Monitoring Sudden Oak Death in California Using High-resolution Imagery[1]

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Abstract

The Sudden Oak Death (SOD) epidemic in California is alarming for those living with, and adjacent to, the complex of oak and tanoak woodland that exist in patches along the coast. Monitoring SOD occurrence and spread is an on-going necessity. Remote sensing methods have proved to be successful in mapping and monitoring forest health and distribution when a sufficiently small ground resolution is used. In this project, digital high-resolution (1-m) ADAR imagery was analyzed for an area including and surrounding China Camp State Park in Marin County, California in the spring of 2000 and 2001. This paper reports on two analyses: First, the individual frame data from 2000 was mosaiced and classified to reveal 5,340 dead and dying trees in the area including and surrounding China Camp State Park. Second, a smaller subset of the study area was used to perform a Normalized Difference Vegetation Index (NDVI) image differencing and thresholding routine between 2001 and 2000. This change detection showed trees that were misclassified in the 2000 image, as well as newly dead trees. For the smaller study area (303 ha) there were 1,091 dead or dying trees in March 2000, and 317 trees that died in the 13 months that followed. Trees that died between March 2000 and May 2001 were located between 5 and 52 m away from existing dead trees.

Introduction

The newly discovered pathogen *P. ramorum* has been killing hundreds of thousands of trees in California since it was first reported in 1995 (Svihra 1999). Tree species hosts of this new disease include but are not limited to two valuable oak species: coast live oak (*Quercus agrifolia*) and black oak (*Q. kelloggii*). The seemingly rapid decline of the symptomatic trees has led to the disease complex name Sudden Oak Death (SOD) (McPherson and others 2000). As of October 2001, the disease has been officially confirmed in 10 coastal counties of California *(fig. 1),* and hosts for the disease exist in several more counties. (It was also detected on 40 acres in southern Oregon and is known to cause leafspots and twig dieback on rhododendron in Germany and the Netherlands.) Marin County is one of the "hot-spots" for SOD with areas displaying dramatic dieback of tanoaks, coast live oaks and black oaks. Establishing the baseline conditions of Sudden Oak Death in California in 2000, and monitoring its spread through 2-5 years is a critical need for management of this new disease (more detailed information about the pathogen will

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be provided in the accompanying papers in this volume and elsewhere (i.e., Garbelotto and others 2001, McPherson and others 2000, Svihra 1999).

According to best knowledge, the pathogen appears to enter through the bark of susceptible oak trees, and cause rapid canker development that leads to girdling and dramatic and often rapid death of the tree (Garbelotto and others 2001). This pattern of disease progression facilitates the use of remote sensing methods for disease analysis. Remote sensing has been used to map and monitor the location and effects of forest disease (Macomber and Woodcock 1994), and in disease studies to map habitat of invertebrate disease vectors (Hay and others 1997) using imagery of multiple spatial resolutions. This paper describes the analysis of high-resolution imagery (1-m) to map and monitor SOD in an especially hard-hit area in Marin County, California. Results from an earlier classification of high-resolution imagery were combined with a change detection routine to refine the earlier classification in order to discern both trees that were mis-classified in the earlier analysis, as well as trees that have died in the period between March 2000 and May 2001. The study area includes area surrounding China Camp State Park in Marin County. An analysis of the distance between recently dead trees and the closest dead tree was also calculated to determine if there was an indication of tree-to-tree infection.

Background

Study Area

The study area for this project is a forested peninsula on the east side of Marin County (see *fig. 1* for general location and *fig. 2* for specific map of the study area).

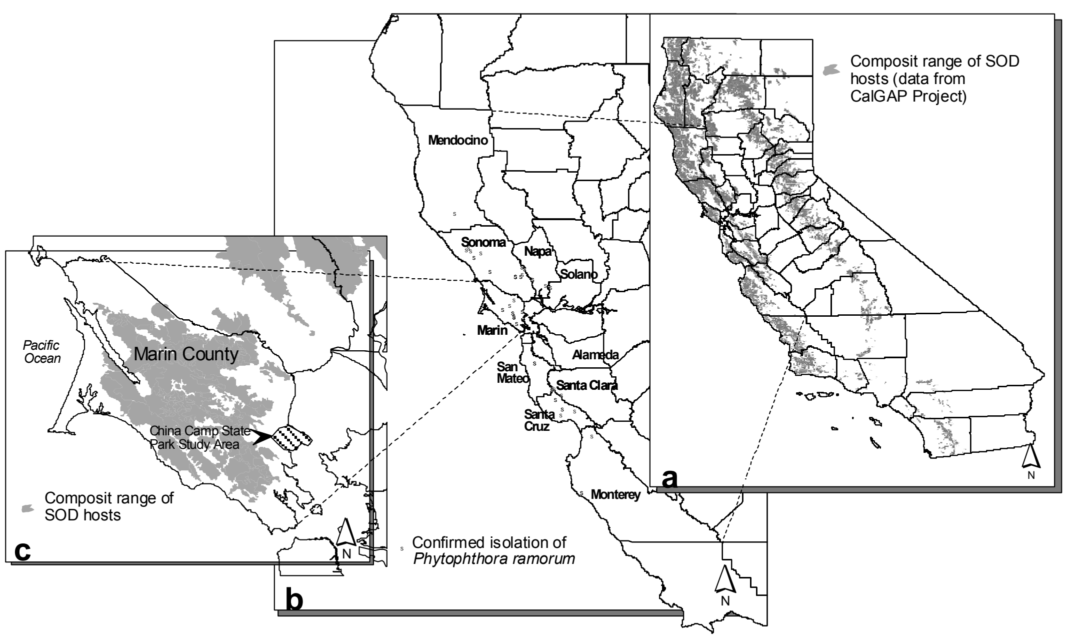

Figure 1—Sudden Oak Death in California: a) California with the distribution of susceptible host species; b) the counties with confirmed SOD, and locations of positive samples; and c) Marin County, showing the study area and the possible range of host species within the County.

The area has moderate to steep topography, with elevations ranging from sea level at San Francisco Bay to over 300 m. Open space here is managed in the northwest by Marin County Open Space, and in the west and south by California State Parks. The area currently managed as China Camp State Park has an interesting land use history, it has been in the recent past an off-road motorcycle range, the location for a renaissance faire, and since 1977 it has been a state park. The forest stands there are near even-age stands, these hillsides were cleared for lumber in the early to mid-1800s. Coast live, black and valley oaks are abundant, and occur in mixed stands with mature madrone and bay trees providing habitat to a variety of wildlife, including deer, squirrels and numerous birds. All of these trees with the exception of valley oak are hosts for *Phytophthora ramorum*.

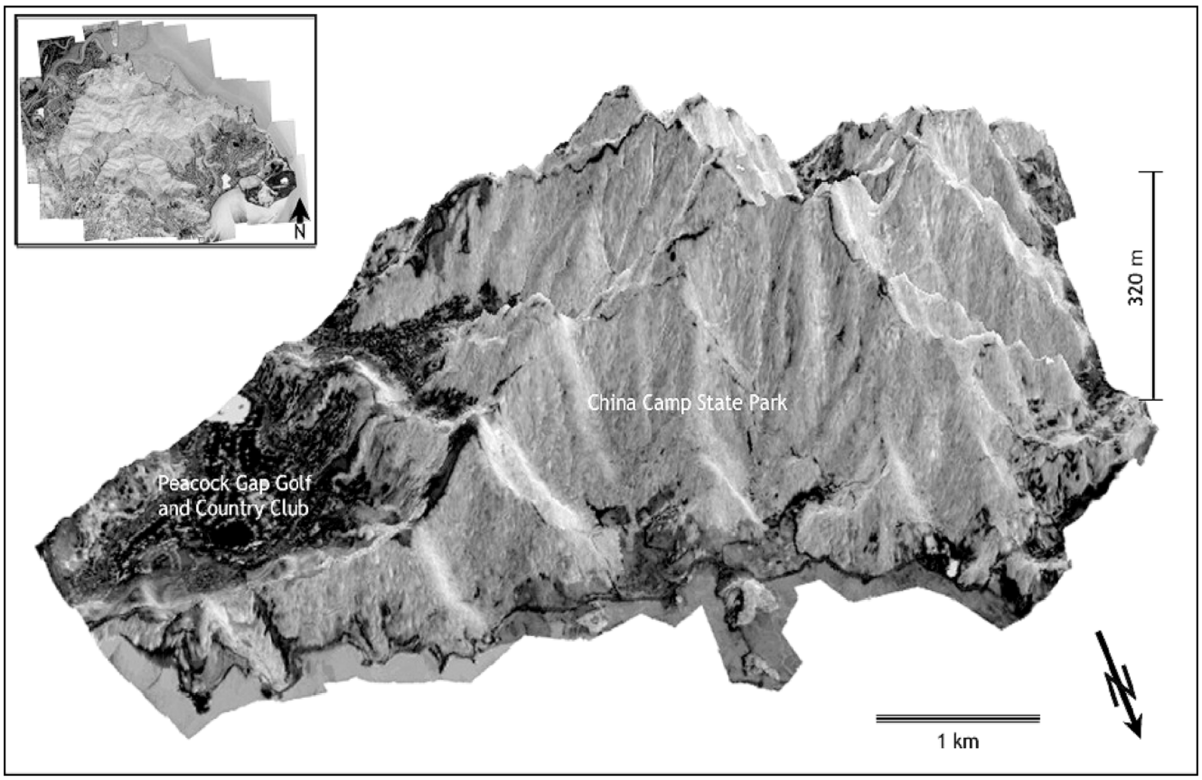

Figure 2—Mosaiced ADAR imagery of the area including and surrounding China Camp State Park in Marin County, California. The image is a false color composite draped over digital elevation model; healthy vegetation is shown in the lighter areas. The undraped mosaic appears in the upper left hand corner; north in this inset is towards the top.

Remote Sensing of Oak Death

The ability to locate and quantify change in an area can be a valuable asset to natural resource management. Change detection methods using digital remotely sensed data have utility in detecting specific disturbances (Kelly 2001a) and changes in landscape composition and structure (Green and others 1994, Lunetta and Elvidge 1998). The use of remote sensed data for monitoring forest health and forest inventories has a recent history (Franklin and others 2000, Macomber and Woodcock 1994, Pinder and McLeod 1999). With some notable exceptions (Boyer and others

1988, Everitt and others 1999, Gong and others 1999), much of this work has examined conifer stands. The pathology of this new disease affords an opportunity for continued development of techniques for remote sensing in hardwood forests. Specifically, the disease has three characteristics that make a monitoring approach that ties remote sensing with fieldwork ideal. First, as the trees with the disease die, in most cases the entire crown changes dramatically from healthy green to brown, and over a short time period. Second, after canopy change has occurred, the leaves can stay adhered to the branches for months giving trees a characteristic "freeze-dried" appearance. Third, in areas where SOD is advanced, the affected trees display spatial clumping, with diseased trees likely to be clustered together. This pattern can result in dramatic spectral reflectance changes across broad areas. In addition, the affected *Quercus* species make good targets for high-resolution imagery. For example, coast live oaks have a broad multi-stem canopy with leaves and a canopy structure that has evolved to maximize contact with sunlight (Pavlik and others 1991). In the study area most affected trees are over 100 years old, and form the dominant overstory canopy. High-resolution imagery can assist in several feature extraction problems. In the ADAR imagery used in this project it is possible to differentiate between some hardwood species (Bay trees and oaks are distinct in this figure), discern healthy appearing and dying oaks (the healthy oaks are dark red in this image, and the dying trees have a blueish grey tone), and clearly map man-made features such as roads and trails *(fig. 3)*.

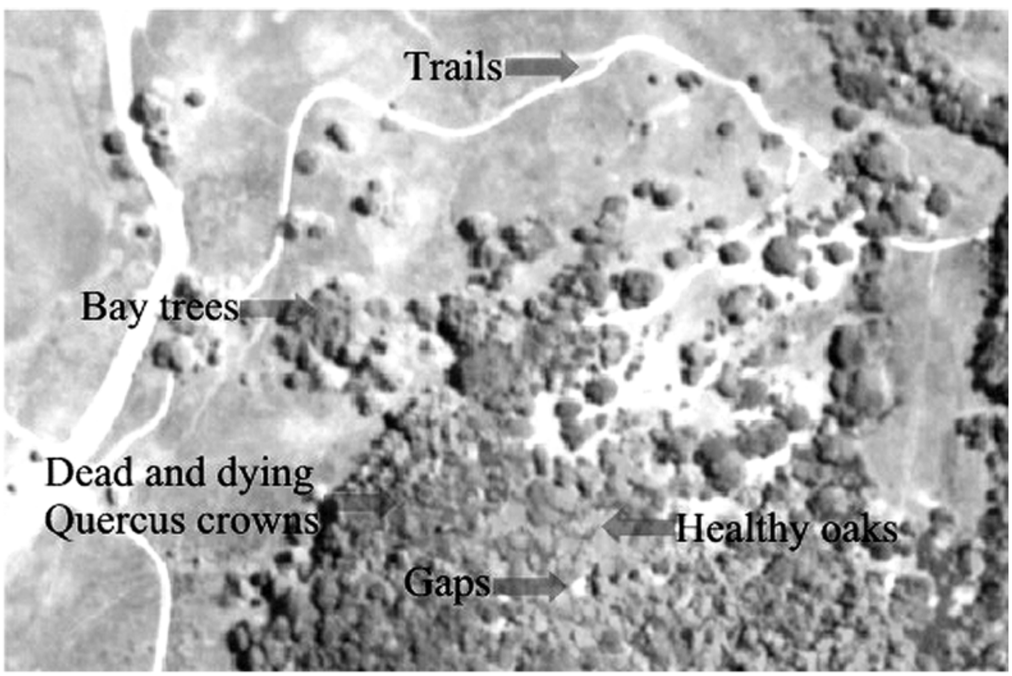

Figure 3—An area in China Camp State Park that has SOD as it was imaged using the ADAR system. The image shows spectral difference from targets. Healthy appearing oaks and California bay trees can be distinguished from dead and dying crowns of oaks.

Methods

Imagery Acquisition and Preprocessing

Digital imagery (ADAR 5500) was acquired for the China Camp study area in 2000 and 2001 with an ADAR 5500 imaging system that was comprised of a SN4, 20mm lens with four mounted cameras (Spectral Bands: Blue: 450-550 nm; Green: 520-610 nm; Red: 610-700 nm; Near Infrared (NIR): 780-920 nm), flown at an average aircraft altitude of 2,205 m. We contracted with a private company (Positive Systems Inc. from Montana) to perform the imagery acquisition and registration. The average ground spatial resolution of the images is 1-meter. Each 1,000 x 1,500 m frame was captured with standard 35 percent end and 35 percent side-lap. Imagery was acquired on March 30, 2000 and May 5, 2001. These near anniversary dates were chosen to maximize the springtime canopy cover changes associated with SOD, and to minimize misclassification caused by early color change of California buckeye, a summer drought deciduous tree that can, when seen from a distance can appear similar to SOD affected trees. Weather precluded image capture in 2000 in April.

The frames from 2000 were mosaiced and geo-referenced using a 6-inch resolution digital ortho-photograph of the entire county provided by Marin Municipal Water District. The contractor provided the image registration using in-house DIME software. Registration accuracy was 0.305 m throughout the scene. The 2000 mosaic was clipped to remove urban and non-wooded areas. *Figure 2* shows the clipped imagery draped over a digital elevation model.

Classification of 2000 Imagery

Once mosaiced, a standard set of topographic correction and spectral enhancements were performed using Erdas Imagine software (Erdas 1999). First, a Lambertian topographic correction was applied to the imagery (Jensen 2000). A variety of spectral (i.e., PCA, Kauth Thomas Tassled Cap, and Normalized Difference Vegetation Index (NDVI)) and spatial (texture) enhancements were evaluated to determine their utility in discerning dead and dying trees from healthy green foliage. These enhancements have been used to map vegetation using remotely sensed data. Many were developed for Thematic Mapper data (Crist 1985, Yuan and others 1998), but as the spectral resolution of ADAR is almost identical to TM in bands 1-4, these enhancements can be used here. NDVI has proven to be a useful in pre-classification enhancement because it is least affected by topographic changes (Lyon and others 1998). Both visual inspections of the study area and field data acquired from a series of plots designed to measure symptom progression provided ground truth to validate the results of the enhancements. The NDVI provided a very useful transformation, with dead and dying crowns visible, as did the 3rd Principal Component (from a standard PCA analysis), and all three indices from a Tassled Cap analysis (greenness, wetness, brightness). A new layer stack that combined the five enhancements mentioned above was created for subsequent unsupervised classification. A simple visible to NIR ratio ((band1 + band2 + band3) / band4) was successful in pulling out trails from background forest, but was too highly correlated with the NDVI to include in the stack.

The 5 enhancements bands were classified using the Erdas Imagine default isodata unsupervised classification cluster algorithm. The isodata clustering routine uses minimum distance formula to form clusters (Erdas 1999). The process yielded 25 classes, 5 of which were clearly dead and dying crowns or bare ground. Confusion between dead and dying crowns and bare areas was eliminated by disregarding patches that were too large or that had shapes uncharacteristic of a tree crown. Field visits were also made to explain the resulting confusion between bare ground and dead and dying trees. Finally, each patch of dead or dying tree was visually inspected in the imagery to determine the likelihood that it was a tree, and not a bare area. A centroid routine was run to determine the centers of all dead and dying crowns, and the number and location of all dead and dying trees.

Accuracy assessment was performed by selecting from the classified imagery 100 randomly located dead and dying trees in the area of China Camp State Park and verifying their status in the field. The fact that the accuracy assessment was performed almost a year after the imagery was flown did not create a problem. Trees that were dead and dying in spring 2000 remained dead in spring 2001 (or showed signs of having been recently removed). Trees that were healthy in spring 2000 and dying in spring 2001 could be assumed to be green in 2000, as the canopy transformation associated with SOD usually takes weeks, not months. This accuracy assessment was not designed to determine spectral class accuracy, but accuracy of a binary image (dead and dying/healthy), so no error matrix was generated.

Image-to-Image Registration and Radiometric Normalization

Initially, the 2001 frames were registered to the 2000 mosaic with a substantially larger root mean squared error (RMSE) (4.5 m), which was unacceptable for a change detection routine. This larger error was due to the extreme terrain in the area. To correct for the problem, the 2000 and 2001 images were clipped to create a smaller study area that had sufficient visible ground control, and less overall terrain, to perform a more accurate image-to-image rectification process for the purposes of this paper. Image to image registration was performed on the clipped portion of the 2001 mosaic, using the clipped portion of the 2000 image as the control. 65 control points were used with a second-order polynomial transformation yielding an overall RMSE of 1.587m.

Radiometric enhancement deals with the individual digital brightness values (BVs) of the pixels in the image. The ranges of BV in both time periods should be similar before change detection routines are used. Radiometric normalization was performed by use of normalization targets. According to this normalization method, a simple linear regression can be performed using the BVs of targets in the base image against the BVs of the targets in the other images to determine radiometric correction values. Appropriate target reflectors are discussed in several places including (Dobson and others 1995). Targets chosen for this project included two spectrally invariant ponds, a parking lot, and a road surface. A simple linear regression model was computed for the BVs of the target reflectors in 2000 and the BVs of the targets in 2001 for bands 3 and 4. The slope and y-intercept of the regression equations were the used to normalize the 2001 image to the 2000 base image: the y intercept provides an additive component that corrects for the difference in atmospheric radiance, and the slope provides a multiplicative term that corrects for the difference in detector calibration, sun angle, Earth-to-Sun distance, atmospheric attenuation and phase angle differences between dates (Kelly 1996).

Change Detection

In the case of SOD in Marin County, there are four states of change that are of interest:

- Case #1: Healthy to healthy: indicating that there is no change in tree condition;
- Case #2: Healthy to dead or dying: indicating trees that have died in the interim between spring 2000 and spring 2001;
- Case #3: Dead to healthy: indicating trees that were classified incorrectly in 2000 as dead or dying, but that are most likely deciduous oaks;
- Case #4: Dead to dead; those dead in 2000 that remain dead in 2001, or dead trees that have been removed in March 2000.

NDVI subtraction and thresholding facilitated quantification of the latter three of these cases. While several methods exist, NDVI subtraction and thresholding is one of the more useful yet least complicated of all change detection routines (Lunetta 1998, Lyon and others 1998, Yuan and others 1998). For this project, the NDVI from 2001 was subtracted from the NDVI from the 2000, yielding a pixel-by-pixel change in spectral reflectance associated with healthy vegetation. The resulting image was thresholded (thresholds were 10 percent at the extreme negative end and 15 percent extreme positive end of the NDVI difference) to show areas of greatest change by comparing the resultant change image with several trees whose change from 2000 to 2001 was known.

This method resulted in many spurious or incorrect areas of false change that had to be screened out. There were two kinds of change to examine here: first, those pixels that indicated NDVI had decreased significantly from 2000 to 2001 (Case #2: new death or tree removal), and second, those pixels that indicated NDVI had increased (Case #3: misclassification as dead of a deciduous, but healthy oak). To remove those pixels that indicated new death but that were obviously erroneous (too large to be a tree, obvious slivers caused by mis-registration, and change over bare areas), clumps of pixels were sorted by size and shape (using shape index “K”—a modified perimeter to area ratio described in Kelly [2001b] and Davis [1986]), and those too large, too small or too elongated to be a tree crown were removed. Following this, all remaining clumps were visually inspected to determine if they denoted newly dead trees. A centroid routine was performed on the remaining clumps to locate the tree center, and these points were added to the dead and dying tree layer. In addition, the distance from these newly dead trees to previously dead trees was calculated. To determine which of the third kind of change—NDVI increase—corresponded to a tree classified in 2000, the point location of all dead and dying trees from the 2000 classification routine were buffered to a distance of 2 m. This buffer coverage was overlaid on a vectorized coverage of NDVI change to determine intersection between the features. All clumps of pixels that showed an increase in NDVI that were within 2m of a dead and dying tree center were called Case #3 pixels. The corresponding point from the dead and dying tree layer was deleted.

Results

Imagery Classification

The classified imagery from 2000 yielded 5,340 dead and dying crowns in the area covered by the entire study area *(fig. 4)*. This clipped imagery covers an area of 917 forested ha. Dead and dying crowns occur throughout the forested area, but visually show definite clustering patterns. The accuracy of this map product was field verified to be 92 percent. However, there was some confusion (reported below) between the deciduous oaks (primarily valley oaks) and dying trees in the 2000 imagery.

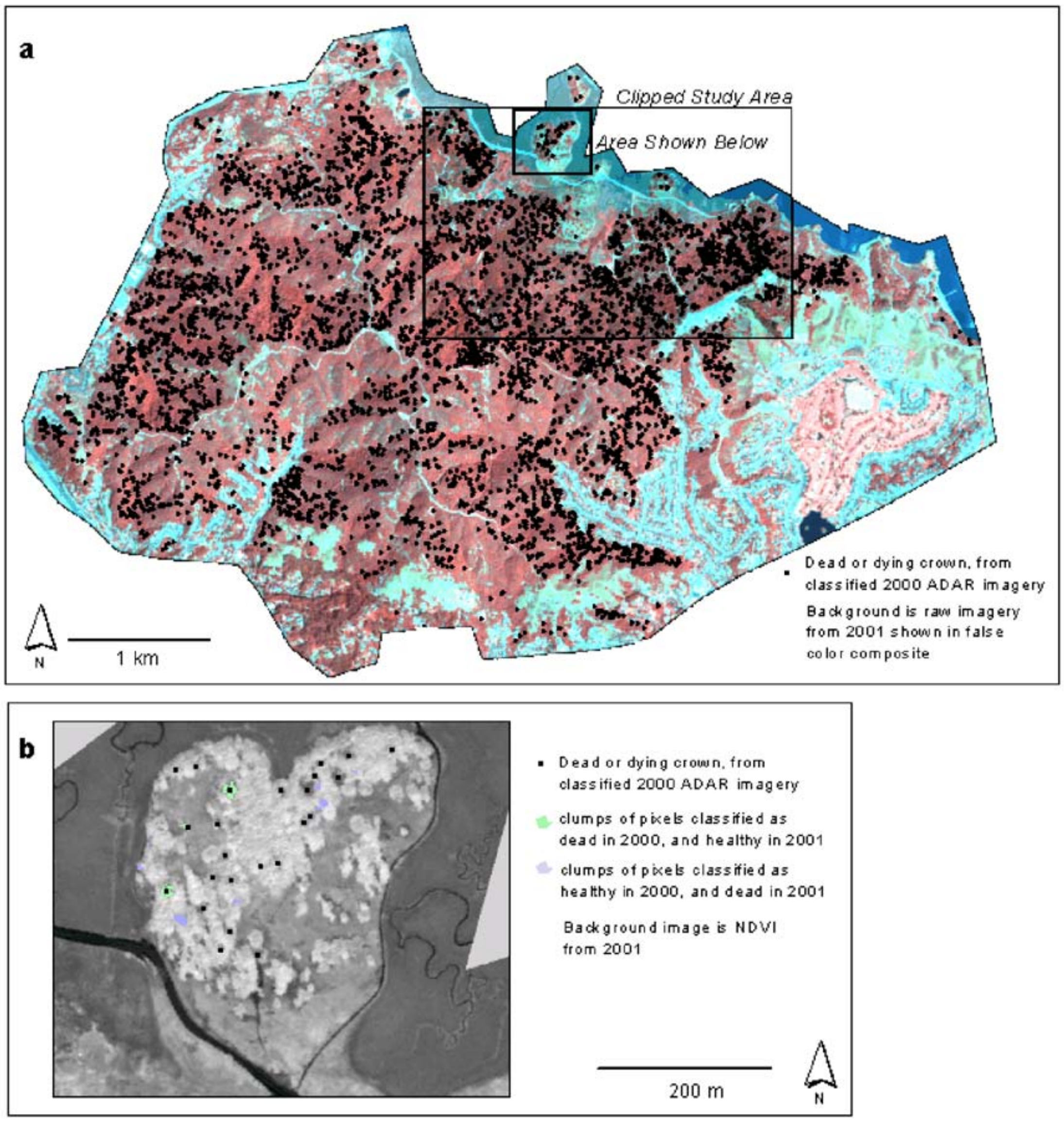

Figure 4—a) Map of dead trees in China Camp State Park area from classification of 2000 mosaiced ADAR imagery. There are 5,340 dead trees distributed throughout the area shown (1,708 ha, of which 917 ha is forested). b) Smaller subset of area used for change detection analysis showing highlighted change areas derived from a NDVI subtraction algorithm. This area highlights newly dead trees, as well as those deciduous oaks that were misclassified in the 2000 analysis.

Change Detection

Within the smaller subset of the study area (shown in *figure 4*) there were 1,523 dead and dying trees as calculated using the analysis of the 2000 imagery data. Of these, 432 trees showed significant increase in NDVI from 2000 to 2001, and were determined to be incorrectly classified. These trees are assumed to be deciduous oaks. This results in an error of commission in the analysis of 2000 imagery to be much higher than earlier reported: 28 percent. In addition, 317 tree crown areas showed significant decrease in NDVI, and were determined to have died in the 13 months between the two time periods.

The newly dead trees were not always close (< 10 m) to already dead trees. The minimum distance a newly dead tree was from an existing dead tree was 0.5 m, and the maximum distance was 52.9 m. The average distance was 17.6 m, and 114 trees are over 20 m from the closest existing dead tree.

Discussion

This research presents total numbers of dead and dying trees over two periods in time, and gives an estimate of the number of trees that have died in the interim. According to this work, the area including and surrounding China Camp State Park in Marin County, California (900+ ha of forested land) has on average about 6 dead and dying trees per ha. The seasonality of imagery acquisition is critical to the success of the classification. While in March 2000 the deciduous oaks had fully leafed out at the time of imaging, the leaves were immature and this negatively influenced the NIR reflectance. This resulted in several cases of misclassification (errors of commission) where deciduous oaks were identified as dead or dying trees. When the second set of images was acquired in May 2001, the deciduous oaks were leafed-out with mature, high reflective leaves. There is also classification confusion not related to seasonality. Spectral confusion exists between dead and dying crowns and small forest gaps, but this was corrected through selection of shape metrics, and field reconnaissance.

The image rectification process with ADAR imagery remains a challenge. ADAR is imaged in frames, and these are then combined and georectified into a continuous mosaic. This process is not trivial, and it can be very problematic. The registration between the 2000 and map base layer was good: 0.3 m. But the registration between the 2000 and 2001 imagery was not as good: 4.5 m. Therefore the registration parameters were recreated and the 2001 image reprojected to reduce the error.

From March 2000 to May 2001 many new trees appeared to have died. While numbers of dead trees, and general rates of dead trees per area are useful for management and public awareness of the disease, the methods described here do not yield other measurements important for understanding of SOD disease progression such as rates of infection and speed of death. Measurement of the rate of infection requires the calculation of the number of susceptible trees in the area, which is not a trivial task. Indeed, estimations of the number of crowns in a closed canopy forest from remotely sensed imagery remains a challenge. Estimation of the population of host species will be pursued in the future.

The broad range of distances from newly dead trees to their immediate dead neighbor confirms new results from research into the pathology of the complex. It is currently believed that oaks are a terminal host for this disease. Infection then will most likely not occur from tree to tree. As most of the newly dead trees occurred between 15-20 m away from the closest dead tree, and some as much as 50+ m away from the closest dead tree, this indicates the presence of alternate hosts between dead crowns. Research will continue to explore the spatial pattern of these alternate hosts.

These results should be interpreted cautiously. The methods outlined here measure only dead and dying overstory crowns and not infected trees. It has not been proven that this method can routinely map infected trees with green crowns (i.e. stressed individuals that have not gone through canopy color changes).

Conclusion

Four-band ADAR imagery is useful in mapping dead overstory trees in forest stands affected by Sudden Oak Death. The methods presented here are sufficient to determine the numbers of trees that are dead and dying in an area using high-resolution imagery, however, they require considerable field knowledge and operator time. It is possible that faster, more automated methods can be developed. Efforts continue to develop and test more automated classification and change detection methods and to refine the rectification results.

It is clear that China Camp State Park exhibits extensive overstory mortality. While we cannot assume that every tree that appears to be dead in the forest is a result of SOD, it seems likely that at least half of the trees are affected by the disease in areas where SOD is well established, such as China Camp. Background rates of oak mortality are not known in these areas, but one written estimate indicates a range from 2 percent to 50 percent (Sweicki and Bernhardt 2001). Clearly more research is needed in determining background oak mortality in this forest. Further field validation of the results will help determine both the accuracy of these maps, and assist in measuring rates of disease infection and progression.

From the initial spatial analysis of the dead crowns it appears that the mortality is not just intensifying areas of infection and remaining close to existing dead trees, but expanding into new areas of infection. These results will be examined further with more robust spatial analysis methods to determine disease spread pattern.

This work is in its initial phase. The disease is new to science, and as new techniques are being investigated for control and management of the disease, the monitoring techniques being developed here are also likely to evolve through the next 5 years as other sensors are evaluated, and new GIS modeling techniques are applied to the problem.

Acknowledgments

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