36 which is only slightly out of the normal range of -0.1 to 0.2, and with a higher with a *sd* = 3.8, these results are less reliable. Average for the Modified Red Edge Normalized Difference Vegetation Index was 0.33, with a *sd* = 0.09, which indicates reliable results, and as it is on the lower end of the spectrum, but is still within the normal range of 0.2 to 0.7. The forest health tool average was 5.5, with a *sd* = 2.72, which indicates a medium level health, although the higher standard deviation also implies less accurate results.

For all of the indices combined, some areas had values that indicated stress, most notably from the forest health tool, although upon further inspection, these areas showed to be soil patches, especially along the tree line along the west side of the mountain. The forest health tool seemed to produce less reliable results compared to the other vegetation indices, as it had low health ratings in areas where the other indices showed normal ranges. The largest area displayed as stressed for forest health vegetation analysis tool, totaled ~180 acres which appeared to be mixed vegetation of

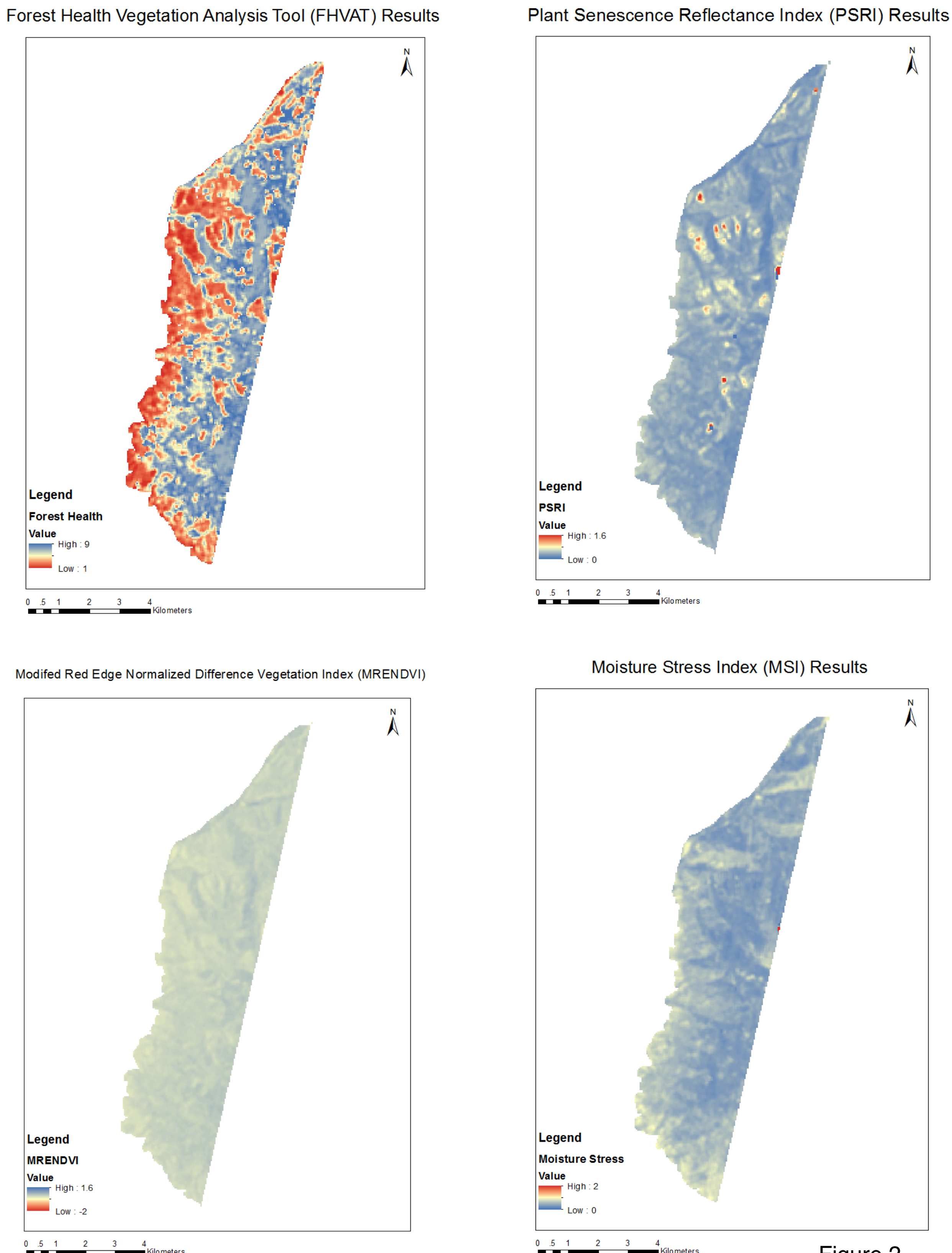

Forest Health Vegetation Analysis Tool (FHVAT) Results
N
Legend
Forest Health
Value
High : 9
Low : 1
0 .5 1 2 3 4
Kilometers
Plant Senescence Reflectance Index (PSRI) Results
N
Legend
PSRI
Value
High : 1.6
Low : 0
0 .5 1 2 3 4
Kilometers
Modifed Red Edge Normalized Difference Vegetation Index (MRENDVI)
N
Legend
MRENDVI
Value
High : 1.6
Low : -2
0 .5 1 2 3 4
Kilometers
Moisture Stress Index (MSI) Results
N
Legend
Moisture Stress
Value
High : 2
Low : 0
0 .5 1 2 3 4
Kilometers

Figure 2

lodgepole pine and mostly shrub along with some areas of soil. Although, this cannot be used as a key representation of vegetation stress in the area, as this is a study focused more on health of lodgepole pine, as well as the soil influencing the results as it did in other areas.

A few areas largely covered by lodgepole pine appeared to be in agreement between the forests health tool and plant senescence index, for instance an area indicated as stressed by the forest health tool with values ranging from ~1.5 to ~4, and plant senescence index values ranging from ~0.6 to ~1.6, however the two other indices did not indicate stress in this area. The majority of areas where the forest health tool showed low values, the plant senescence index showed normal ranges, and for the most part, the plant senescence index was in agreement with the modified red edge index and the moisture stress index. This indicates that the forest health tool results are less reliable, and was likely influenced largely by the Smaller Carotenoid Reflectance Index 2 and the Structure Insensitive Pigment Index, as we can see the modified red edge index that was used outside of the forest health tool to determine the influence on this tool is largely in disagreement with the forest health tool. Carotenoid Reflectance Index 2 was likely the main reason this tool results were poor, as it preforms better in areas of high canopy cover with areas of high carotenoid concentration, whereas the Structure Insensitive Pigment Index is meant to be calibrated for influences of canopy structure.

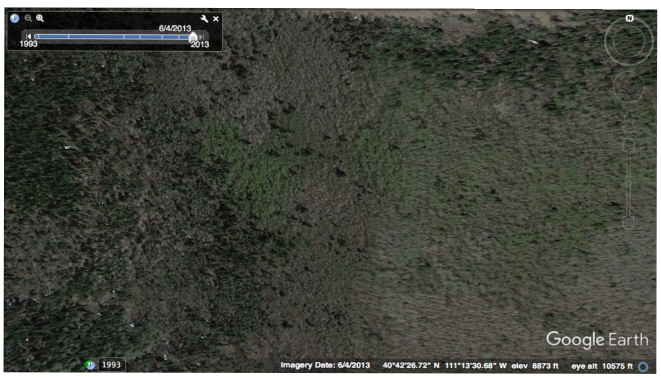
Conclusion

The results show the area is in generally good health, and unlikely experiencing red or green attack stages, likely due to the fact that the area has already experienced the apex of mountain pine beetle infestation, where the healthy and less susceptible trees remain in good health. This is further corroborated when multiple time lapse true color aerial photos are looked at for the area to assess the accuracy of the indices, where we can see normal tree stands followed by the indicative red attack stage where a large numbers of trees can be seen with a red crown in 2009, followed by the gray stage in 2013 (Figure 3). It is also clear from the true color images that the infestation has spread from the epidemic level area on the north slope of the Uinta-Cache-Wasatch National Forest. This stage was undetected by the indices as they rely on reflectance values from leaves, and other methods to detect gray attack stage would be needed to fully understand the extent and areas in this stage. This study further indicates that the remaining trees have not responded negatively to the mortality, possibly because of less competition for resources, although further studies would be needed regular intervals to determine if this holds true. To give a more robust explanation of the results of this paper, a field study to collect samples and preform other tests would be needed to better determine the accuracy of the indices and to assess how spatially accurate they are. Also, to better determine the health of the area before and during the pine beetle attack, Landsat imagery can be used to give a better overall picture of attack in this area.

Example of Mountain Pine Beetle Induced Mortality Near the Central Region of the Study Area, 2009-2013

2009

2011



2013

2013

Figure 3. Source: Google Earth

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