Detecting Plant Metabolic Responses Induced by Ground Shock Using Hyperspectral Remote Sensing and Physiological Contact Measurements

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CTBT OSI Plant Stress Final FY 96 Report

Detecting Plant Metabolic Responses Induced by Ground Shock using Hyperspectral Remote Sensing and Physiological Contact Measurements

A DOE and NASA Collaborative Remote Sensing Field Experiment

by

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Summary

A series of field experiments were done to determine if ground shock could have induced physiological responses in plants and if the level of the response could be observed. The observation techniques used were remote sensing techniques and direct contact physiological measurements developed by Carter (Ref 1,2) for detecting pre-visual plant stress. The remote sensing technique was similar to that used by Pickles (Ref 3) to detect what appeared to be ground shock induced plant stress above the 1993 Non Proliferation Experiment’s underground chemical explosion (Ref 5). The experiment was designed to provide direct plant physiological measurements and remote sensing ratio images from the same plants at the same time. The simultaneous direct and remote sensing measurements were done to establish a “ground truth” dataset to compare to the results of the hyperspectral remote sensing measurements. In addition, the experiment was designed to include data on what was thought to be the most probable interfering effect, dehydration. The experimental design included investigating the relative magnitude of the shock induced stress effects compared to dehydration effects.

Data from this experiment show that ground shock does induce measurable time dependent responses in plant physiology. Water deprivation also produces measurable time dependent effects which are the same or larger in magnitude than the shock induced effects. The shock induced effect on photosynthetic rate was not observed in plants that were watered each day. This suggests that at least for potted plants daily watering, or lack of it, has a stronger effect on photosynthetic rate than the ground shock used in our field tests. We have also identified the possibility of a longer term shock induced increase plant “health” effect in the potted plants. The shock induced plant health effect appears to start with in a week and may last for a relatively long time. In certain cases this effect may extend the time period during which we can detect disturbed ground following an underground explosion. These findings are only first results observed in our data. There is a large amount of data we collected in these experiments that remains to be
exploited in understanding shock induced plant metabolic responses and how they relate to the responses caused by other agents.

Introduction
The DOE Comprehensive Test Ban Treaty (CTBT) Research program was created to further knowledge about technologies that could be used for on-site inspections and confidence-building measures that may be called for under the provisions of the CTBT, which was signed by President Clinton on September 24, 1996. The philosophy of the LLNL On-Site Inspection (OSI) project was to investigate technology areas which showed promise to be of great value for an OSI or confidence building, but were insufficiently developed. Four technologies, three of which apply to OSI and one which applies to confidence building, were identified for funding during FY95 and FY96. The OSI technologies are aftershock monitoring, noble gas transport modeling and sampling, and remote sensing of disturbed ground. This report covers the results from investigations into using shock induced plant stress as a method for remote sensing of disturbed ground recently carried out by William Pickles of the LLNL CTBT OSI disturbed ground detection project and Gregory Carter of Earth Systems Science Office at NASA's Stennis Space Center (SSC).

Field Experiment Description
The primary purpose of this experiment was to determine if ground shock causes observable metabolic responses in plants. This information is necessary to support the tentative conclusion made from the Non Proliferation Experiment that an underground explosion can cause observable plant stress (Ref 3). All of the planned field tests were successfully performed between May 13 and May 22, 1996, near Sunol California, in the local growing grounds of the Valley Crest Tree Company, a large commercial nursery. Robert Crudup, the vice president for operations, and Francisco Riez, the supervisor of the Sunol growing grounds for the Valley Crest Tree Company, both participated in these experiments and were very helpful in conducting the field tests and providing information about plant reactions that influenced the experimental plan.

In these field tests, we measured plant physiological response and hyper-spectral imagery of trees that were physically shocked under highly controlled conditions. The trees used were in pots at the Valley Crest Tree Company's Calaveras Growing Grounds. The growing ground, or nursery, has separate areas for each species. Each area has large numbers of plants that are nearly identical and have been sitting in pots, under carefully controlled conditions, for long periods of time. The species of trees we selected for our tests were Alnus Rhombifolia, or White Alder. This tree species is native to arid California hill country. The sixteen trees we used were in 15 gallon plastic pots and were part of several hundred trees that had been sitting completely undisturbed since January 24, 1995.
The section of potted trees in the growing grounds in Sunol are shown in Figure 1 below. The photo was taken from the empty section just west of the trees. Pickles, Ruiz, and two nursery workers are shown discussing the dropping procedure to be used. Each pot had a watering tube that fed water and fertilizer from the main distribution lines which can be seen running across the bottom of the photo. Figure 1 shows the original positions and condition of all the trees used in the experiment. The **Alnus Rhombifolia** trees were highly uniform in their size and condition as can be seen in the photo. The trees had been allowed to grow undisturbed for 17 months in the local environment. Each tree had received a five minute watering each day during the 17 months.

![Image of potted trees in Sunol](image)

**Figure 1.** The trees selected for this experiment were growing undisturbed in this section of the nursery. Pickles and Ruiz on the left are explaining the experiment methodology to the workers who will move and drop some of the trees.

We designed our experiment to be statistically valid even though we were constrained to use only as many trees as we could process in a week or so of field effort. We decided to randomly pick twelve of the pots from the two rows of trees near the edge of the section shown behind Pickles and Ruiz in Figure 1. These twelve pots were then individually picked up, carefully transported into position in the edge row, and then randomly
dropped from different heights. Four of the trees already in the edge row were left undisturbed as controls. The process of dropping a tree is shown in Figure 2 below. The two nursery workers picked up a randomly chosen pot, and carefully walked it into the new position it would occupy. The height the pots were dropped from was either one, two, or three feet. The drop height of one, two, or three feet was randomly chosen for each pot. The workers carefully raised the pot to the chosen height under the direction of Ruiz. He measured the height with a ruler as can be seen in the photo in Figure 2, which was taken just as one of the pots was dropped. The potted trees' free fall and subsequent shock of hitting the ground was designed to simulate slap down conditions that the earth surface experiences following a large underground explosion. The heights of one, two and three feet are approximately equal to the distance the surface of the earth moved in different areas around ground zero above the NPE explosion. This experimental method simulates only the second half of the shock process that occurs above a real underground explosion. The first half of a real explosive shock, where the surface is accelerated sharply upward was not simulated in this experiment design.

Figure 2. The pots were dropped from a measured height of one, two, or three feet.
Plant physiological measurements and hyper-spectral images were obtained of the twelve trees that were dropped and also of the four control trees that were left undisturbed. In summary, of the sixteen trees, four trees were dropped from 1 foot, four from 2 feet, four from 3 feet, and four were not dropped or moved. The 16 tree experiment was made up of four logical or “treatment” groups of four trees each. The different groups of trees had been dropped from each of three different heights and the control group was left untouched in the positions they had occupied for 17 months.

The final configuration of the 16 trees lined up to form a uniformly spaced row is shown in figure 3. The pots were each clearly labeled with square yellow tags. This was done to provide a clear view of all the trees for the NASA filtered CCD camera which is also shown in position in figure 3. The camera could image four trees at a time. To image all sixteen of the trees the camera was moved four times each day. A black plastic backdrop can also be seen behind the edge row of trees. It was placed to block the camera from viewing the trees behind the edge row. The labels on the pots could be read in the CCD camera images.

Figure 3. All sixteen trees are shown in their final positions in front of the black plastic backdrop. The pots are all labeled and are in clear view of the NASA filtered camera.
As can be seen in the photo of the final experimental configuration, figure 3 above, the tops of the trees are above the black plastic backdrop. The camera images taken from this position do show leaves from all of the trees in the section. The bottom half of the images taken of each of the sixteen trees that are in front of the backdrop show only their leaves and not those of the trees that are further into the section. Plastic tubes that feed water from the distribution system were reinserted in the pots that had been moved.

Experiment Design Expansion to Include Separate Watering Effects and Shock Effects

Robert Crudup and Francisco Riez, who have extensive experience with operating the Sunol growing grounds, both cautioned us that plants in pots are much more sensitive to regular watering than similar plants that are in the ground. Because of their warnings, we began to consider carefully the exact watering schedule to maintain for the trees in our experiment. After extensive discussions, we decided that the watering schedule might possibly have a much stronger effect on the potted trees than any ground shock we had given them. We decided we needed to further subdivide the experiment to provide information about the magnitude of water stress effects versus shock-induced plant stress effects. It turns out that this was an important addition to the design of our experiment.

To create this expanded experiment we decided to randomly withhold water from two of the four plants in each of the four groups, and continue to water the other two plants in each group exactly as they had been watered for the previous 17 months. The regular watering schedule had always been to water enough every morning to just make all the soil in the pots damp. On very hot days the watering was then repeated in the late afternoon. The water used always contained the same, small concentration of fertilizer. The fact that some fertilizer is present in the water may be important in interpreting the "health effect" for shocked plants that we think may have been observed in our data. This is discussed in the results sections later in this paper.

The selection of the trees, the dropping, and the watering option selection took place on the first day of the experiment. We began the plant physiology measurements and the hyper-spectral imagery measurements on the second day. We repeated the entire suite of measurements daily except for the weekend days when the nursery was closed. The measurements were made during the week after the dropping occurred.

Experimental Measurements and Instrument Descriptions
The suite of measurements were made using equipment provided by NASA-SCC. The NASA-SSC equipment is the same that Greg Carter has used in his previous plant stress studies. (Ref 1, 2) The physiological plant stress measurements were done with a leaf water potential measuring system, a plant photosynthesis rate measuring system, and a
leaf reflectance, high resolution, visible and infrared spectrometer system. The hyperspectral images were taken with the new NASA handheld specially filtered CCD camera which has five bands which have six to ten nanometer width in wavelength acceptance.

Leaf Water Potential
Leaf water potentials, $\Psi_w$, (Ref 5, Nobel, 1991), were measured for two leaves per tree. We used a pressure chamber system, Model 1001, made by the PMS Instrument Company, Corvallis, OR, USA. This leaf water potential measuring instrument is shown in figure 4. It is located near the center of the rear of the van beside the nitrogen bottle and its pressure gauges. This van housed all of our equipment and served as our mobile laboratory. The water potential measuring system consists of a pressure chamber that can be pressurized with dry nitrogen from the storage bottle.

Figure 4. The portable water potential measuring system is shown deployed in the rear of the van used to transport and house all our experimental equipment. A close-up of the instrument is shown in picture on the right. The pressure vessel is seen behind the frame of the back pack near the center of the image. The nitrogen cylinder used to pressurize the vessel is shown on the right in both images.

A leaf can be placed partially inside the pressure vessel with its stem extending out

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through the top of the vessel. The pressure vessel is then sealed up. The leaf is inside the vessel but the leaf stem passes through a pressure seal and extends out into the air outside. The nitrogen gas pressure is increased inside the vessel until it just equals the pressure with which water is held within the plant leaf. The water in the plant then begins to exude fluid from the end of the stem, which is exposed to the air. The pressure required to just start water exuding from the leaf is then recorded. In general the higher the pressure required the greater was the water stress experienced by the plant.

On the right in Figure 4 there is a inset with a magnified view of the water potential measuring system and the nitrogen storage bottle. The top of the pressure vessel appears as a disc in the center of the inset just above the "A" shaped aluminum frame that is part of the back pack for this instrument.

Two leaves were picked from each tree, each day, and placed into the pressure chamber. The pressure in the vessel was increased until water was just starting to be expressed from the leaf stem. The pressures measured were recorded by hand in our log book and transcribed later into a database in the laptop computer.
Photosynthetic Rate Measurement

Photosynthetic rate was measured using the portable instrument shown in Figure 5. It is a portable gas exchange system (model LI-6200 with 1 liter transparent chamber, LI-COR, Inc., Lincoln, NE, USA). This instrument measures net photosynthetic CO₂ flux, which is called $J_{CO2}$, and the stomatal conductance to water vapor, which is called $g_{wv}^s$, following the convention found in Ref 5, (Nobel, 1991)

Figure 5. The portable LI-6200, photosynthetic rate measuring instrument showing the chamber sitting on top of the ice chest and the system control and data recording computer standing on its four legs.

The photosynthetic rate is the rate at which the leaf is metabolizing carbon dioxide and removing it from the surrounding air. The photosynthetic rate instrument has a chamber which can be clamped over a living leaf. The instrument then measures the amount of carbon dioxide removed from the chamber and the amount of water introduced into the chamber, per second, by the area of the living leaf clamped inside the chamber. In
our measurements, the leaf area inside the chamber was 12.5 cm\(^2\). Leaf area, together with the rates at which the leaf depleted CO\(_2\) and increased humidity in the chamber during a 10 sec period were used to compute the photosynthetic rate, \(J_{CO_2}\), and the stomatal conductance, \(g_{sw}\). This computation that is performed by the LI-6200 is described in Ref 6 (Leuning and Sands, 1989).

Figure 6 shows Greg Carter using the LI-6200 instrument to measure the photosynthetic rate and stomatal conductance in the living leaves on the tree.

Figure 6. The Photosynthetic Rate being measured on living leaves by Greg Carter

Two mature leaves on each tree were measured each day. The measurements were started at about 10:00 a.m. so that the plant photosynthesis was probably near the maximum. The order in which the trees were measured was identical on each day of our experiment. The leaves chosen were always on the same side of the trees. The skies normally were cloudless as can be seen in the photo. The photon flux of sunlight on the leaf was measured to be that of “full sunlight”.

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The instrument has an on-board computer which recorded the photosynthetic parameters from each leaf. The parameters from all of 32 leaves measured was then downloaded to the database in the notebook computer at the end of each day.

The rate at which a plant can metabolize CO₂ is a direct measure of its viability or health. For more information, a good reference to the subject of vegetation stress, is the book "Vegetation Stress", edited by H. K. Lichtenhaller, (Ref 7). This book is actually the proceedings from the First International Conference on Vegetation Stress held in 1995.

Visible and Infrared High Resolution Reflectance Spectrometer

The reflectance spectrometer used in this experiment to measure leaf reflectance spectra is shown in Figure 7 below.

Figure 7. The visible and infrared spectrometer used to measure leaf reflectances.

The spectrometer was set up as shown. Each day, two leaves from each tree were care-
fully removed from the trees and placed on the white pad on top of the case shown in Figure 7. The spectrometer was used to measure the leaf reflectance wavelength spectrum from 400 nanometers to 850 nanometers. The spectrometer’s slits were set to an opening of 0.5 mm which produced four nanometer wavelength resolution. The spectra were however read out using 1.0 nanometer resolution. The data from the whole day was accumulated in the internal memory and then downloaded to the laptop in the evening. These measurements provide the most detailed and direct link between narrow band leaf reflectance and the physiological contact measurements. Carter is working on a paper which studies the relationship between the high resolution leaf reflectances and the various physiological parameters for pine trees infested with pine beetles. We hope to apply his results to our reflectance spectra at some time in the future.

The leaf reflection spectra were measured starting at approximately 10:00 each morning and took about two hours to complete. The order in which the trees were measured was the same on each day.
NASA Filtered CCD Portable Camera System

Figure 8 NASA portable filtered CCD Camera system as deployed in the nursery.

The CCD camera was equipped with a five position filter wheel. The filters used are narrow band thin film interference filters. To acquire an image, the wavelength is chosen by rotating the filter wheel to the desired filter. Then the light admitting aperture is adjusted to put the scene in any unsaturated brightness range. The analog CCD image output is digitized by a commercial frame grabber and displayed and stored in the laptop computer. To acquire another wavelength image of the same scene this process is repeated. In our experiment we acquired images at four wavelengths for each scene. The wavelengths were 443, 675, 698, and 790 nanometers. The acceptance width of the filters was between 6 and 10 nanometers. Each scene consisted of three or four of the trees in their pots with the gray scale placard out in front. This meant acquiring about 16
images per day. This took about 2 or 2.5 hours per day. The camera system was positioned each day, about 50 feet to the west of the row of trees approximately as shown in Figure 3. Imaging was started at about 14:00 PDT so that the sun was at our backs and shining on the trees at about a 20 or 30 degree angle from vertical or nadir. Because the date was late May, the sun was almost directly overhead at noon.

The camera and plants were stationary during the acquisition of the four different filtered images for each scene. However, the wind was blowing strongly and moving the leaves around. Consequently, the leaves and small branches were in somewhat different places in each of the four images. This makes using these images to form ratio images rather difficult. Forming a ratio between images requires that at least some parts of some leaves are in the same position in the two images. Since our purpose was to ascertain the stress condition of all the leaves on the plant so day to day comparisons could be studied, the leaf motion was a definite limitation. The spatial resolution of the camera system was about 1 centimeter at the distance we were using between the trees and the camera. This was excellent spatial resolution for our purposes because the leaves were of the order of 10 cm in areal extent. Each leaf then had many pixels in the image and this may be why the ratio images were able to be formed with some success in this experiment.

The time required to digitize the analog CCD camera image which is called “frame” grabbing” was 1/60th of a second. This time interval was probably short enough so that most leaves did not move significantly during the acquisition, but it would not be a fast enough “shutter speed” if there were any camera motion or violent motion of the leaves.

The length of time required to finish all the imaging each day was also long enough that there was a considerable change in sun angle during the acquisitions. To try and compensate for this effect, we started imaging at the same time every afternoon. The order in which the trees were imaged was the same on each day. This camera system was the weakest part of our experimental instruments. A true hyperspectral camera system, with a short image acquisition time, will be required in any future experiments that involve imaging for plant stress effects.

Data Analysis
The data accumulated from all of the measurements on all of the plants was downloaded to computers at LLNL and at NASA Stennis Space Center. All of the physiological measurements were processed by Carter and Pickles at NASA Stennis using commercially available statistical analysis computer software. The software package is called the Statistical Analysis System (SAS) and is produced by the SAS Institute located in Cary North Carolina. The data reduction of the large amount of leaf reflectance spectrometer measurements is still in process at NASA Stennis by Carter. The filtered camera images have been partially processed at LLNL by Pickles. Here again, the amount of
image data is very large and a complete analysis will require additional effort. In view of the limited manpower resources, the images that have been processed were selected based on the effects observed in the physiological data. The tree images selected are the same ones in which the shock induced stress effects were observed.
Experimental Results, Shock Induced Plant Stress
We have found some important results that support the use of plant stress observations to detect ground disturbed by underground explosions. The first is that we definitely see a downward trend in the mean photosynthetic rate as a function of the shock level, i.e., the height from which the trees were dropped. This downward trend of the mean measured photosynthetic rate is first observed on the day after the drops occurred and is still observed on the third day after the drops. This can be seen clearly in the front row of histograms on the left in Figure 9.

Figure 9. Mean Photosynthetic rates for the trees that had water withheld, plotted as a function of drop height and time.
The actual photosynthetic means and their variances measure on May 8 are shown in Figure 10 below. The data shown in Figure 10 is the numerical plot of the first row in the histogram plot Figure 9.

The photosynthesis data shows that there is greater stress in trees that were dropped compared to the controls. The downward trend in the mean values of the measured photosynthetic rate is approximately linear with respect to the height of the drop. This is shown below. The size of the variances plotted were calculated by SAS and are reasonable because each mean is obtained from data from only four trees.

![Figure 10. Mean photosynthetic rates, on May 8, as a function of drop height for the subgroup of trees that had water withheld.](image)

As can be seen in Figure 9, the mean photosynthetic rate for the trees that were dropped from three feet, remains low, through May 10 which is three days after the drops occurred. The mean photosynthetic rate of the trees dropped from three feet rises to
approximately the same value as all the other trees in this group by May 13 which was 6 days after the drops occurred. The time intervals observed in this experiment for the onset of plant stress and then the annealing or recovery of the plants are almost exactly the same as those observed following the Non Proliferation Experiment (NPE). Reference 3 and 4. This supports the hypothesis that the plant stress effects observed following the NPE could indeed have been induced by the ground shock caused by the underground explosion.

Possible Shock Induced Plant Health
In this experiment we have also discovered the possibility of a longer term shock induced increased plant “health” effect in the potted plants. During our field tests the weekend during which we were unable to take measurements was very hot. After this weekend, we see a very strong reduction in photosynthetic rate in all plants. The Photosynthetic rates of the trees that continued on an uninterrupted daily watering program are shown in Figure 11. The shock levels and the dates form the horizontal axes. The measured photosynthetic rates for the continuously watered trees are plotted vertically. Note that after the weekend, which was very hot, all the plants are recovering from depressed photosynthetic rates. The plants that are in the group that had been dropped from three feet on May 7 have increased their photosynthetic rates more quickly than the others as can be seen by looking at the rows of data for May 13 and 14 on the right hand side of the 3D histogram plot.
Figure 11 Photosynthetic rate for the subgroup of trees that were continually watered

This could possibly be interpreted as the shock having loosened the soil around the roots of the plants, thus allowing more effective water penetration to the roots, and hence a quicker recovery to healthy photosynthetic rates. Another interpretation is possible. It may be that the shock of dropping the trees caused them to react by closing their stomata or leaf pores, as part of reducing their metabolism. Then when the weather turned extremely hot the shocked plants were already in a semi-shut-down state and were better able to survive the adverse conditions. We may be able to ascertain if either of these interpretations is correct from our data, but it would require further analysis.

The actual photosynthetic rate means and variances for May 14, the last day of data taking, are plotted versus drop height in figure 12. This data is from the right most (brown colored) row of histograms shown in Figure 11.

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Figure 12. Mean Photosynthetic rate on the last day, May 14 as a function of shock level.

The variances are relatively large as would be expected in an experiment with only four leaf measurements per mean value. The variances may be larger for the more highly shocked trees because the shock of dropping, and the very hot weekend may be enough stress to start bringing out differences in the ability of various trees to respond. There does however, seem to be definite trend towards greater photosynthetic activity for the trees that were dropped from three feet. This interpretation seems to be further supported by the daily leaf water potential data and the internal leaf conductance rates. We
are however still studying the other physiological data in an attempt to correlate the effects observed in those data with the photosynthetic rate data effects. The physiological data forms a large and complete database that hopefully can be used to understand the complex interaction observed between the shock effects and watering effects in the potted plants.

In addition, the shock induced plant health effect may last for a relatively long time. In subsequent inspections of the plants used in the field tests, the plants that were shocked the most strongly appear to be significantly more robust than the plants that were not shocked. Further physiological measurements have however not been made. The robust description is a subjective observation made by Pickles during several return trips to the nursery. This effect was not expected and deserves to be studied in greater detail in a new experiment. If this effect could be established with more data it may be very important for On Site Inspections or other disturbed ground applications. In certain cases this effect may extend the time period for detecting disturbed ground following an underground explosion, or other event. This result, as are all the results presented in this paper is for potted plants. Plants that are growing in the ground may respond entirely differently. It would be valuable to have some experiments that explore the differences, if any, between shocked potted plants and shocked plants in the ground.

**Results from the NASA Narrow-Band-Filtered-Camera Images**

We have a partial analysis of the filtered-camera images taken as part of our field tests. As stated earlier, The data has been transformed into multi-band hyperspectral images and ratio images have been created. Ratios of all possible pairs of the four bands at 443, 675, 698, and 790 nanometers were studied. There is some indication that the more highly shocked plants do produce brighter ratio images for the 698, 443 pair and the 790, 698 pair of bands.

The images are difficult to use properly for forming band to band ratio images because the individual bands were acquired sequentially, at several minute intervals. The camera did not move between each of the four band acquisitions, but the wind was blowing causing the leaves to move around between the separate images. The individual leaf positions are different in each band image. This makes co-registration of all the leaves on the plant in each of the four bands impossible. If future experiments are to include hyper-spectral imagery, a new camera system that acquires all the bands simultaneously will be required.

Examples of the filtered images and the ratio images that can be formed are shown in Figures 13 and 14. The image shown is of pots number three, four, and five and was taken on May 9, the day after the plants were dropped. This image of these trees was chosen because trees with two levels of shock and a control tree, all with water withheld, are in the image. Which tree is which will become apparent as you read on. Figure 13 was made by combining all four separate filtered images into one four band image. This
four band image was then used to create a false color image by making band 1 blue, band 3, green and band 4 red. In this composite of three images the coregistration of the leaves appears to be reasonably good. The image is more or less lifelike. The leaves' images are not too badly smeared out and appear to have a normal color. Any lack of coregistration appears as an "odd" single color lining on the edge of a feature. Some of this is apparent in the image. Look at the left edge of the tag on the leftmost pot for an examples of this slight lack of registration. This may have been caused by a slight motion of the camera while changing the band-filter-selector knob. The number of leaves that have some lack of coregistration between bands is about equal for the three trees shown. The black plastic backdrop is visible in this image.

Figure 13. This a "false color" image of pots 4, 5, and 6 created using the 443 nanometer band (1) as blue, the 698 band (3) as green, and the 790 nm band (4) as red.
The four band image used to produce the false color image shown in figure 13. This four band dataset was then used to form various ratio images using two of the bands at a time. An example of the result of one such ratio is shown in Figure 13 below. The figure is a “pseudocolor” gray scale image. The brightness of the leaves in the image is inversely proportional to the value of the ratio. In this particular image, the ratio used was formed by dividing the value in the 790 nm band (4) by the value in the 698 nm band (3), for each pixel. The ratio of the wavelengths in these bands is one of those shown by Carter in previous publications (Ref 1,2) to be sensitive for detecting pre-visual plant stress. In the final ratio image displayed the smaller the numerical value in the pixel the whiter it appears. This image was created by using a look-up-table or LUT that has a negative slope over the range of ratio values that represent the leaves. The inanimate objects in the image were given enough brutishness so that the positions of the trees in their pots can be seen by the reader. The ratio of 790/698 has the useful characteristic of having different ranges of ratio values for the inanimate objects and the leaves. The “glare” or “blaze” angle reflections from the leaves appears to have ratio values similar to the inanimate objects. This makes it possible to remove most of the glare reflections from the leaves in the image. This was done in the image shown in figure 13 below.
Figure 13. Ratio image created by dividing the 790 nm band (4) by the 698 nm band (3). The lower the value of this ratio, the higher the plant stress for the leaf images. The lower ratios are shown as brighter in the image.

So except for the inanimate objects, the brighter the image the more plant stress is indicated. Please look at figure 13 and judge for yourself if the three trees appear to be different in their overall stress levels. If so, then order them with respect to stress level in your own mind. The trees are numbered 4, 5, and 6 from left to right. If you will please, write down your determination of the order of the stress level, if any, before reading on.
Pot number 4 on the left was dropped from three feet and had water withheld. Pot number 5, in the middle was a control and was not dropped or moved, and it did not have its water withheld. Pot 6 on the right was dropped from one foot and did not have its water withheld. We feel that the leftmost pot, number 4, appears to be the brightest, followed by pot 6 and pot 5, the control. The average brightness then follows the level of shock in a consistent way. As was discussed earlier, a camera system that acquired the various bands simultaneously and in a short period of time would eliminate mis-registration effects in the ratio images. There is enough of an observable effect in these ratio images to warrant repetition of these experiments with an improved camera system.

Conclusions and Possible OSI Applications
Now that the shock-induced plant stress effects have been confirmed in our controlled experiments in the growing grounds at Sunol, the technique of using remote sensing to discover shock induced plant metabolic response can be further developed. This work could include the background or baseline studies that would lead to understanding the interactions between natural and induced effects. Hardware could be designed to create handheld “on-the-ground”, imaging systems for future experiments. In addition, hyperspectral systems could be built and tested for application as a low altitude, air-borne, on-site-inspection technique.

These plant metabolic response techniques are particularly valuable for on-site inspections because they do not require “before and after measurements”. These techniques utilize remote sensing measurement of the plant metabolic responses to distinguish plants that are behaving differently than their nearby neighbors in response to the natural environmental influences that they are both experiencing. This should allow location of an area of disturbed ground in an otherwise undisturbed larger area. This technique is well suited to develop into a “live”, on-line system that could be used by a local or remote operator to search large areas for telltale signs of plant metabolic abnormalities.

Hyperspectral remote sensing of previsual plant stress caused by ground shock may be an important technique for locating traces of large underground explosions. The work reported here shows that the technique has some special requirements or constraints. First, the images taken must have spatial resolution smaller than the plant leaves or appropriate groups of leaves. Larger, or coarser spatial resolution may be effective if the plant leaves present a continuous cover visually. Examples where the coarser spatial resolution may be effective would be when imaging smoothly covered grass lands, jungle canopys, forests, dense scrub brush, water plants on lakes and streams, and plankton in the ocean. We have however, not yet studied water plants for stress effects. Second, the individual narrow band images must be acquired nearly simultaneously. Third, the time to acquire the images must be shorter than the required spatial resolution divided by the combined velocity of the camera and the leaf motion. This means that, in most situations, the acquisition time should be 10 millisecs or less.
References


   Also available in Journal of Plant Physiology, 1996, Vol.148, No. 1/2, 248pp special issue I, II, and II as three separate publications. This special issue contains a large selection of the papers presented at the First International Symposium on Vegetation Stress, held at the GSF Research Centre Neuherberg in Munich, Germany, on 19-21 June, 1995. The main emphasis is given to stress effects induced by UV-B radiation, air pollution, acid rain, forest decline and increased carbon dioxide levels. This special issue and special issues II and III will also appear as a book entitled Vegetation Stress.

Key words: stress\stress factors\plants\ultraviolet radiation\irradiation\air pollution\ozone\sulfur dioxide\climatic change\nutrient deficiencies\plant nutrition\heavy metals\forest decline\techniques\instrumentation\fluorescence\chlorophyll\reflectance\photosynthesis\conferences\Vegetation stress\forest trees