Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

Elsevier Internet Homepage – http://www.elsevier.com
Consult the Elsevier homepage for full catalogue information on all books, major reference works, journals, electronic products and services.

Elsevier Titles of Related Interest

AN END TO GLOBAL WARMING
L.O. Williams
ISBN: 0-08-044045-2, 2002

FUNDAMENTALS AND TECHNOLOGY OF COMBUSTION
F. El-Mahallawy, S. El-Din Habik
ISBN: 0-08-044106-8, 2002

GREENHOUSE GAS CONTROL TECHNOLOGIES: 6TH INTERNATIONAL CONFERENCE
John Gale, Yoichi Kaya
ISBN: 0-08-044276-5, 2003

MITIGATING CLIMATE CHANGE: FLEXIBILITY MECHANISMS
T. Jackson
ISBN: 0-08-044092-4, 2001

Related Journals:
Elsevier publishes a wide-ranging portfolio of high quality research journals, encompassing the energy policy, environmental, and renewable energy fields. A sample journal issue is available online by visiting the Elsevier web site (details at the top of this page). Leading titles include:

Energy Policy
Renewable Energy
Energy Conversion and Management
Biomass & Bioenergy
Environmental Science & Policy
Global and Planetary Change
Atmospheric Environment
Chemosphere – Global Change Science
Fuel, Combustion & Flame
Fuel Processing Technology

All journals are available online via ScienceDirect: www.sciencedirect.com

To Contact the Publisher
Elsevier welcomes enquiries concerning publishing proposals: books, journal special issues, conference proceedings, etc. All formats and media can be considered. Should you have a publishing proposal you wish to discuss, please contact, without obligation, the publisher responsible for Elsevier's Energy program:

Henri van Dorssen
Publisher
Elsevier Ltd
The Boulevard, Langford Lane
Kidlington, Oxford
OX5 1GB, UK

Phone: +44 1865 84 3682
Fax: +44 1865 84 3931
E.mail: h.dorssen@elsevier.com

General enquiries, including placing orders, should be directed to Elsevier's Regional Sales Offices – please access the Elsevier homepage for full contact details (homepage details at the top of this page).

Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Edited by

Sally M. Benson
Lawrence Berkeley Laboratory
Berkeley, CA,USA

and Associate Editors

Curt Oldenburg[1], Mike Hoversten[1] and Scott Imbus[2]
[1]Lawrence Berkeley National Laboratory
Berkeley, CA, USA
[2]Chevron Texaco Energy Technology Company
Bellaive, TX, USA

Volume 2

ELSEVIER
2005

Amsterdam – Boston – Heidelberg – London – New York – Oxford
Paris – San Diego – San Francisco – Singapore – Sydney – Tokyo

ELSEVIER B.V.
Radarweg 29
P.O. Box 211, 1000 AE Amsterdam
The Netherlands

ELSEVIER Inc.
525 B Street, Suite 1900
San Diego, CA 92101-4495
USA

ELSEVIER Ltd
The Boulevard, Langford Lane
Kidlington, Oxford OX5 1GB
UK

ELSEVIER Ltd
84 Theobalds Road
London WC1X 8RR
UK

© 2005 Elsevier Ltd. All rights reserved.

This work is protected under copyright by Elsevier Ltd, and the following terms and conditions apply to its use:

Photocopying
Single photocopies of single chapters may be made for personal use as allowed by national copyright laws. Permission of the Publisher and payment of a fee is required for all other photocopying, including multiple or systematic copying, copying for advertising or promotional purposes, resale, and all forms of document delivery. Special rates are available for educational institutions that wish to make photocopies for non-profit educational classroom use.

Permissions may be sought directly from Elsevier's Rights Department in Oxford, UK: phone (+44) 1865 843830, fax (+44) 1865 853333, e-mail: permissions@elsevier.com. Requests may also be completed on-line via the Elsevier homepage (http://www.elsevier.com/locate/permissions).

In the USA, users may clear permissions and make payments through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA; phone: (+1) (978) 7508400, fax: (+1) (978) 7504744, and in the UK through the Copyright Licensing Agency Rapid Clearance Service (CLARCS), 90 Tottenham Court Road, London W1P 0LP, UK; phone: (+44) 20 7631 5555; fax: (+44) 20 7631 5500. Other countries may have a local reprographic rights agency for payments.

Derivative Works
Tables of contents may be reproduced for internal circulation, but permission of the Publisher is required for external resale or distribution of such material. Permission of the Publisher is required for all other derivative works, including compilations and translations.

Electronic Storage or Usage
Permission of the Publisher is required to store or use electronically any material contained in this work, including any chapter or part of a chapter.

Except as outlined above, no part of this work may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without prior written permission of the Publisher.
Address permissions requests to: Elsevier's Rights Department, at the fax and e-mail addresses noted above.

Notice
No responsibility is assumed by the Publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. Because of rapid advances in the medical sciences, in particular, independent verification of diagnoses and drug dosages should be made.

First edition 2005

Library of Congress Cataloging in Publication Data
A catalog record is available from the Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record is available from the British Library.

ISBN: 0-08-044570-5 (2 volume set)

Volume 1: Chapters 8, 9, 13, 14, 16, 17, 18, 24 and 32 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. EU co-funded work appears in chapters 19, 20, 21, 22, 23, 33, 34, 35, 36 and 37. Norwegian Research Council (Klimatek) co-funded work appears in chapters 1, 5, 7, 10, 12, 15 and 32.

Volume 2: The Storage Preface, Storage Integrity Preface, Monitoring and Verification Preface, Risk Assessment Preface and Chapters 1, 4, 6, 8, 13, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. Norwegian Research Council (Klimatek) co-funded work appears in chapters 9, 15 and 16.

♾ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).
Printed in The Netherlands.

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER BOOK AID International Sabre Foundation

Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 2
D.C. Thomas and S.M. Benson (Eds.)

Chapter 22

HYPERSPECTRAL GEOBOTANICAL REMOTE SENSING FOR CO_2 STORAGE MONITORING

William L. Pickles[1] and Wendy A. Cover[2]

[1]Lawrence Livermore National Laboratory, Livermore, CA, U.S.A.
[2]University of California at Santa Cruz, Santa Cruz, CA, U.S.A.

ABSTRACT

This project has developed an airborne remote sensing method for detection and mapping of CO_2 that might be leaking up from an underground storage formation. The method uses high-resolution hyperspectral imagery to detect and map the effects of elevated CO_2 soil concentrations on the roots of the local plants. The method also detects subtle or hidden faulting systems which localize the CO_2 pathways to the surface. Elevated CO_2 soil concentrations deprive the plant root systems of oxygen which is essential for a healthy plant. Excessive soil CO_2 concentrations are observed to significantly affect local plant health, and hence plant species distributions. These effects were studied in a previous remote sensing research program at Mammoth Mountain, CA, USA. This earlier research showed that subtle hidden faults can be mapped using the spectral signatures of altered minerals and of plant species and health distributions. Mapping hidden faults is important because these highly localized pathways are the conduits for potentially significant CO_2 leaks from deep underground formations.

The detection and discrimination methods we are developing use advanced airborne reflected light hyperspectral imagery. The spatial resolutions are 1–3 m and 128 band to 225 wavelength resolution in the visible and near infrared. We are also using the newly available "Quickbird" satellite imagery that has spatial resolutions of 0.6 m for panchromatic images and 2.4 m for multispectral. These are two commercial providers of the hyperspectral imagery acquisitions, so that eventually the ongoing surveillance of CO_2 storage fields can be contracted for commercially. In this project we had a commercial provider acquire airborne hyperspectral visible and near infrared reflected light imagery of the Rangely, CO enhanced oil recovery field and the surrounding areas in August 2002. The images were analyzed using several of the methods available in the suite of tools in the "ENVI" commercial hyperspectral image processing software to create highly detailed maps of soil types, plant coverages, plant health, local ecologies or habitats, water conditions, and man-made objects throughout the entire Rangely oil field and surrounding areas. The results were verified during a field trip to Rangely, CO in August 2003. These maps establish an environmental and ecological baseline against which any future CO_2 leakage effects on the plants, plant habitats, soils and water conditions can be detected and verified. We have also seen signatures that may be subtle hidden faults. If confirmed these faults might provide pathways for upward CO_2 migration if that occurred at any time during the future.

INTRODUCTION

The purpose of this research program has been to further develop remote sensing methods that can detect and discriminate the effects of elevated soil CO_2 concentrations on the local plants, their local habitats or ecologies, and to map possible hidden faulting systems at the surface above underground geological CO_2 storage formations. These effects were studied in a previous remote sensing research project at Mammoth Mountain, CA, USA (Figures 1–5). This earlier research mapped areas of tree kills and surrounding regions of tree plant stress, created by elevated CO_2 soil concentration levels. These elevated soil concentrations reach as high as 98% and are caused by CO_2 effluents from the magma interactions with formations below

Figure 1: At Mammoth Mountain CO_2 emission levels burst on short time scales to hazardous levels in small areas.

Figure 2: Trees killed at Mammoth Mountain, CA by highly elevated CO_2 soil concentrations. This area is near Horseshow Lake.

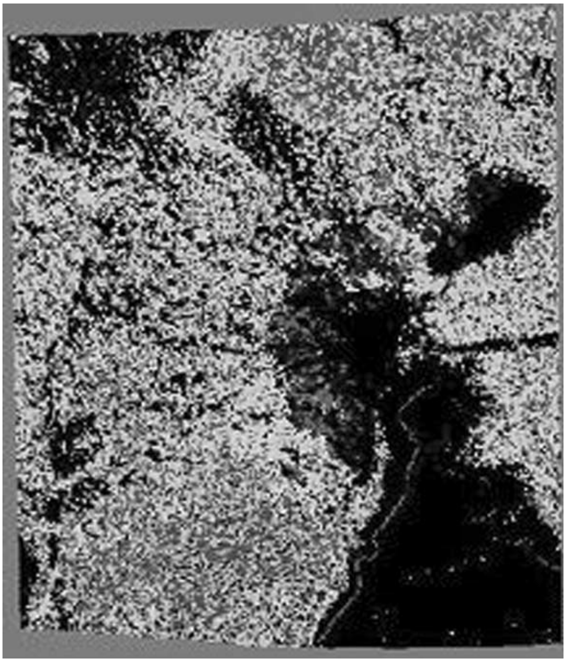

Figure 3: Tree health from hyperspectral imagery: dark, unhealthy; light and speckled; healthy.

the mountain. The mapping was produced by analysis of advanced airborne reflected light hyperspectral imagery acquired by a commercial provider. The spatial resolution was 5 m and wavelength resolution was 128 bands in the visible and near infrared reflected light spectrum between 420 and 2500 nm. The bands are of equal width and are contiguous covering the entire wavelength region.

Hidden faults were also located using the hyperspectral imagery at Mammoth Mountain, CA and similar hyperspectral imagery of the geothermal region near Dixie Valley and Dixie Meadows, NV, USA. Please see the first six references for discussion of the methods and results of the earlier research projects [1–6].

Subtle hidden faults have been detected by mapping mineralization and plant signature shifts in the hyperspectral images (Figure 5). This is potentially important for CO_2 sequestration. CO_2 escaping from an underground storage formation would probably convect along cracks, joints, and faults if there were any. Mapping all the subtle faulting in area above a CO_2 underground storage formation will help focus locations for leak monitoring efforts. The CO_2 escaping into the air at Mammoth Mountain is highly localized spatially and has large variations in emission rates (Figure 4).

The localization of CO_2 effluent was measured by the USGS Menlo Park personnel using hand-held CO_2 instruments at Mammoth in the air, just above the ground. They found very high spatial variability on the order of a few feet and very large changes in effluent rates [7,8].

In this study we are extending these techniques and experience to an enhanced oil recovery (EOR) field at Rangely, CO, USA. The field has been injected with CO_2 for 15 years for EOR. We acquired airborne hyperspectral imagery of the Rangely oil field, the surrounding areas including the town of Rangely, CO in August 2002. Two extensive field trips have been conducted to Rangely, one in August 2002 and a second in August 2003.

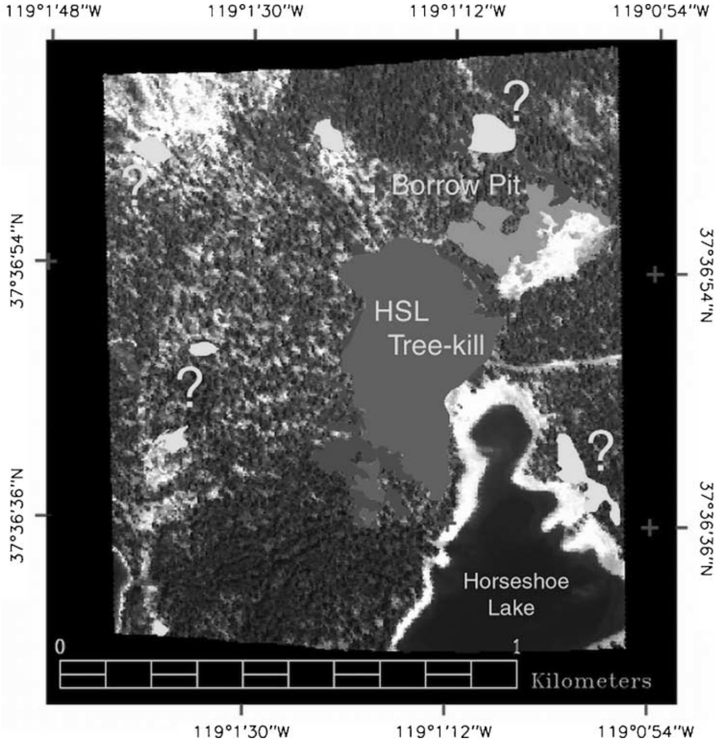

Figure 4: Plant mapping from hyperspectral imagery [3].

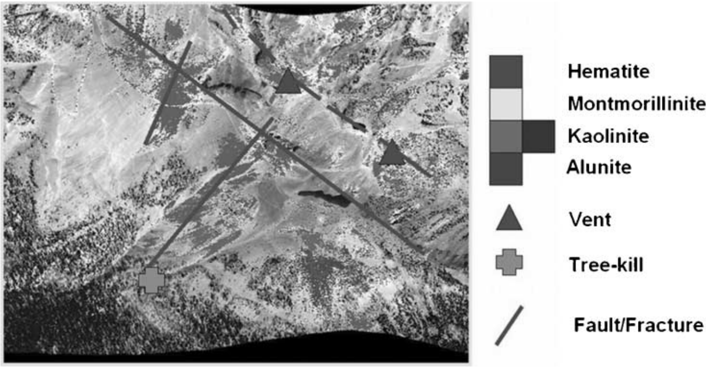

Figure 5: Hidden faults, mineralization and tree kill mapping from the hyperspectral imagery at Mammoth.

In our study of the plant life at Rangely, CO oil field and surrounding areas on the second field trip in August 2003, we did not observe any plant life effects that might be due to CO_2 effluents. There are some CO_2 and methane soil concentrations at about a dozen sampling locations in the area that are elevated above normal levels. Ron Klusman, (Colorado School of Mines in Golden, CO, USA) made measurements as part of a DOE funded project to study CO_2 and CH_4 concentrations in soils and in the air at the Rangely oil field. The elevated readings he observed were as great as 100 times the natural CO_2 concentrations caused by the activities of the microorganisms in the soil. He found winter to summer variations. He also did isotopic analysis on the CO_2 and CH_4 at many locations. These measurements were made over several years. The soil CO_2 concentration levels that were measured do not affect the "plant health" noticeably as represented by any measurements we made, in the imagery and on the ground using the field portable spectroradiometer in August 2000. What we did discover during our fieldwork at Rangely this summer is that the hyperspectral imagery of this relative dry high desert area maps the complex spatial distributions of a number of subtlety different "habitats". We speculate that if CO_2 soil concentrations were to start rising "significantly" above normal levels in well-defined spatial zones that the habitats in that area might change their boundaries or the spacing of plants within the habitats. If the average concentrations of soil CO_2 were high enough for several months it would be possible to species populations changing. The hyperspectral imagery analysis does map the habitat boundaries and does allow some species type differentiation so it could provide a mapping of some of these changes over time if the average CO_2 soil concentrations start rising to levels like those observed at Mammoth Mountain. However, the lowest levels of CO_2 soil concentration that would begin to affect plant health, or the shape and types of local ecologies or habitats are not known. The effects of time dependent and spatially dependent CO_2 effluent variations on the plants are also not known.

The hyperspectral geobotanical remote sensing techniques that we are developing use advanced commercial airborne imaging spectrometer systems now available in the USA and worldwide. The sensor system we normally contract for in our overhead imaging missions produces visible and near IR reflected light images with spatial resolution of 1–3 m in 128 wavelength bands (see http://www.hyvista.com/).

The HyVista sensor spatial and wavelength imagery resolution and signal-to-noise ratio of over 1000 to 1 allows us to detect and discriminate individual species of plants as well as the complexities of the geological and man-made objects in the images. The imagery is of sufficient quality that subtle local plant ecologies can be discriminate in verifiable detail.

EXPERIMENTAL/STUDY METHODOLOGY

The experimental method we have used is summarized in the following series of sequentially executed steps:

(1) Determine the area above the formation to be monitored including some surrounding areas that are thought to be outside the influence of any CO_2 that might migrate to the surface.
(2) Work with the airborne hyperspectral image acquisition contractor to develop a set of flightlines along which the images will be acquired (Figure 6).
(3) If possible make a group trip to the area to start to become familiar with the special characteristics of the region at the time planned for the airborne overhead image acquisition. Using hand-held DGPS and digital cameras visually record the soils, plants, minerals, waters, and man-made objects in the area.
(4) Remain on location to be available to the pilots and image sensor operator while the imagery is being acquired. This is usually 1 day between 10:00 and 14:00. But it can be 2 days. We normally all meet at the aircraft before and after the day's flight to go over the plans and check results.
(5) After the acquisition is completed our team reviews the imagery and georectification at the plane or in a motel. Our acquisition contractor then sends it to their main facility for final post-processing.

The set of all flightline images is returned on DVDs as three products; raw, corrected to reflectance including atmospheric absorptions, and georectification control files. This usually takes less than a few weeks. The imagery on the DVDs is analyzed using the ENVI commercial computer software on Windows and/or Unix platforms, by our researchers at UCSC, LLNL, and HyVista Corp., working as a team. ENVI is considered as the standard for the hyperspectral image analysis community worldwide.

The algorithms in the ENVI program are used to produce classification regions in the imagery that correspond to plant species types, plant health within species types, soil types, soil conditions, water bodies,

Figure 6: Morning preparations of the B 300 Twin Otter aircraft rented by HyVista. The LLNL UCSC team meets with the HyVista team while they are preparing the HyMap sensor, the georectification system, and computer system for the hyperspectral image acquisition. Note the clear skies, which is ideal.

water contents such as algae or sediments, mineralogy of exposed formations, and man-made objects such as roads, buildings, playgrounds, golf courses, etc. Some of the classification regions are distinct "ecologies". The classification regions derived from the imagery analysis are then studied to look for species of plants where they would normally not be found, relative plant health patterns, altered mineral distributions, soil type distributions, soil moisture distributions, water and water contents, and other categories.

We then return to the field with our analysis to verify and further understand the complex classification regions produced. Based on the verification results the analysis can be "fine-tuned" in the field to produce more accurate results. Since the imagery is georectified and the pixel size is 3 m individual objects such as trees, outcropping minerals, jeep trails, well heads, and pads can all be located using the maps and a hand-held GPS. The verified maps are extremely accurate. We also use a backpackable field spectroradiometer to measure reflectance spectra from a large number of plants, soils, and minerals. Figure 7 shows the backpackable ASD spectroradiometer being used at Rangely during our second field trip in August 2003. The spectrometer itself is in the backpack. The computer that controls the spectrometer and displays the acquired spectra is in a front pack sling. The pistol grip lens is connected to the spectrometer by a fiber optic cable.

The classification regions derived from the analysis of the imagery are a snapshot of the conditions at the time of acquisition. They show any areas of existing anomalous conditions such as plant kills and linear species modifications caused by hidden faults. They are also the "baseline" that is used to chart any future changes that are not due simply to normal seasonal and weather variations. This is accomplished by reimaging the area routinely over the years to monitor and document any effects that would be caused by significant CO_2 leakage reaching the surface and near subsurface defined by the root depth of the local plants.

The sensor used for the image acquisition at Rangely, CO is the HyMap™ hyperspectral scanner manufactured by Integrated Spectronics Pty Ltd (Figures 8–9). The HyMap sensor provides 126 bands

Figure 7: Using the ASD field spectroradiometer to measure reflectance spectra at Rangely in August 2003. The spectrometer is in the backpack. The computer that controls the spectrometer and displays the acquired spectra is in a front pack sling. The pistol grip lens is connected to the spectrometer by a fiber optic cable.

across the reflective solar wavelength region of 0.45–2.5 nm with contiguous spectral coverage (except in the atmospheric water vapor bands) and bandwidths between 15 and 20 nm.

The sensor operates on a 3-axis gyro-stabilized "IMU" platform to minimize image distortion due to aircraft motion. The HyMap sensor provides a signal-to-noise ratio ($>$500:1). Laboratory calibration and then daily operational system monitoring is done by HyVista to ensure that the calibration of the imagery is stable which is required for our very demanding spectral mapping tasks. Geolocation and image geocoding is achieved with an-on board differential GPS (DGPS) and an integrated IMU (inertial monitoring unit). Typically the HyMap sensor is operated with an angular field of view (IFOV) of 2.5 mr along track, 2.0 mr across track, FOV of 61.3° (512 pixels), DGPS and an integrated IMU, GIFOV—3–10 m (typical operational range). The DGPS and IMU is fully integrated with the image acquisition. The latitude and longitude of each pixel is recorded along with the hyperspectral image. Experiments to date indicate that the accuracy of this method is about one or two pixels over flat ground. The fact that the imagery and/or analysis results can be georectified at any time allows analysis of the data in any series of complex steps, without having the georectification process to influence the results. Then the georectification process can be applied to convert the final product to a highly accurate georectified form that can be verified and studied in the field.

Figure 8: The hyperspectral sensor is shown in the aircraft used by our acquisition contractor for image acquisitions.

The georectification subroutine is built into the ENVI software. It uses the georectification data files (IGM files) recorded in the airplane.

The sensor characteristics and a discussion of overhead hyperspectral imagery acquisition can be found at the web site of our imagery acquisition contractor http://www.hyvista.com/ and at http://www.intspec.com/.

RESULTS AND DISCUSSION

Many analysis of the August 2002 Rangely hyperspectral imagery have been done using ENVI. The analysis results have been combined with the photos, topographic maps, and digital elevation models of the Rangely oil field, town and surrounding areas. All of the products are georectifiable using the GLT files provided by HyVista as part of the imagery, as explained in the experimental section of this report. The accuracy of the precision of the georectification is about two pixels or 6 m. The accuracy is also about 6 m on flat ground. We made a second field trip to Rangely in August 2003 with all our analysis results. The complex and highly detailed classification region patterns that emerged from the analysis were easily verified because of the accuracy of the georectification. The ENVI "SAM" analysis picked out classification regions that were verified to be "habitats" or local ecologies. The perimeter of these habitats was mapped using a hand-held DGPS and recording a "waypoint" every few meters. The downloaded waypoint list from the hand-held DGPS was then compared to the pattern of the perimeter of the classification region identified as the habitat area. The two agreed in all the details, to within about 3 m.

The Field Site

The White River Basin is shown running from the center right to the lower left corner (Figure 10). The Rangely oil field basin is in the center of the figure. The 18 flightlines that were flown to acquire the 18 strip images are shown as dark lines. They are exactly due north and south by design. The folded formations whose motion created the oil field are easily seen running from southeast to northwest on either side of the basin and east–west across the top. Mellen Hill and the Mellen Hill fault can be easily seen at the northwest end of the oil field basin.

Figure 9: The acquisition contractor's sensor operator and flight commander. He is shown with the onboard computer system that controls the sensor systems and records the image, and the exact geolocation of each pixel in the image as it is acquired.

The individual flightlines are all georectified and are mosiaced together to produce an image of the whole region (Figure 11). All of the imagery shown in this report is georectified and true north is straight up on the page.

We have analyzed all the flightlines for the level of "plantness" with an "NDVI" ratio formula that uses individual bands in the hyperspectral image. The result is a computed ratio formula image that is normally called the "NDVI" or "Vegetation Index" image. The NDVI numerical value is high for lush green plant life and low for soils or man-made objects.

The NDVI images of each flightline were mosiaced together to produce the composite NDVI image of the whole region. The resulting NDVI image is shown in Figure 12 as a grayscale image. It can be presented as a pseudocolor image just as easily, but the grayscale image shows the results in a more understandable way. The brighter, or whiter, that a pixel appears, the more "healthy plant like" the contents of the pixel are. This means that the brighter the pixel in the image is, the bigger percentage of the pixel area is healthy vegetation and the healthier the plants. So the brightness of the pixel is a combination of the percentage of plant area coverage and the distribution of levels of health of the plants within the pixel. Understanding the causes

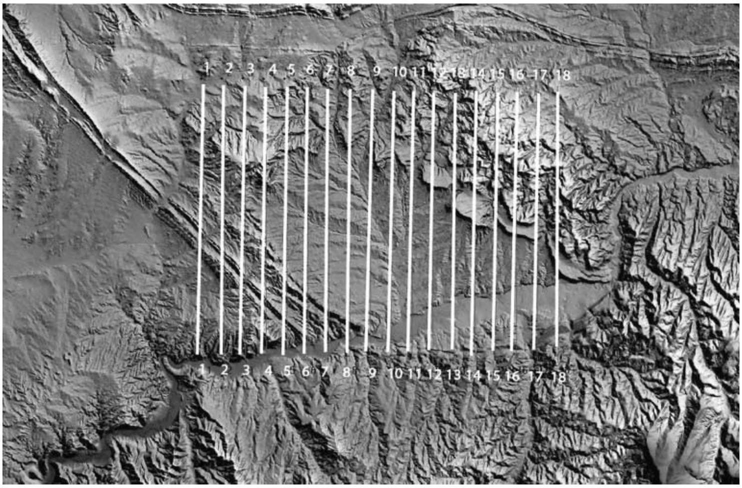

Figure 10: This is a digital elevation model of the Rangely oil field basin and surrounding formations with flightlines.

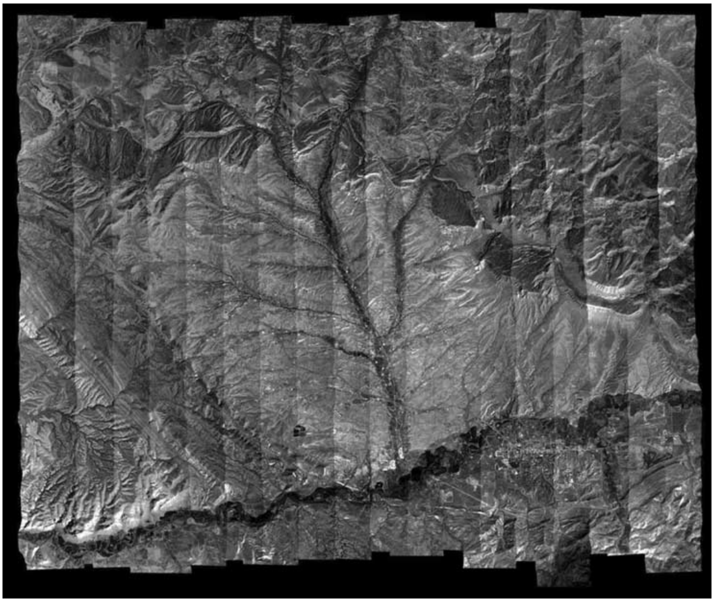

Figure 11: All the flightlines used to make a "true color" RGB image of the whole Rangely oil field basin, the surrounding formations and the town of Rangely.

of variation in the NDVI image is critical in this arid high desert environment, with its sparse vegetation. In general most plants are somewhat smaller than the 3 m pixel size of the Rangely imagery. In between the sparse plants the spectra from the low grasses that may be seasonally dry or bare soil will mix with the plant spectra. A very healthy plant smaller than 3 m surrounded by dirt will have some intermediate NDVI value.

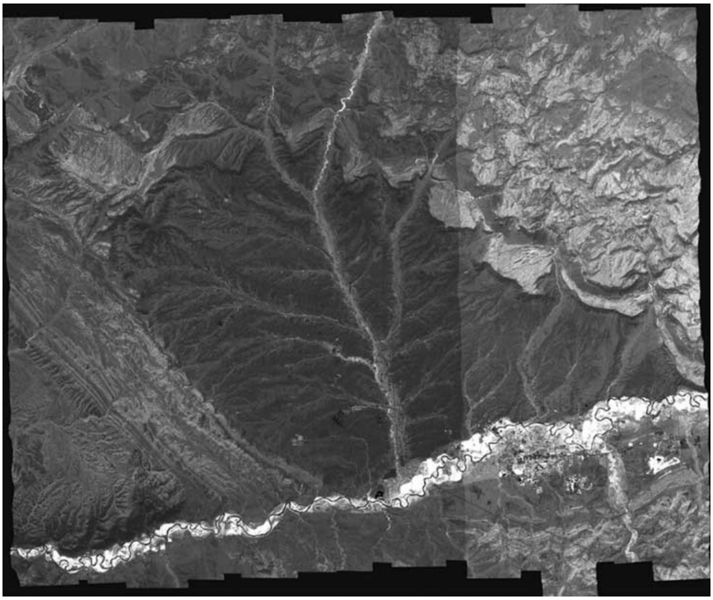

Figure 12: All the flightlines images converted to NDVI images and mosiaced. This is a gray scale image. The whiteness or brightness of each image pixel means both that there is a higher percentage of plant coverage in the pixel area and/or that the plants are exposing more chlorophyll in their leaves and stems.

It is a mistake to use an intermediate NDVI value to say that there are no healthy plants in that pixel. Users interpreting geobotanical features from an NDVI remote sensing analysis unfortunately often make this kind of mistake. An additional mistake can easily be made using the NDVI for mapping plant health in high desert regions even when there is 100% of a pixel covered by vegetation. Some plants in these regions can look desiccated and brown on the outside while they are perfectly healthy on the inside. They are just waiting for water, or they are in their seasonal cycles. With all those cautions we still can make important use of this NDVI mapping of the Rangely region for CO_2 leak detection and baselining.

The NDVI map shows the exact location of almost every live plant in the entire region on the acquisition day. We can infer that there is less percentage of plant coverage in the darker pixels. Darker pixels may also, however, have reasonable percentage of plant coverage, but the plants may appear highly desiccated or woody on the outside. Or both may be true. This can be resolved, for a particular location, by additional hyperspectral image analysis or by simply driving to the exact location using a DGPS and observing what the plant coverage and health are.

The NDVI analysis then does provide an important map for locating exact places for further study. In addition, it does show the very complex patterns of plant coverage/health. It provides a very good baseline snapshot of the geobotanical conditions in the field. If a CO_2 leak of significant magnitude did develop, it is likely to darken the NDVI pixels in the area where the soil CO_2 concentration has risen significantly, either because of decreasing plant percentage coverage or decreasing plant health or both. Judging from the tree kill areas at Mammoth Mountain, both would occur.

By inspecting the NDVI composite image in Figure 12, we see that the oil field basin appears generally dark. The basin does have relatively low percentage plant coverage in most open flat areas, and the plants also appear woody or desiccated. Most of the plants in the basin are in fact perfectly healthy; they are just well adapted to their environment. In the arroyos, streambeds and drainage patterns there is a significantly higher percentage of vegetation coverage, and many different types of species that appear less woody and have more green showing. These areas in the basin are brighter in the NDVI image. The surrounding areas that are higher in altitude have much higher vegetation coverage and species that are very much greener. These areas are also much brighter in the NDVI. The White River Basin that runs across the bottom of the image has very high plant coverage and it is lush green. These areas are the brightest of all in the NDVI. The town of Rangely that is just south of the White River has many lush green areas such as the golf course which is the very bright object in the lower right corner.

The NDVI mosaic shown in Figure 12 clearly shows the difference in the plant health before and after the first rainstorm of the season. The flightlines on the left, numbers 1 – 12 were acquired on Tuesday. Then it rained for the first time in the summer on Wednesday and Thursday. Then the flightlines on the right, numbers 12–18, were acquired on Friday, which was a clear day. The flightline number 12 was reacquired to provide a direct comparison of before and after rain on the plants in the same flightline. The two flightlines 12A and 12B are shown in Figure 13.

The NDVI produced from flightline 12A acquired before the rain storms is shown in Figure 13. The NDVI produced from flightline 12B is shown on the right. In studying this carefully we find that most pixels are brighter, or whiter, in 12B. This is what we expect if the rain did trigger the high desert plants into increased photosynthetic activity. There are some pixels in 12B that remain as dark as the same pixel in 12A. These are probably pixels with only soils or man-made objects in them. When we were on our second field trip at Rangely we noted that most areas had vegetation cover. The rain probably activated many of these high desert species. This hypothesis is in agreement with the widespread elevation of the NDVI values between 12A and 12B throughout most of the area imaged.

The arroyos and washes in the basin and the junipers on top of the surrounding higher elevations seemed to have brightened the most, as you would expect. Also it appears that the complex pattern of vegetation distribution has not changed, only the relative observable photosynthetic activity. This is a very important observation. The plants have not had time in 2 days of rain to change their habitat distributions. This comparative NDVI mapping shows that clearly. This shows that we have a reasonably correct view of the overall response of plants and habitats to natural environmental variations and understand the time scales involved. That increases our chances of being able to detect and discriminate CO_2 soil concentration induced anomalous habitat distribution changes at an early stage. It also shows the power of having repeat imaging of the area to be monitored. Imaging seasonal and weather-induced variations may be very powerful for the early detection of elevated soil CO_2 concentration effects on the plants and habitats.

This area shown in the photo in Figure 14 is located at about the top three quarters mark in flightline 3 image shown in Figure 15. Examples of detailed mapping in the oil field using the hyperspectral image analysis are presented in the following sections and include the area in the photograph. The well pads, roads, vegetation, vegetation patterns or habitats and various soils can be seen in the photo and the classified regions in the flightline image.

Figure 15 is an unsupervised classification of flightline 3 done using ENVI. In this analysis, an algorithm separates the pixels in the image into some number of groups, in this case 35 groups. Individual pixels are grouped so that the complete spectral signatures and brightness are most similar for the pixels in each group. This process is what you would do if asked to sort a pile of multicolored “Indian corn” kernels into smaller piles where the kernels in the new piles were most like each other in size, colors, and patterns. As you went through the process you would create more and more separate piles. Then if you wanted to limit the number of piles you would be forced to recombine piles. In recombining two piles you might decide to resort the piles along with several other piles to reduce the overall number of piles. This could iterate for a long time so at some point we would call halt to the process unless you had decided that the piles were not changing much between iterations. This is exactly what the unsupervised classification algorithm does using the brightness and spectral shapes in each pixel. This process is “blind” in that there is absolutely no information about what is causing the brightness or spectral shape in the pixels involved. This is always a wise step to take at the beginning of analyzing imagery of a new area, because it alerts you to the complexities of the region. This result is georectified as are all the analysis products after they are created. Therefore, it can be used as a very effective tool to sort out different types of soils, plants, etc. during

Figure 13: NDVI line 12A left, 12B right.

a subsequent field trip to the site. Unfortunately, this method of classification is very sensitive to the overall brightness of the pixel. We used this type of analysis initially to tell us the quality of image data that had been acquired. As can be seen in the figure shown on the left the large number of categories and the complexity of the patterns indicate that the imagery is extremely information rich.

The two images on the right are the analysis of flightline 3 using the ENVI minimum noise fraction (MNF) procedure. In this procedure the original 128 bands of spectral information in each pixel are transformed

Figure 14: View of the Rangely oil field south of Mellen Hill.

into a new smaller set of objects that are referred to as MNF "pseudo-bands". They are not spectra any more, but they are "pseudo-bands" that contain the most noise free information that was in the original hyperspectral image. MNF "pseudo-bands" 1,2,3 are presented as RGB in the center image. MNF pseudo-bands 4,5,6 are presented on the far right. This step in the ENVI "hourglass" procedure shows that there is a very large and detailed amount of information contained in the hyperspectral image. The MNF results were not the final step.

We continued on to do a Spectral Angle Mapper (SAM) analysis that is shown in Figure 16.

The ENIV "hourglass" set of algorithms that ends with a SAM analysis is the method that is the most able to detect and discriminate plant habitats or ecology types, soils, mineralization, water conditions, and man-made objects. Figure 16 provides an example of the result of using this process on the flightline 11 hyperspectral imagery. Fifty-eight different categories were found. Many categories were tentatively identified using the USGS mineral spectral library, which we found to be a reasonable guide to what we actually found when we visited the locations of the categories during the second field trip taken in August 2003. The unknown categories were found to be mixed vegetation "habitats" upon on-site inspection in the field with these analysis products.

There is a "True" color image made from flightline 11 bands 15,9,2 as RGB on left of Figure 16. Note the difference between a color "picture" on the left and the SAM analysis for mixed vegetation "habitats", soils, and water on the right. This process was repeated for all the flightlines.

The ENVI SAM analysis has picked out classification regions that are a finely detailed mapping of local ecologies or "habitats". Some of these habitats are found to extend across the entire Rangely oil field and into the surrounding areas. These ecologies are made up of a narrow range of percentage admixtures of two or three very specific plant types and soil types.

The products are all georectified and so we were able to drive to the exact locations that were being picked out by the analysis and visually inspect them. We were able to walk back and forth between adjacent areas

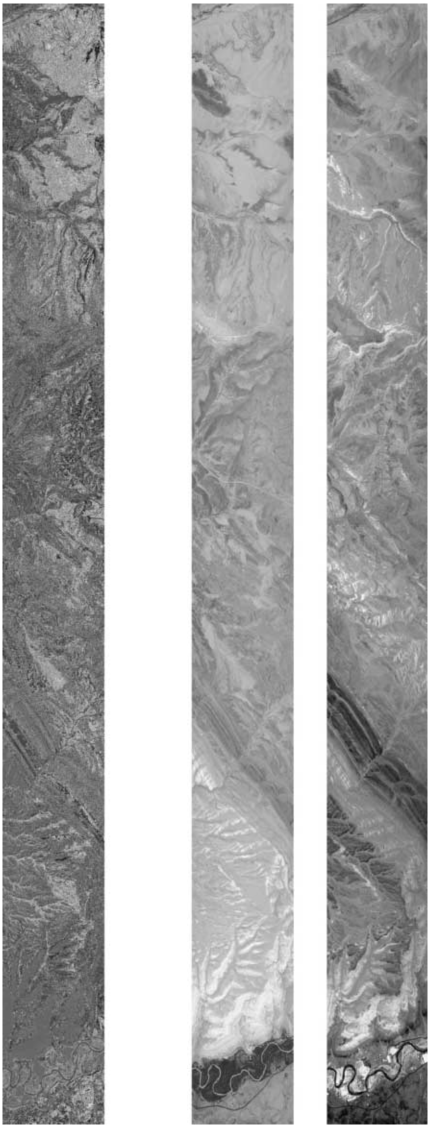

Figure 15: Unsupervised minimum noise fraction (MNF).

that were being picked out by the analysis. The computer analysis was sorting out regions based on the relative mixture of plant types, plant sizes, plant spacings, intervening ground cover such as grass types and soils. Within these regions things like roads, paths, animal trails, man-made objects such as oil well pad areas, tanks, buildings are all also apparent and are picked out separately by the algorithm.

The area where we discovered that our analysis was picking out habitats is in the flightline 3 image. The SAM analysis of flightline 3 is shown on the right-hand side of Figure 17. The SAM analysis categories shown in light blue and in green were found to be two distinct mixed vegetation "habitats" surrounded

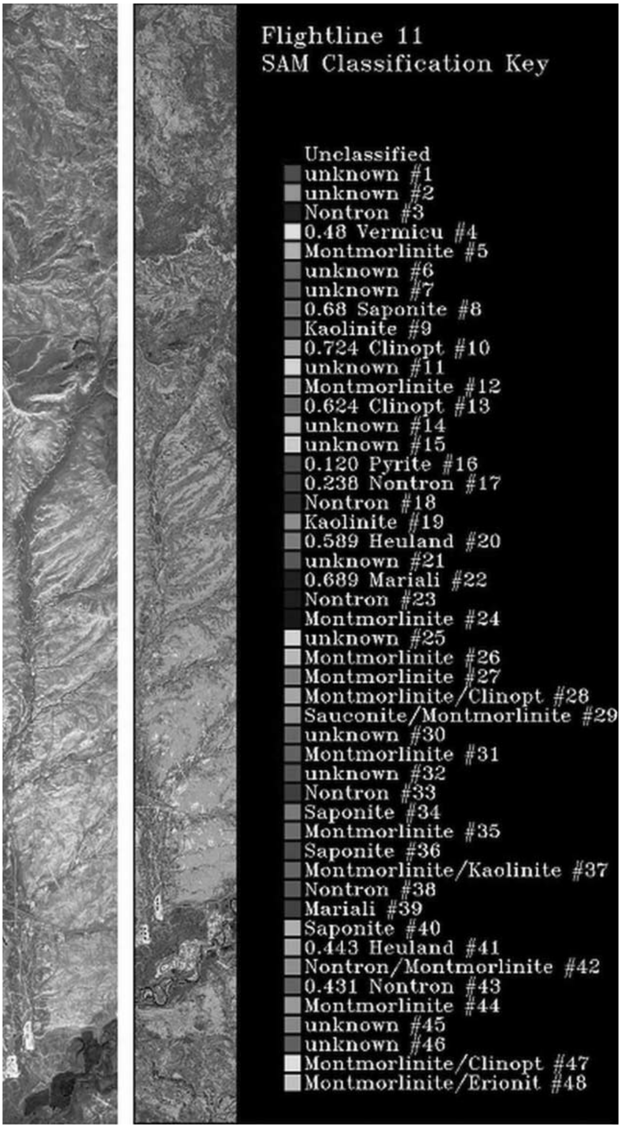

Figure 16: Detailed habitat mapping that results from an ENVI "hourglass" process. This process ended with a Spectral Angle Mapper (SAM) analysis of flightline 11 that is shown in the center. On the left is a "true color" RGB image of flightline 11.

by a third distinct habitat when we went back into the field at Rangely with these analysis products. The habitats consist of healthy sagebrush, mixed with golden dry cheek grass, and a percentage of dry soils. We found these two habitats were all over the Rangely region once we learned to recognize them from the SAM analysis. This result was unexpected and is a powerful means of mapping subtle meso-ecologies or "habitats" with mixed vegetation and soils.

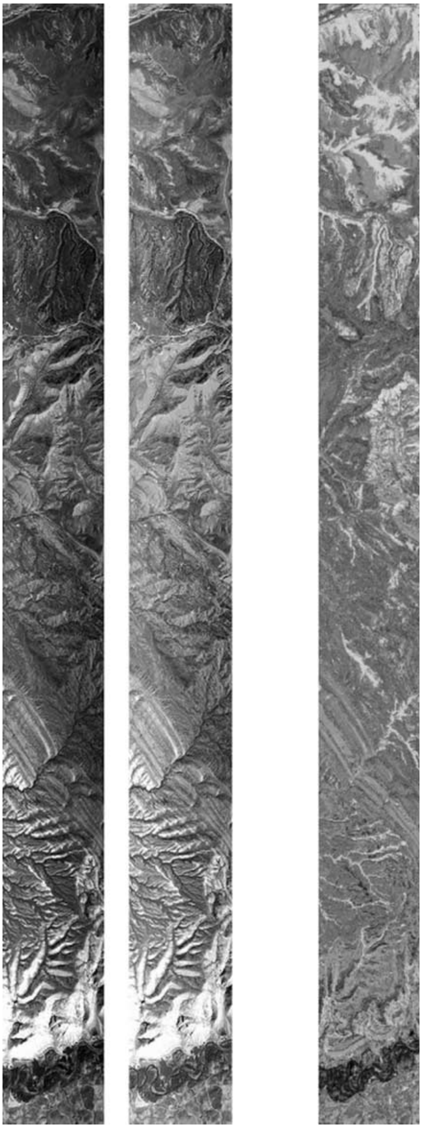

Figure 17: Habitat mapping using flightline 3 hyperspectral image. True color (15,9,2 RGB) on right, infrared is in center, SAM habitats on the right.

The other images shown in Figure 16 are a "true color" of flightline 3 made with bands 15,2,9 as RGB on the left. In the center is a different 3-band image used to produce the equivalent of an infrared photograph, called a "color infrared". Then an analysis that maps the mineral Montmorillonite and Kaolinite in soil mixtures, shown in yellow–orange, has been laid on top. The lush green vegetation that is found primarily near the White River appears in red near the bottom of the image. Healthy vegetation reflects very strongly in the near infrared and so it appears very bright.

The “color infrared” image is made from the hyperspectral image using the bands 27, 16, and 7 as red, green, and blue, respectively.

Figure 18 is an enlarged view of the SAM analysis for the top of flightline 3 showing two of the habitats discovered by using the imagery analysis to guide us in the field. Light blue was found to be healthy sagebrush, mixed with golden dry cheek grass, and almost zero percentage of dry soils. Dark green was found to be smaller sagebrush plants mixed with cheek grass but with dry soil showing over about 50% of the area between the sagebrush plants. We walked the edges of some of these areas with DGPS and found the mapping to be accurate to 1 or 2 pixels. We speculate that any CO_2 leakage would begin to affect the

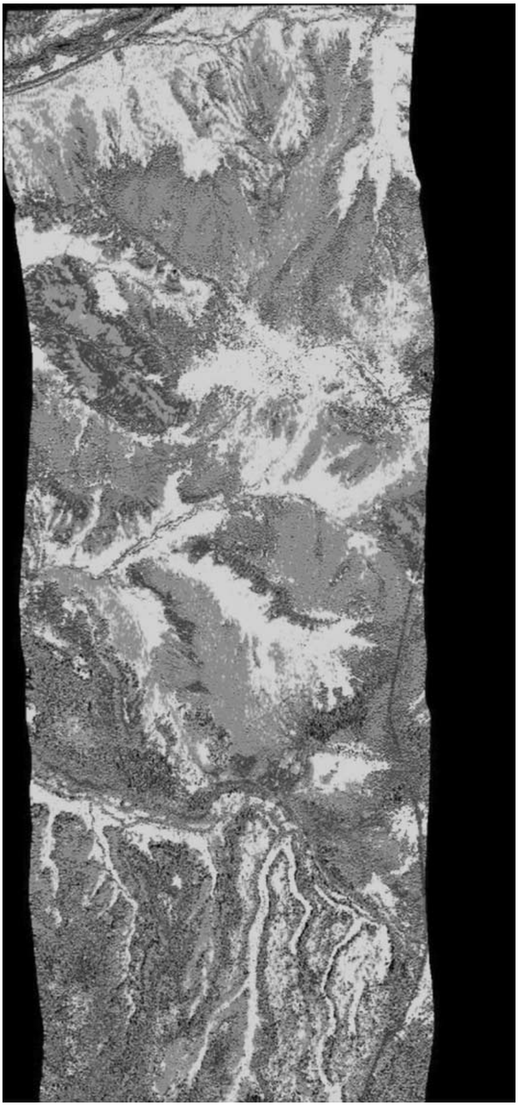

Figure 18: Close-up of line 3 SAM analysis showing the newly discovered habitats.

shape of these habitats and hence be easily seen in subsequent reimaging as a change. Of course that would only target the changed area and map it so that a team could go to that spot and check for excessive CO_2. This would also target a place to put CO_2 sensors.

Photos of these two habitats are shown in Figures 21 and 22. The top two photos in Figure 21 are of the habitat mapped by the light blue SAM category in Figure 18. The bottom photo is of the habitat mapped by the green category in the SAM analysis. The location of this habitat area is shown in Figures 19 and 20 by the DGPS waypoints shown as dots. The DGPS was left on all day each day in the SUV and recorded the "trip" (Figure 19). Figure 22 shows taking reflectance spectra of a plant using the ASD field spectrometer at the southern boundary between these two habitats (Figure 23).

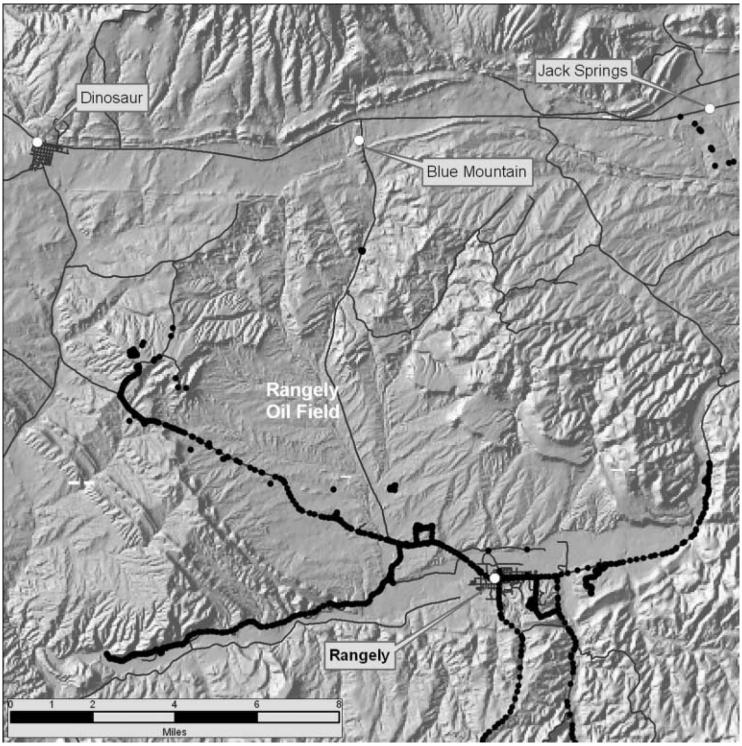

Figure 19: Continuous recording of our hand-held DGPS "track" during 1 day of the July 2003 field trip showing the sites visited that lead to the creation of the "habitat" mapping concept.

The match between the DGPS waypoints (dots) collected by walking the perimeter of the habitat shown in the top half of Figure 20 and the 1990 airphoto is remarkably accurate just as it is with the SAM analysis of the hyperspectral image. The exception is the area shown in the upper left. Apparently the habitat has been stable over the 23 years, except that junipers have intruded into the area along the two roads to the northwest just outside the boundary observed in July 2003. The area outside the red dot DGPS boundary to the lower left is the other habitat shown in the lower half of Figure 20. The circular pattern in the lower left is a well pad. Photos of the habitat outside or at the edge between the habitats are shown in Figures 24 and 25.

By carefully selecting ENVI SAM "endmembers", four of the most obvious "habitats" or ecologies, were mapped in all the flightlines imaged at Rangely. These ecologies are discernable and mappable even though

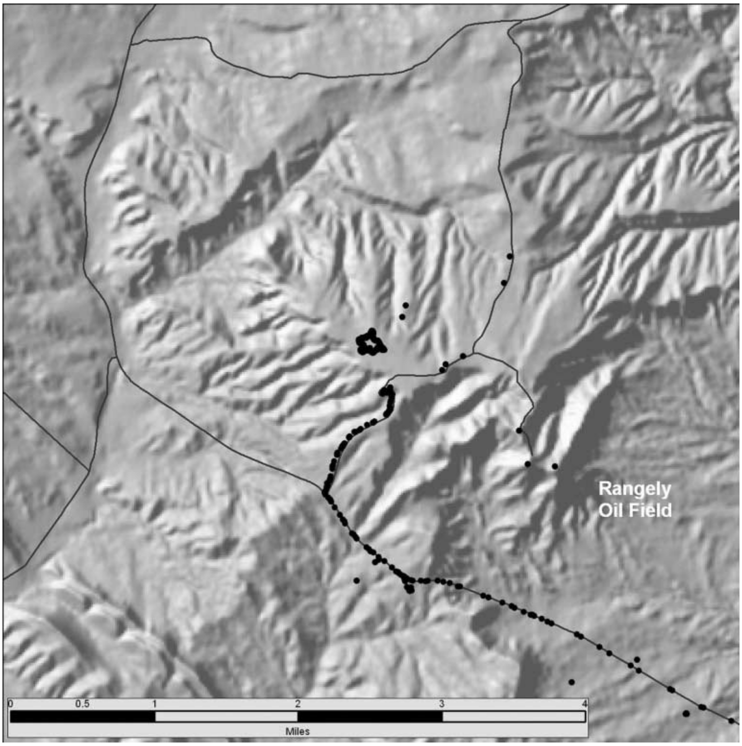

Figure 20: Close-up view of the location of the area where we discovered that the SAM analysis was mapping “habitats”. The DGPS waypoints acquired while walking the habitat picked by the SAM analysis of the line 3 hyperspectral image are shown as the group of dots at the top center. The other dots on the roads to the northeast (upper right) were places mapped by the SAM analysis as the same habitat types. We drove to these sites guided by our georectified SAM imagery analysis and found they were indeed the same type of habitats. Once we became educated about we began to recognize these habitats.

the eastern 1/3 of the flightlines that were acquired on Friday after the heavy rains on Wednesday and Thursday. This leads us to believe that we are indeed mapping ecologies that are independent of detailed weather conditions by using this SAM analysis. Figure 26 shows the four ecologies in four different colors. The black pixels are all other categories. The mapping is accurate to the individual pixel (3 m in size) level throughout all 18 flightlines of the entire Rangely region, including the imaging on the western side before and imaging on the eastern side after the first seasonal rainstorm.

This research has demonstrated ability to do regional scale meso-ecology mapping from the hyperspectral imagery. It also establishes the basis for further progress in the refinement of these methods. The serendipitous rainfall that occurred during the data collection period provided the opportunity to observe short-term changes in the vegetation hyperspectral images. Observing deviations from these normal patterns will allow targeting of specific locations for making on-the-ground measures to detect CO_2 releases.

A new very high-resolution commercial satellite called QuickBird is now being operated by the Digital Globe Corp. The panchromatic imagery has a resolution of 0.6 m, and for the band multispectral

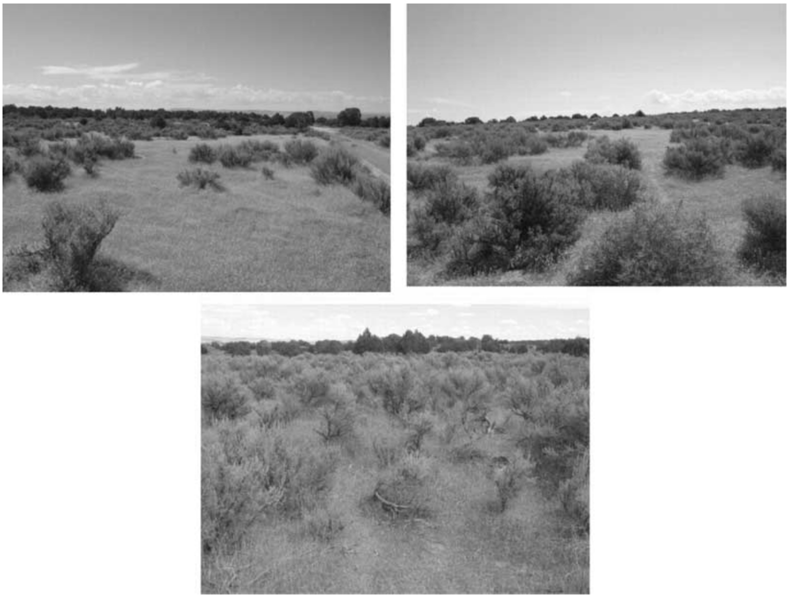

Figure 21: The two adjacent habitats discovered by using the line 3 SAM analysis categories.

Figure 22: Measuring reflectance spectra of a plant at the border between two habitats. Notice the well pad.

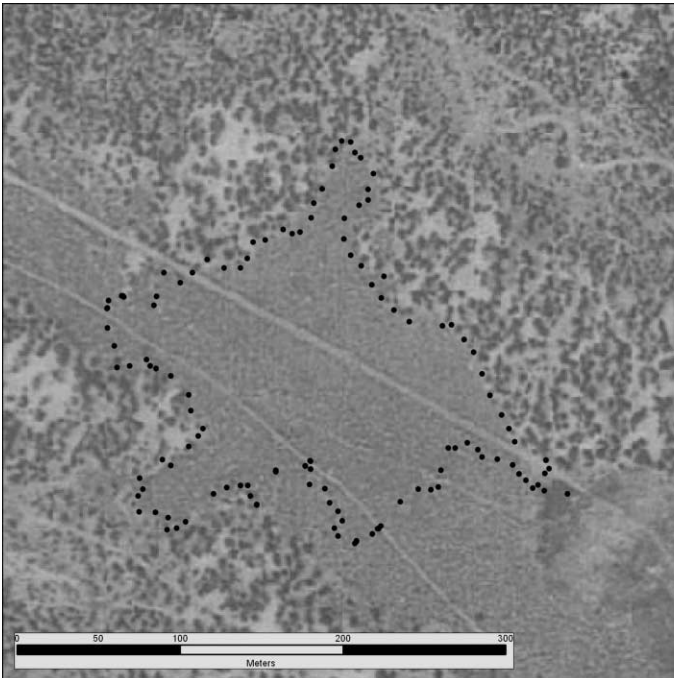

Figure 23: The dots are DGPS waypoints collected by walking the perimeter of the habitat shown in the top half of Figure 20. The DGPS points are shown overlaid on the 1990 airphoto.

Figure 24: Northern boundary of habitat and the next habitat of Junipers. The edge is accurately mapped by SAM analysis and the DGPS waypoints (dots).

Figure 25: Close-up of the northern boundary between habitats. This is the top if the “finger” in the top of the DGPS waypoints (dots) shown in Figure 23.

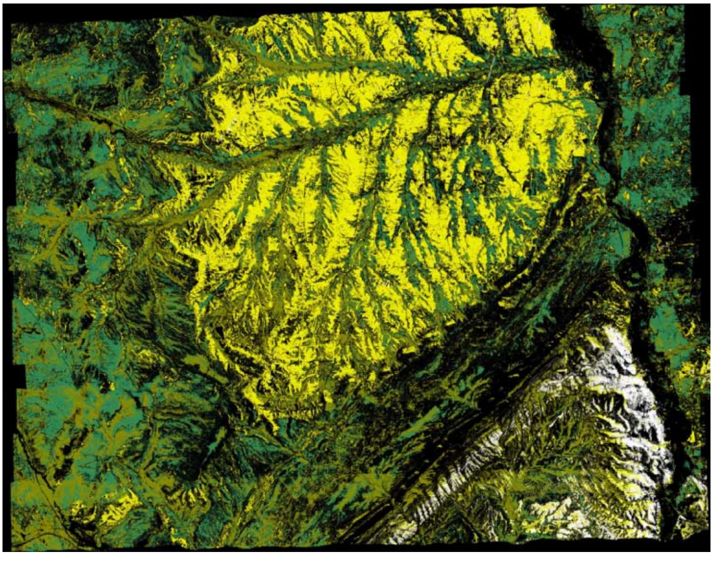

Figure 26: Three distinct habitats (yellow, green, and brown) and a soil type (white) mapped across the entire Rangely region.

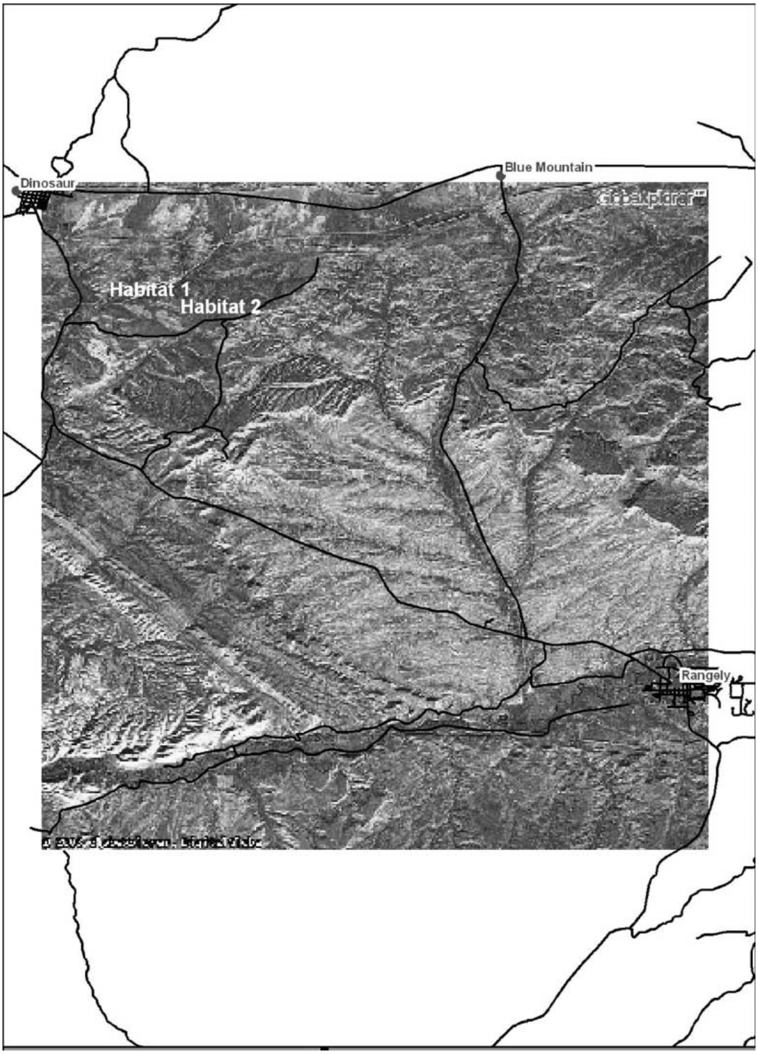

Figure 27: Airphoto image of Rangely with GIS information overlaid.

imagery spatial resolution is 2.4 m. Quick Bird has not yet imaged Rangely, CO. Estimated costs for this would be $4000. Figure 27 shows what a QuickBird multispectral image of the Rangely oil field and surrounding areas would look like. This imagery is an orthorectified airphoto. The town and roads are shown. The areas that established the habitat mapping results are labeled Habitat 1 and Habitat 2 in the upper left.

CONCLUSIONS/RECOMMENDATIONS

In conclusion, we have found an unexpected result that is potentially very important to the task of monitoring for CO_2 that has leaked to within the plant root depths near the surface. The discovery is that one of our analysis techniques has picked out finely detailed mapping of local ecologies that extend across the entire Rangely oil field and surrounding areas. These ecologies appear to be made up of a fairly narrow range of percentage admixtures of two or three very specific plant types and soil types. The products are all georectified and so we were able to drive to the exact locations that were being picked out by the analysis and visually inspect them. We were able to examine adjacent areas in detail that were being picked out by the analysis. The computer analysis was sorting out regions based on the relative mixture of plant types, plant sizes, plant spacings, intervening ground cover such as grass types and soils. Within these regions, things like roads, paths, animal trails, man-made objects such as oil well pad areas, tanks, buildings, town, golf courses, are all also apparent and are picked out separately by the algorithm.

The results show georectified, detail and complexity in the mapping of ecologies, soil types, plant types, plant health, water conditions, and human use features. This work does provide a "snap shot" of the ecological complexity of the entire area as of August 2002. Interestingly, we found that the August 2002 imagery analysis seemed to be completely valid in August 2003 during our return field trip. We have not found any evidence in the imagery analysis or anywhere on the ground, during our field trips in August 2002 and 2003 of any plant life responses that might indicate CO_2 leakage from the formation below. In fact, detailed analysis and observations of areas where elevated CO_2 and methane fluxes had been observed provided no indication of any effect on the soils or vegetation.

We strongly recommend a long-term research effort that will establish what CO_2 soil concentration levels produce observable changes in the biosphere and the corresponding subtle and complex ecological distributions in various environments (including terrestrial and marine). This is an extremely important and highly relevant task for CCP SMV to pursue. The biosphere is always integrating, and responding to and creating changes. We are well advised to learn to read and understand all the subtle signs it is providing to us, continuously.

We also recommend trying to measure directly CO_2 and CH_4 gas concentrations in the air using airborne hyperspectral imagers. We recommend using infrared hyperspectral imaging spectrometer sensors that have enough wavelength resolution to measure the CO_2 and CH_4 absorption resonances in the infrared that are due to rotational, stretch, and vibrational molecular absorption mechanisms. The sensors will have to be able to distinguish the CO_2 and CH_4 resonances from other resonances caused by molecules that are likely to be present. The sensitivity will have to be great enough to measure normal background concentrations in air, so that anomalies can be detected.

We also recommend starting a program to develop inexpensive, nanotechnology sensor to detect CO_2 and CH_4 concentrations in soils and at the surface. New sensors that are unpowered autonomous and read out by pulsed rf or optical interrogation during a fly over could be placed along faults, near well head, and at any features thought to possible venting paths. These would be permanently installed and readout at whatever interval was required.

NOMENCLATURE

FOV	field of view
GPS	global positioning system
DGPS	differential GPS using the two GPS designated satellites for reference
IMU	inertial monitoring unit
GIFOV	ground field of view nominal
mr	milliradians of angular view
LLNL	Lawrence Livermore National Laboratory
UCSC	University of California Santa Cruz
EOR	enhanced oil recovery (field)
CO_2	carbon dioxide

REFERENCES

1. W.L. Pickles, G.D. Nash, W.M. Calvin, B.A. Martini, P.A. Cocks, T. Kenedy-Bowdoin, R.B. Mac Knight IV, E.A. Silver, D.C. Potts, W. Foxall, P. Kasameyer, Geobotanical Remote Sensing Applied to Targeting New Geothermal Resource Locations in the US Basin and Range with a focus on Dixie Meadows NV, Geothermal Resources Council Transactions, vol. 27, October 12–15, 2003, Geothermal Resources Council, Davis, California, USA, UCRL-JC-153443.
2. B.A. Martini, E.A. Silver, W.L. Pickles, P.A. Cocks, Hyperspectral Mineral Mapping in Support of Geothermal Exploration: Examples from Long Caldera, CA and Dixie Valley, NV, USA, Geothermal Resources Council Transactions, vol. 27, October 12–15, 2003, Geothermal Resources Council, Davis, California, USA.
3. B.A. Martini, New insights into the structural, hydrothermal, and biological systems of long valley Caldera using hyperspectral imaging, a dissertation submitted in partial satisfaction of the requirements for the Degree of Doctor of Philosophy in earth sciences, UC Santa Cruz, December 2002, http://eed.llnl.gov/other/martini/.
4. B.A. Martini, Thesis Chapter 3 and 4 are found at: Hyperspectral imaging in long valley Caldera: volcano-associated biological communities, http://eed.llnl.gov/other/martini/chapter3.pdf, http://eed.llnl.gov/other/martini/Ch3_Figures.pdf.
5. Hyperspectral imaging in Long Valley Caldera: tracking volcanogenic CO_2 and its lethal effects, http://eed.llnl.gov/other/martini/chapter4.pdf, http://eed.llnl.gov/other/martini/Ch4_Figures.pdf.
6. K.A. McGee, T.M. Gerlach, Annual cycle of magmatic CO_2 at Mammoth Mountain, California: implications for soil acidification, *Geology* **26** (1998) 463–466.
7. J.D. Rogie, D.M. Kerrick, M.L. Sovey, G. Chiodini, Measurement and Analysis of Diffuse Degassing of Magmatic CO_2 at Mammoth Mountain, California, 1997–2000, Eos Trans. AGU, 81 (48), Fall Meet. Suppl., Abstract V72D-12, 2000.
8. J.D. Rogie, D.M. Kerrick, M.L. Sovey, G. Chiodini, D.L. Galloway, Dynamics of carbon dioxide emission at Mammoth Mountain, California, *Earth Planet. Sci. Lett.* **188** (2001) 535–541.