Project Title: An Unmanned Aerial System of Visible Light, Infrared, and Hyperspectral Cameras with Novel Signal Processing and Data Analytics

(Performance Period: September 30, 2019 - September 30, 2022)

Missouri S&T

Missouri University of Science and Technology

Contract #693JK31950005CAAP

PI: Dr. Genda Chen

Students: Pengfei Ma and Ying Zhuo

Sponsors & Team Members

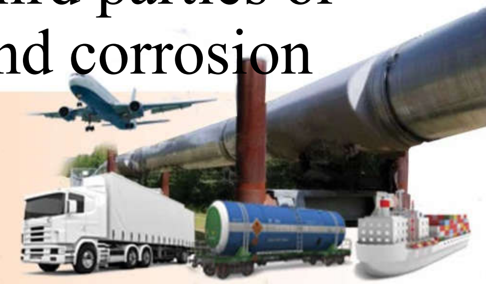
- Sponsors
  - Pipeline and Hazardous Materials Safety Administration (PHMSA)
- PI: Dr. Genda Chen (gchen@mst.edu)
- Team Members
  - Pengfei Ma (pm7m8@mst.edu)
  - Dr. Tarutal Ghosh Mondal (tg5qf@mst.edu)
  - Ying Zhuo (yingzhuo@mst.edu)
  - Dr. Zhenhua Shi (zhs@mst.edu)
  - Drs. Bo Shang and Liujun Li

Knowledge or Technology Transfer

- Publications
  - Pengfei Ma, Ying Zhuo, Genda Chen, and Joel Burken. “Gas Induced Vegetation Stress Leakage Identification and Discrimination via Hyperspectral Reflectance,” Remote Sensing of Environment (under review).
  - Pengfei Ma, Liujun Li, and Genda Chen. “Gas Leakage Detection with Hyperspectral Imagery-Based Vegetation Stress Indices,” Pipeline Research Council International 2021 Virtual Research Exchange, March 2-5, 2021.
  - Pengfei, Zhenhua Shi, and Genda Chen. “Pipeline Leakage Detection by Mapping Vegetation Stress Indices from Hyperspectral Imaging,” Poster Competition (2nd placement award), Geo-Resolution 2022, September 2022.
- Workforce Training
  - Pengfei Ma, Ph.D. Student (September 2019 – September 2022); Mr. Ma’s Ph.D. study was partially supported on this project.
  - Ying Zhuo, Ph.D. Student (September 2019 – September 2022); Mr. Zhuo assisted Pengfei in this project during the field and laboratory study. His Ph.D. research is funded by another PHMSA CAAP Project No. 693JK31850012.
  - Tarutal Ghosh Mondal, Post-doctoral Fellow (April 2022 – January 2023); Dr. Mondal contributed to the classification of plant stress states from deep learning of hyperspectral images on this PHMSA CAAP Project.
  - Liujun Li, Research assistant professor (November 2021 – August 2022); Dr. Li started the flight mission plan and trained other team members for follow-up work.
  - Zhenhua Shi, Post-doctoral Fellow (June 2022 – September 2022); Dr. Shi as a FAA approved pilot developed and executed flight mission plans.
  - Bo Shang, Post-doctoral Fellow (September 2019 – September 2022); Dr. Shang contributed to the preliminary design of the integrated drone equipped with remote sensos.

Problem Statement

- 2021 PHMSA Statistical Data
  - Approximately 2.9 million miles of pipelines for gas distribution, gas gathering, gas transmission, and hazardous liquid transport, including plastic pipelines primarily in the gas distribution system
  - Less than 10% of the total mileages or 229,949 miles for the distribution of liquid and highly volatile liquid (HVL) such as biofuel, CO_2, crude oil, HVL flammable toxic, and refined products
- 2022 PHMSA Statistical Data
  - Over 12,781 pipeline incidents between 2003 and 2022, which results in $10,816,193,735 property loss, 274 fatalities, and 1,120 injuries
  - Incident causes - natural forces (earth movement, wind gusts, heavy rains/floods, lightening), excavations from third parties or operators, operation negligence, material defects, and corrosion



Project Overview

- Objectives
  - To develop and integrate a robust and stable, semi- or fully-automated Unmanned Aerial System (UAS) with multiple sensors for multi-purpose pipeline safety data collection,
  - To explore and develop novel signal and image processing techniques for data analytics and condition classification, and
  - To evaluate and validate field performance of the integrated UAS for pipeline safety inspection.

Task 1 (~$80,000)

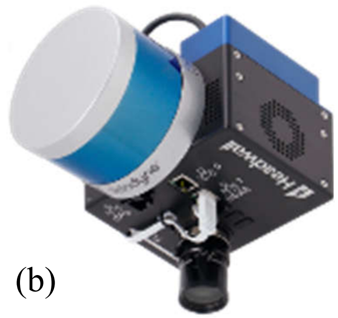
- Design and prototype a UAS for the collection of coherent types of images from visible light, infrared, and hyperspectral cameras.
  - Design of a UAS for multimodal data collection
  - Testing of the designed UAS

Design of the UAS

- Selection of sensors and airframe

(a)

FLIR Duo Pro R640 infrared camera



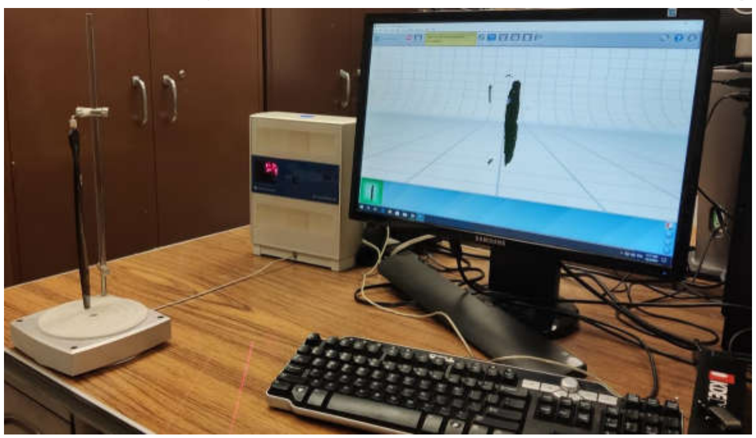
(b)

Headwall Nano-Hyperspec VNIR camera

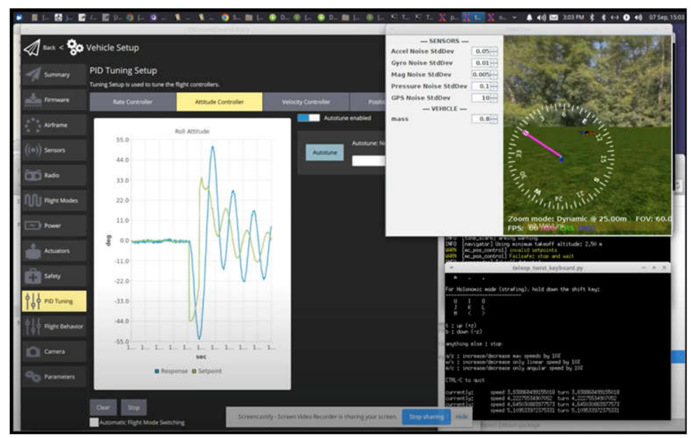
(c)

Hexacopter to carry cameras

- Aerodynamics of flight



3D scanning of the blades for hexacopter modeling

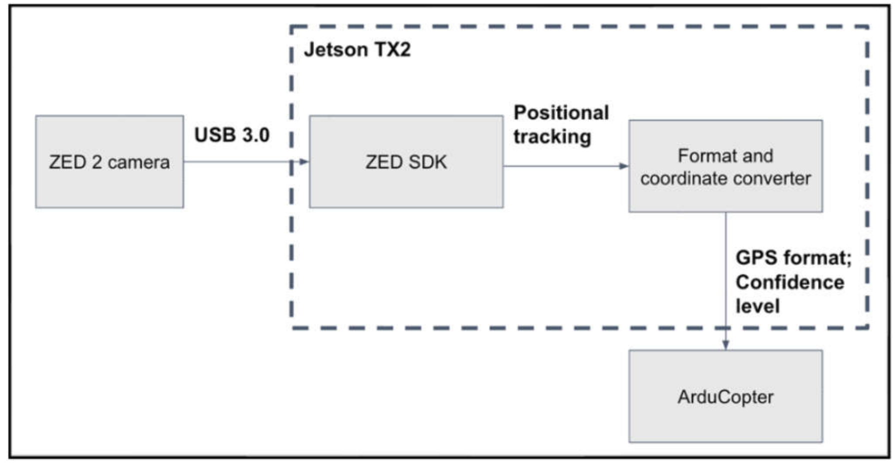


Hexacopter modeling in jMAVSim and PX4

Design of the UAS

- Control test of a test quadcopter

Non-GPS navigation based on visual odometry



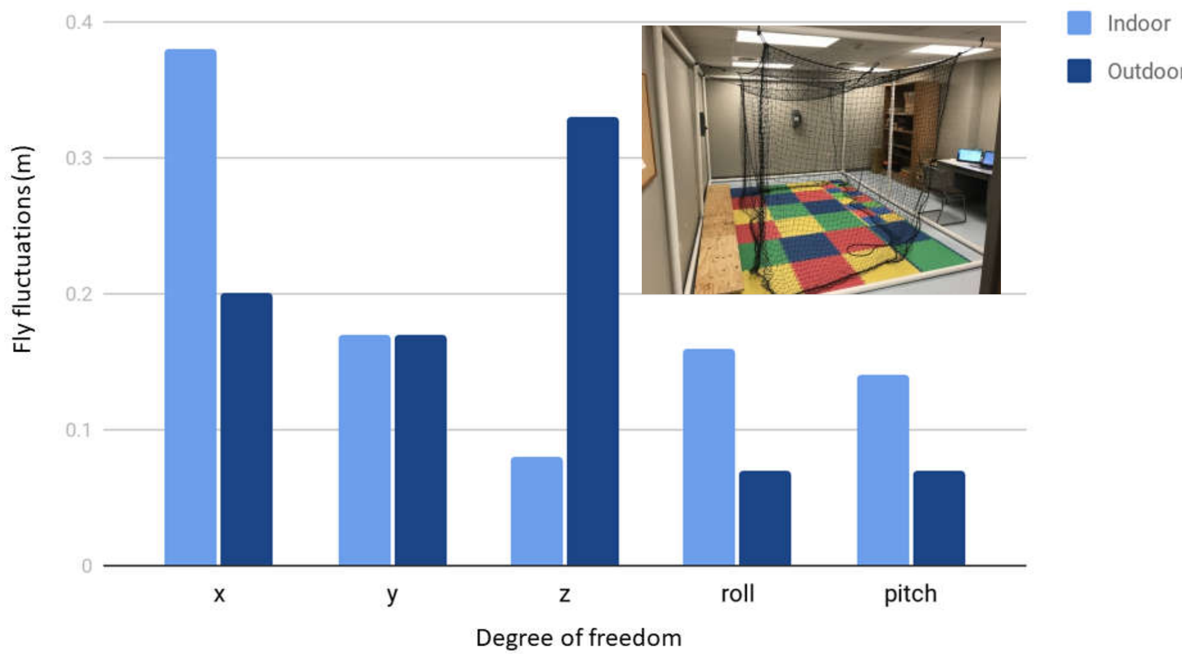
Control flow diagram of the UAS system

  - A ZED 2 depth camera integrated into the drone as a visual odometry and data collector,
  - A Jetson TX2 embedded computer with GPU interfaces to connect with different types of sensors, and
  - Remote control of the drone by a ZED SDK to provide computation for track positioning.

Testing of the designed UAS

- Indoor test results

Position fluctuation (in meter) of the UAS when flying indoor



Flight stability comparison of the UAS in each DOF

- The indoor flight nearly doubles the fluctuation in X, roll, and pitch DOF.
- The indoor flight is nearly four times more stable than the outdoor flight in Z DOF.

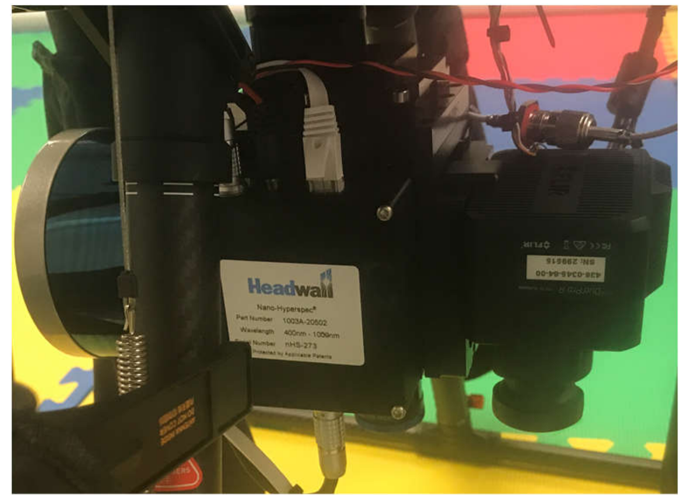
Testing of the designed UAS

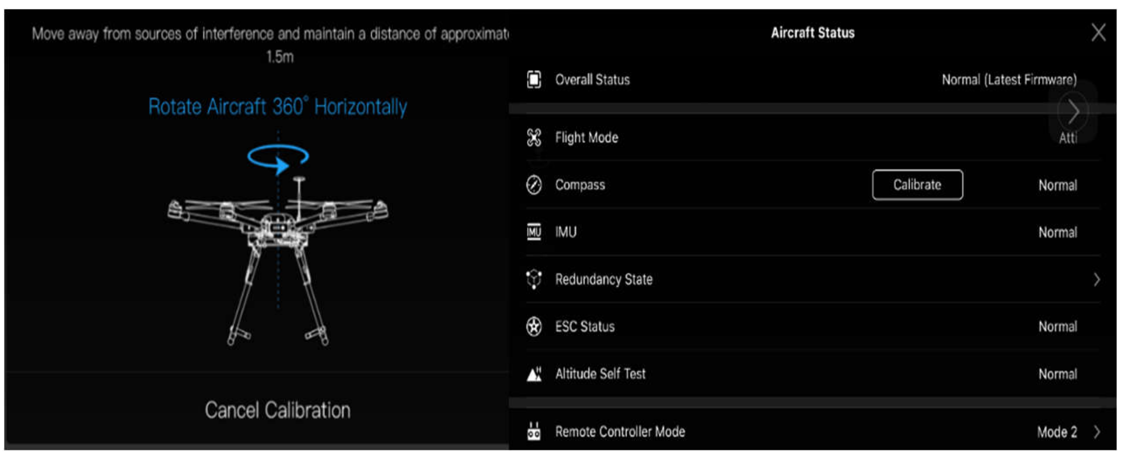
- Subsequent indoor test in a large drone net to confirm stability during flight

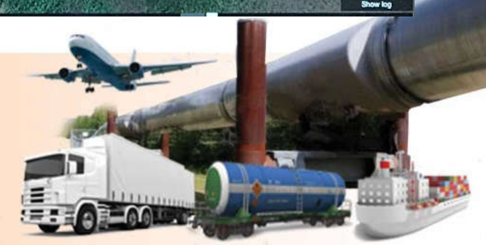
10 m × 8 m × 6 m drone net for control testing,
Which is 16 times as large as the small drone net

Testing of the UAS prototype

- Outdoor testing of a Headwall M600 drone







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Task 2 (~$90,000)

- Develop and validate imagery and spectral processing techniques for two-dimensional (2D) image classification of stress conditions and three-dimensional (3D) object volume estimates
  - Greenhouse test for plants under natural gas/ methane treatment with other natural stressors
  - Data processing and leak detection algorithm
  - Vegetation stress detection results
  - Volume estimate demonstrated in Task 3

Greenhouse test setup

- The effects of methane leak on plants are simulated in lab. Other natural stressors that may confuse the detection of methane are considered. All plants are cultivated in a greenhouse.

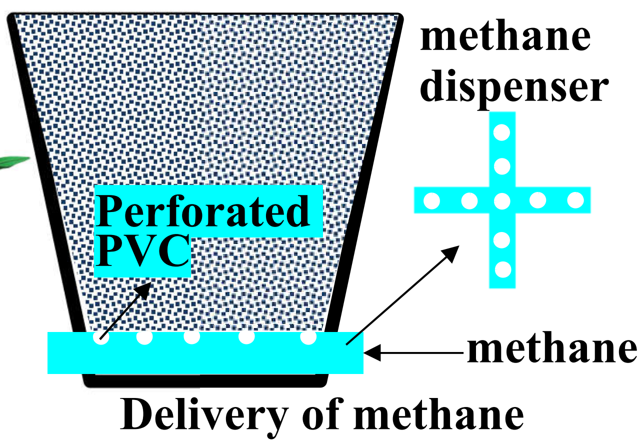
Shrub-Winter Gem

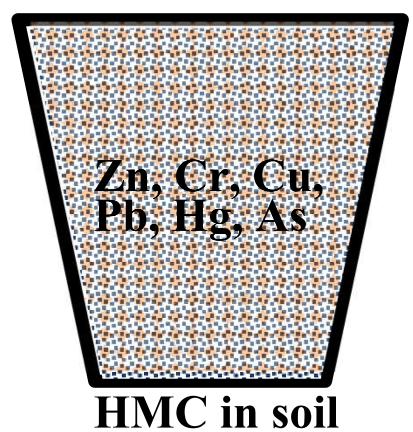
Shrub-Southern living

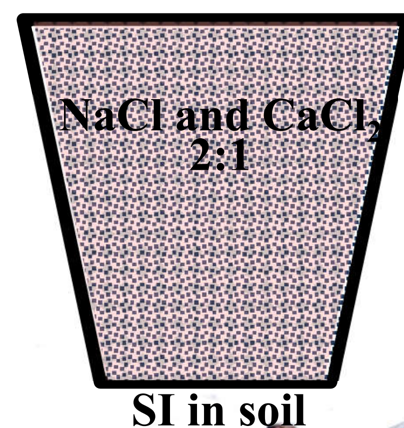
Grass-Ornamental grass

Methane and other stressors

- Methane is delivered at the bottom of pot,
- Salt is added to the cultivation soil to create the saline soil; Salinity Impact (SI) is control by soil electrical conductivity,
- Heavy Metal Contamination (HMC) is compliant with the USDA regulatory limit, and
- Drought Exposure (DE) is simulated by reducing half of the irrigation water.

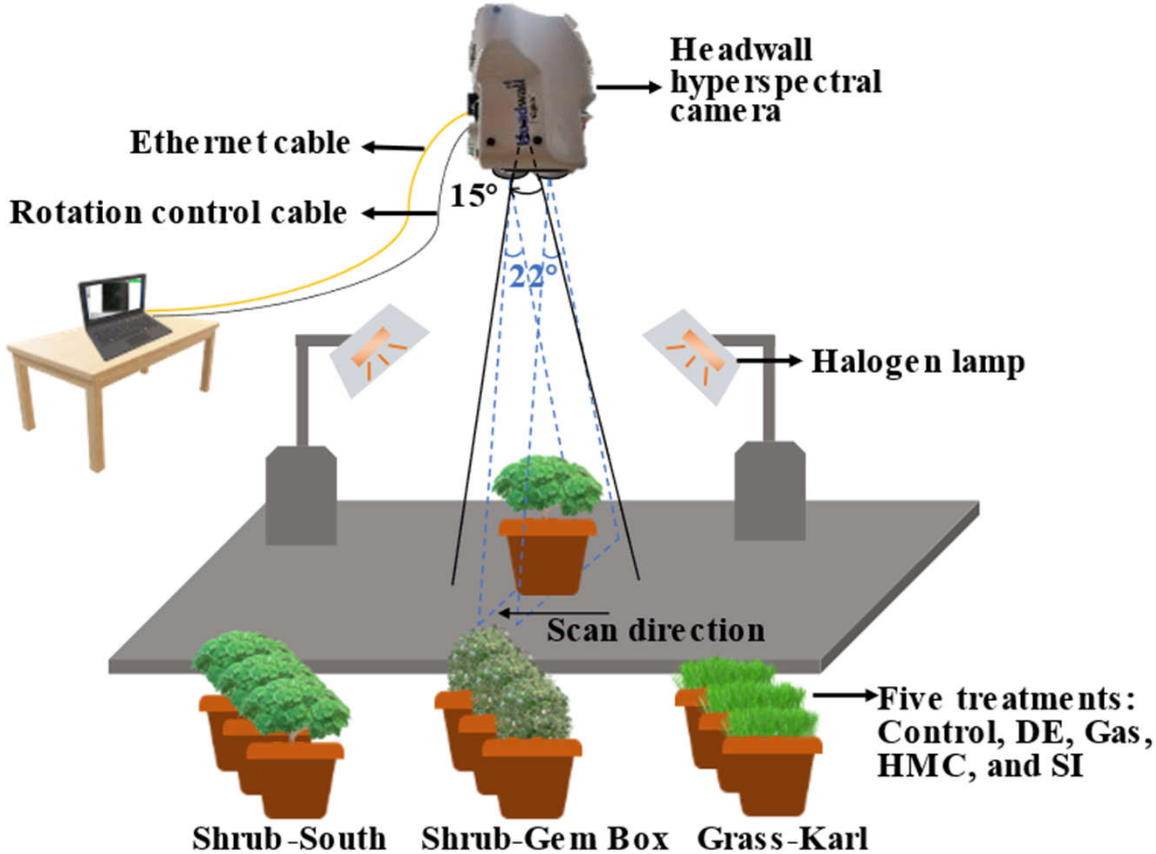






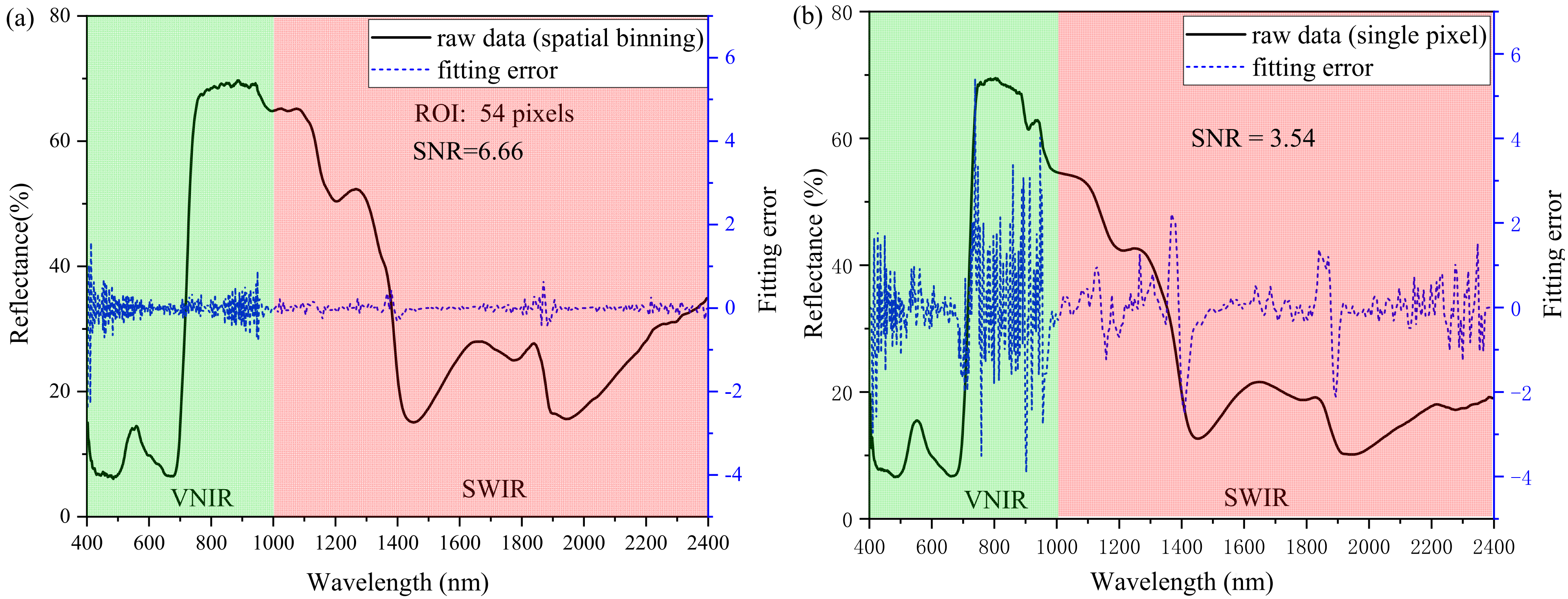
Hyperspectral image collection

- Headwall dual lens camera in the range of VNIR (400-1000 nm) and SWIR (1000-2500).



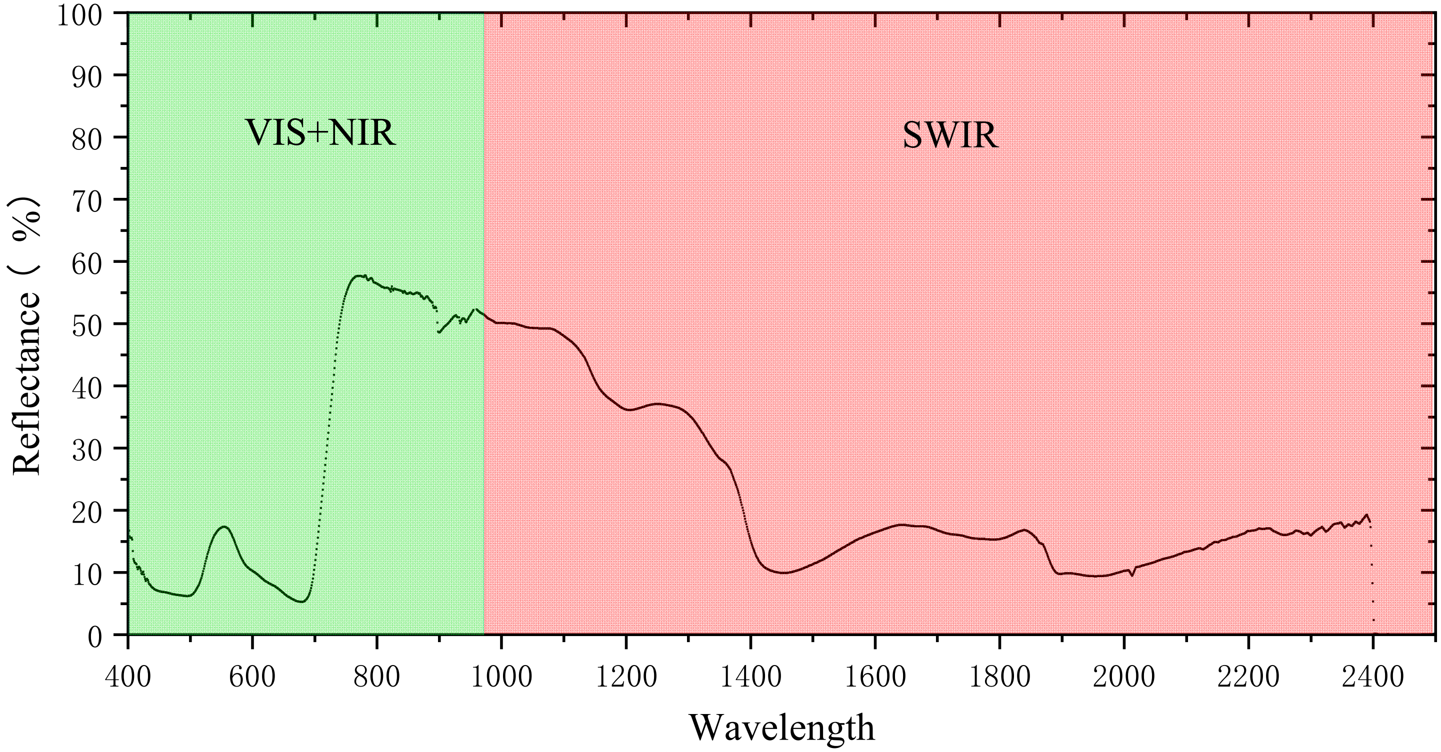
Spectra extraction

- A spectrum is extracted from the canopy of a plant by averaging the spectra at all pixels within the canopy to enhance signal noise ratio (SNR).



Spatial binning of pixels **Single pixel**

Spectral signature analysis



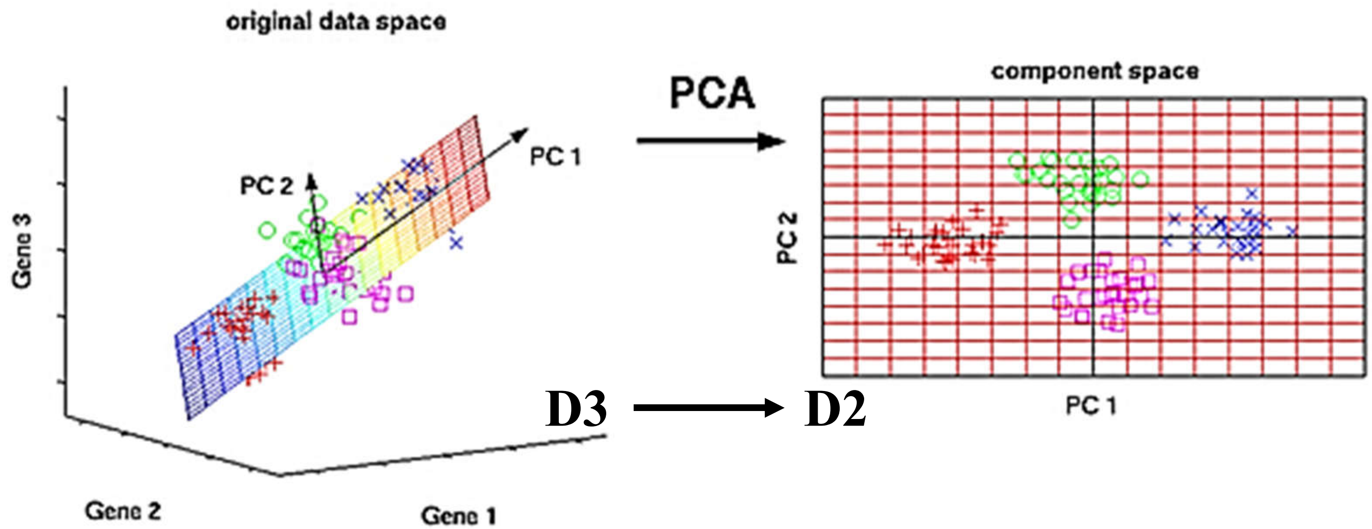
- 245 (VIS+NIR) + 244 (SWIR) = 489 points
- Independent reflectance at different wavelengths
- Varying change in spectral signature over a notable wavelength range due to different treatments $F(x_1, x_2, .., x_n) = a_1 * x_1 +, .., + a_n * x_{489}$

Dimension reduction

- Multicollinearity of bands in close range provides redundant information of vegetation with treatments.
- Selection of the bands which contribute to the change more potentially reduces the disturbance of the other nondominant bands.
- Dimension reduction optimizes the extraction the most informative message on the spectral signature to facilitate the discrimination due to various treatments.

Dimension reduction by PCA

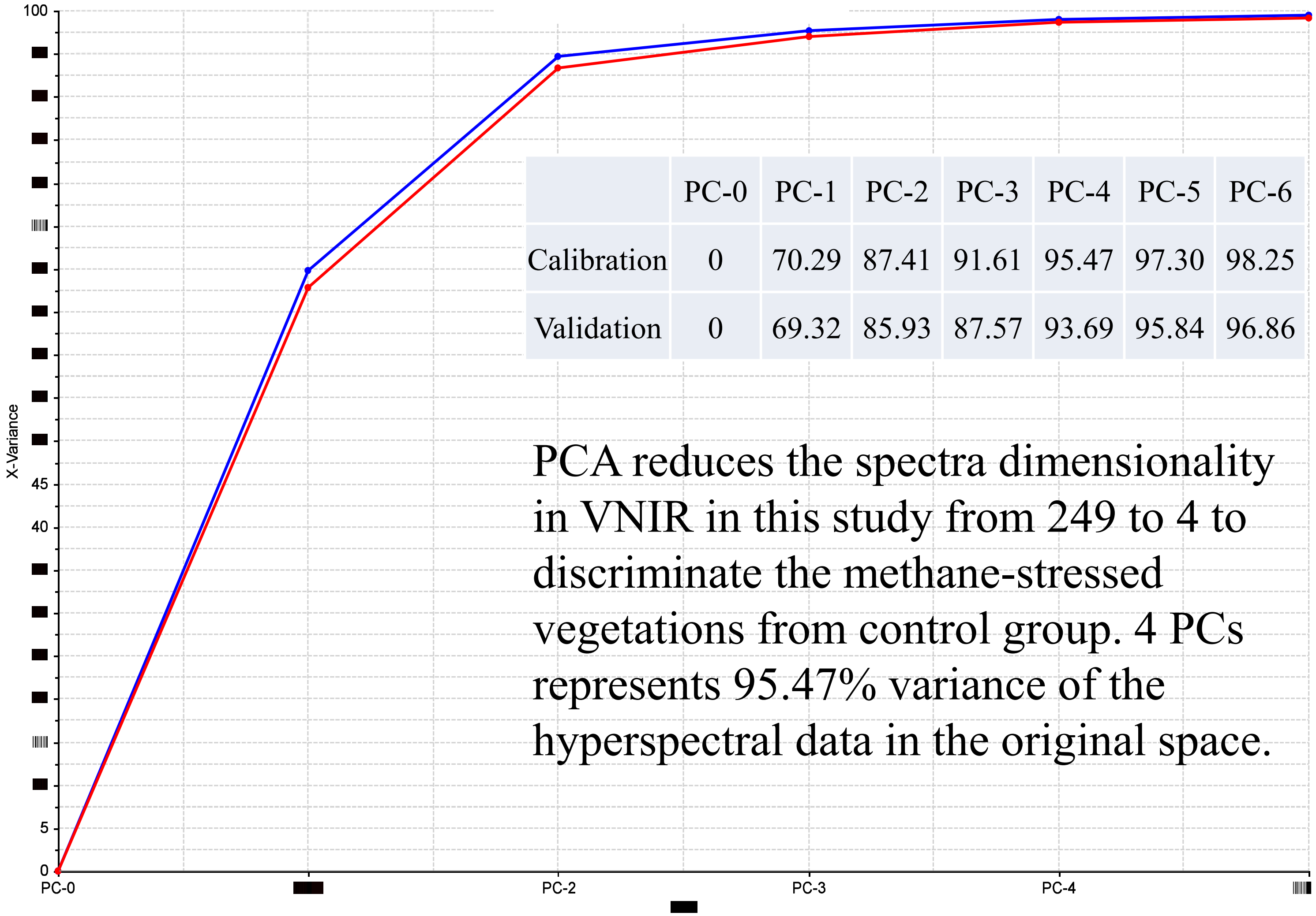
- Principal component analysis (PCA) is to reduce the dimensionality of a data set consisting of many variables correlated with each other by retaining the variation. The process is done by transforming the variables to a new space with lower dimensions.



Features remained from three dimensions to two dimensions

PCA by unscrambler

- Determine the number of significant PCs.

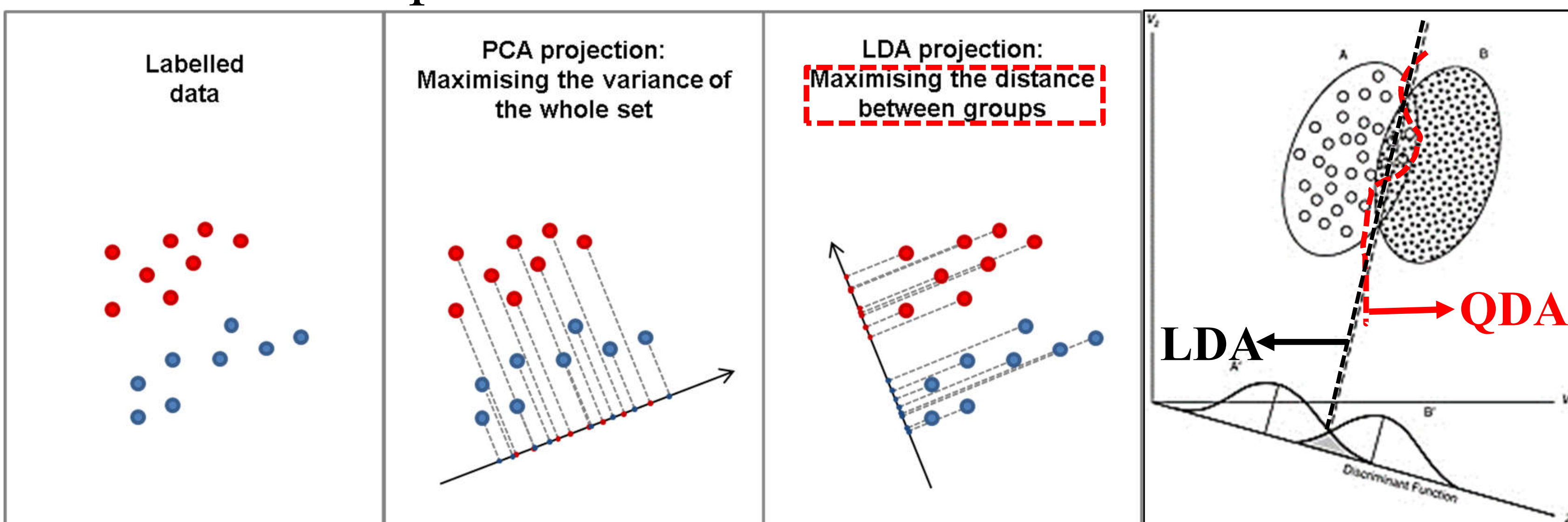


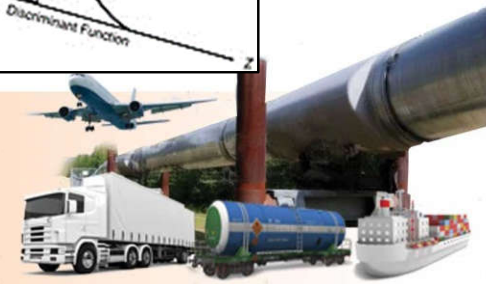
	PC-0	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6
Calibration	0	70.29	87.41	91.61	95.47	97.30	98.25
Validation	0	69.32	85.93	87.57	93.69	95.84	96.86

PCA reduces the spectra dimensionality in VNIR in this study from 249 to 4 to discriminate the methane-stressed vegetations from control group. 4 PCs represents 95.47% variance of the hyperspectral data in the original space.

Discrimination analysis

- Linear discrimination analysis (LDA) and quadratic discrimination analysis (QDA) are performed to identify the methane stress and discriminate the methane stressors from other disturbance stressors respectively in this study.
- LDA is a generalization of Fisher's linear discriminant to find a <u>linear combination</u> of features that characterizes or separates two or more classes of objects or events. QDA separates classes with a quadratic boundaries.





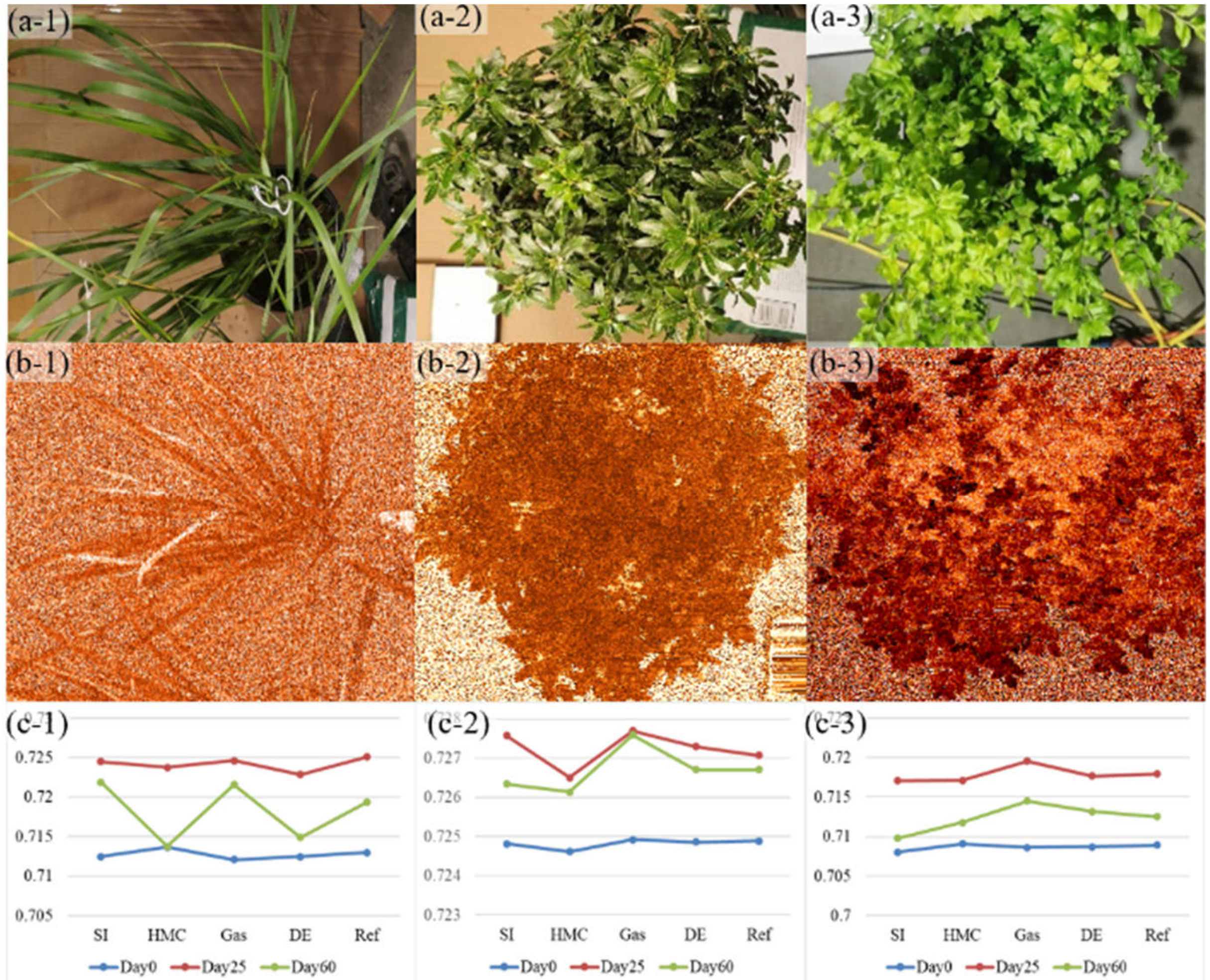
Methane leak detection by vegetation

Vegetation works as a biosensors to detect the methane leak from underground in transmission. Research objects include:

- Whether the methane leak can be identified by vegetations?
- The time needed for stress demonstration on plant from hyperspectral imaging;
- If different natural vegetation stressors co-present, whether methane stress on plants is still distinguishable?

Stress demonstration on vegetations

- Stress demonstration indicator, red edge position indicator, is used to show the change of potential changes on vegetations.



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Methane stress identification by LDA

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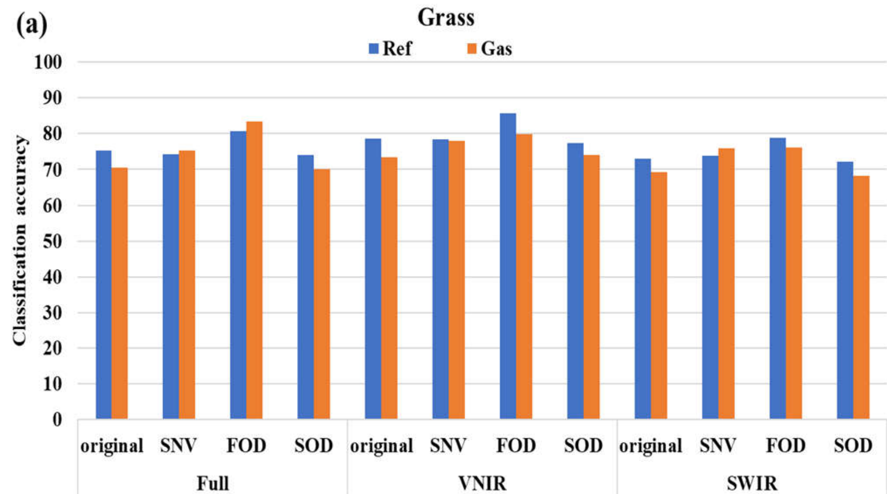
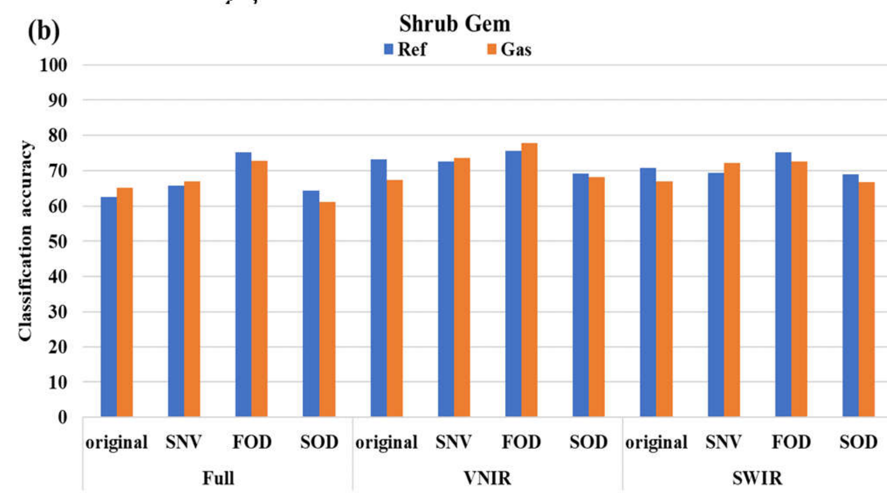
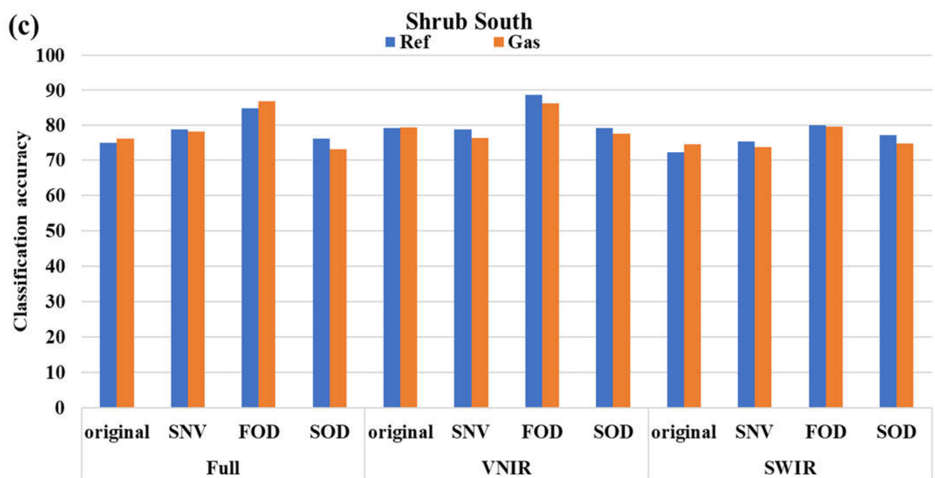
- Different spectral zones, VNIR, SWIR, and VNIR+SWIR to test the most sensitive zone in natural gas stress detection.







Results:

1. VNIR yields the best natural gas stress detection and FOD performs better than other spectral transformations;
2. Average stress detection accuracy reaches 85% and shrub Gem yields the least results.

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Natural gas stress development

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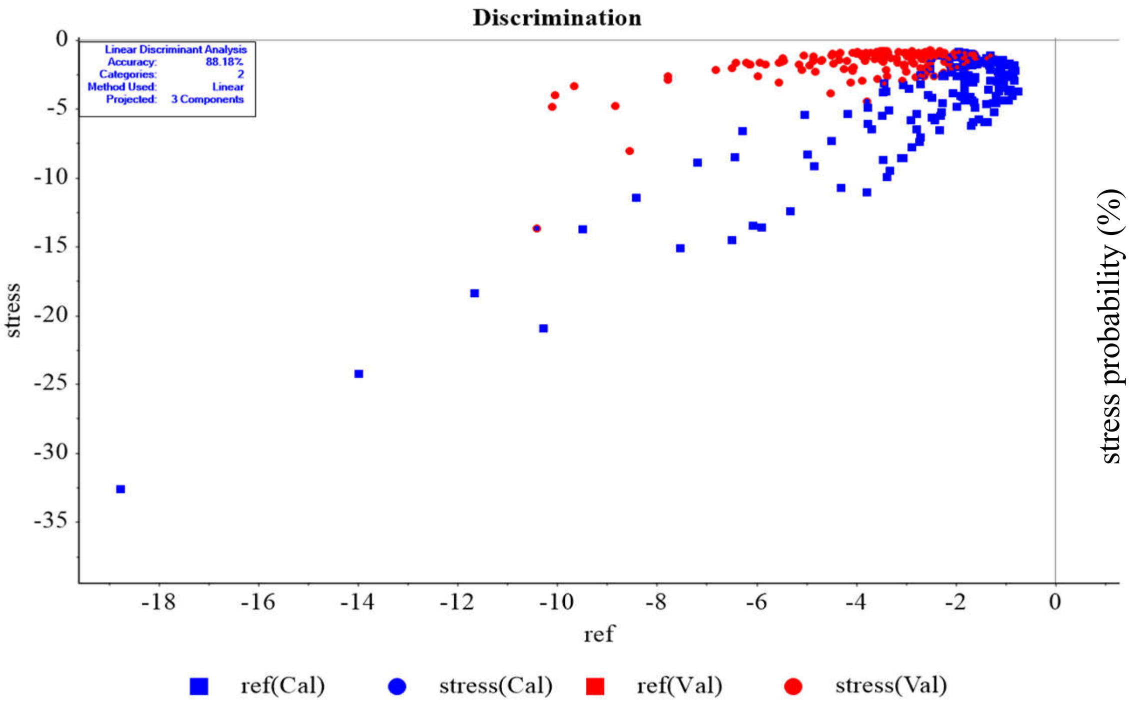
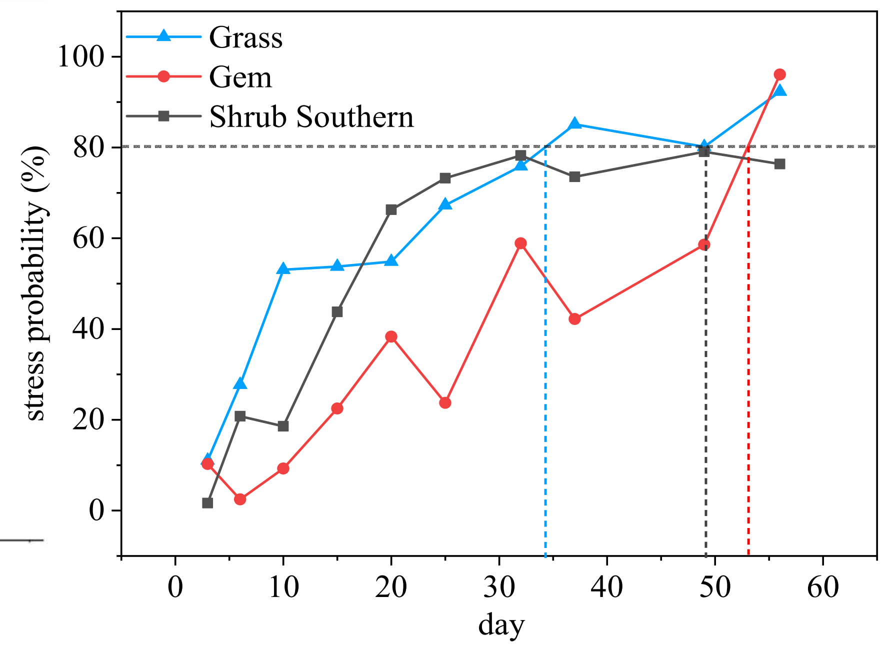
- The earliest detection of underground natural gas leak will facilitate timely remedies to prevent potential hazards.



LDA model for natural gas stress detection

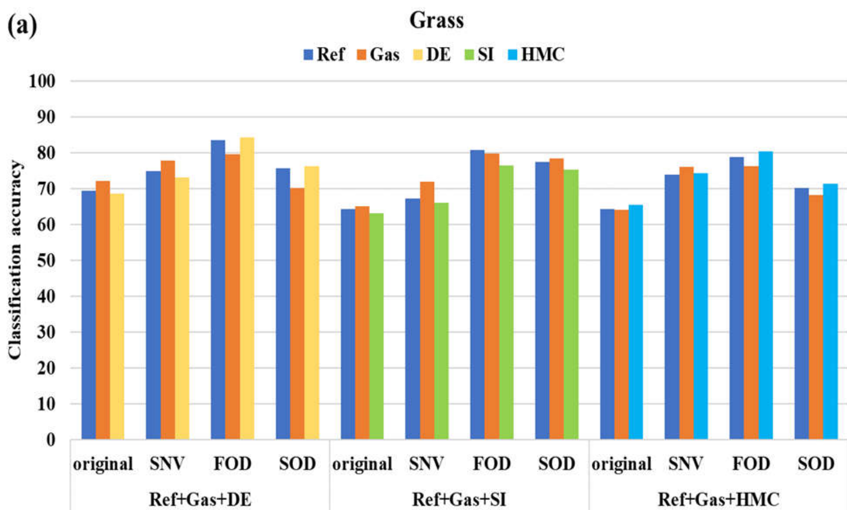


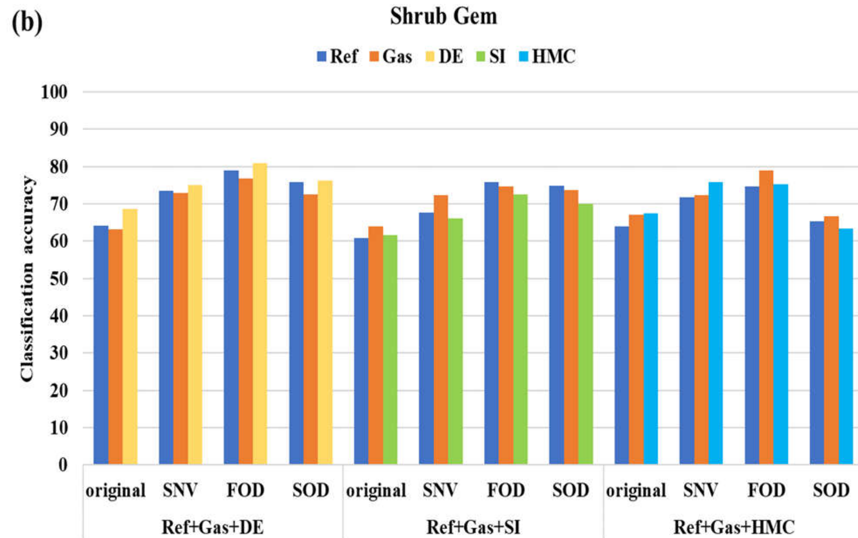
Natural gas stress probability in time series

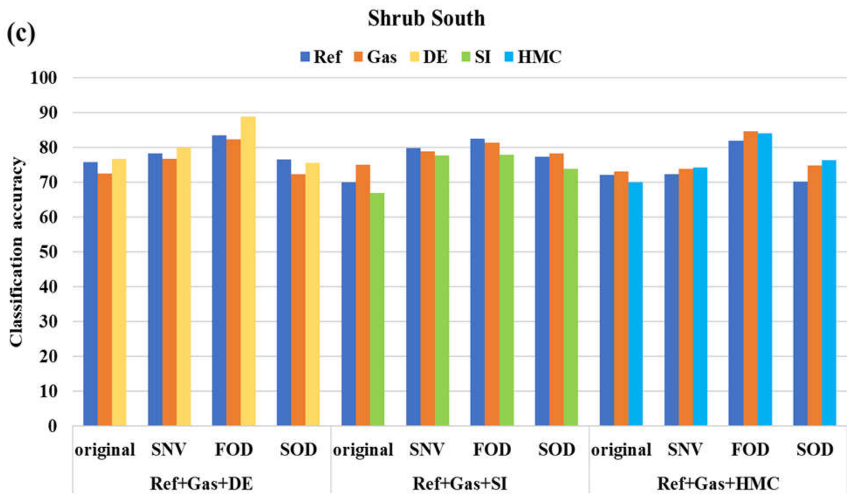
The sensitivity to natural gas differs among plants. Grass finds natural gas leak stress in 34 days while Gem and shrub southern takes 49 and 56 days respectively.

Natural gas stress discrimination

- The discrimination of natural gas stress from other natural vegetation stressors.







Results:

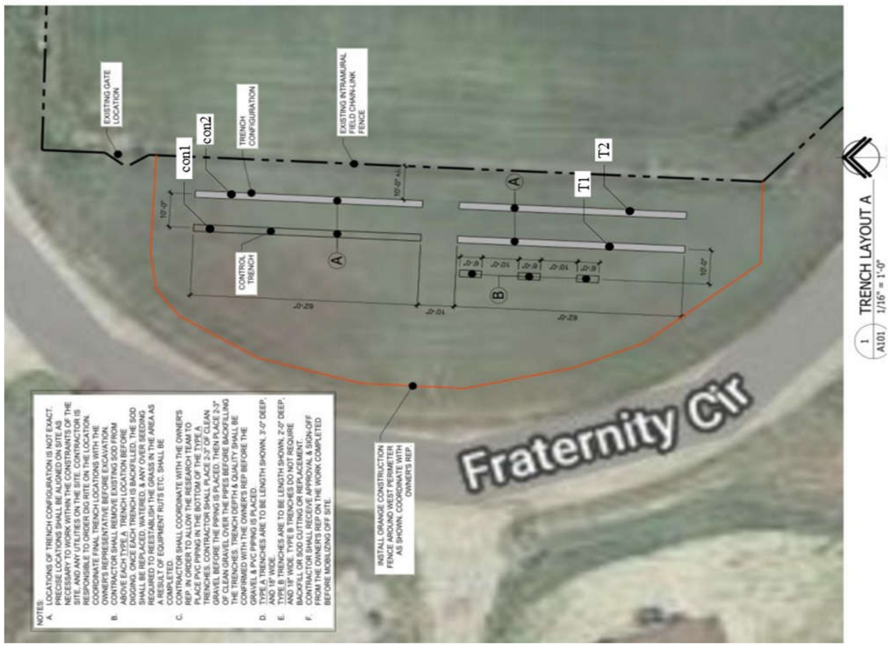
1. VNIR yields the best natural gas stress detection and FOD performs better than other spectral transformations;
2. Average stress detection accuracy reaches 85% and shrub Gem yields the least results.

Task 3 (~$80,000)

- Develop a deep learning neural network for the assessment of pipeline and ground surface conditions.
  - Field test of the pipeline leak simulation
  - Methane leak detection from stress indicators
  - Methane stress detection from a deep neural network

Methodology-field test

- A field test was performed to simulate underground natural gas leak.
- Four test trenches (20×0.3×1.0 m) are constructed with two for natural gas simulation and two under control for stress-free reference.

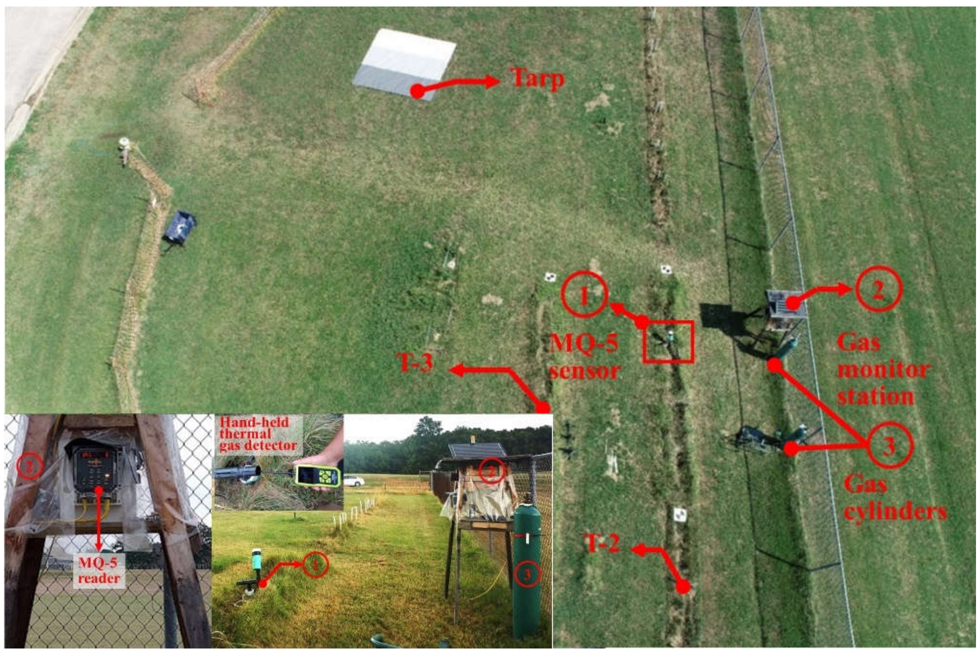


Configuration of the test field and trenches

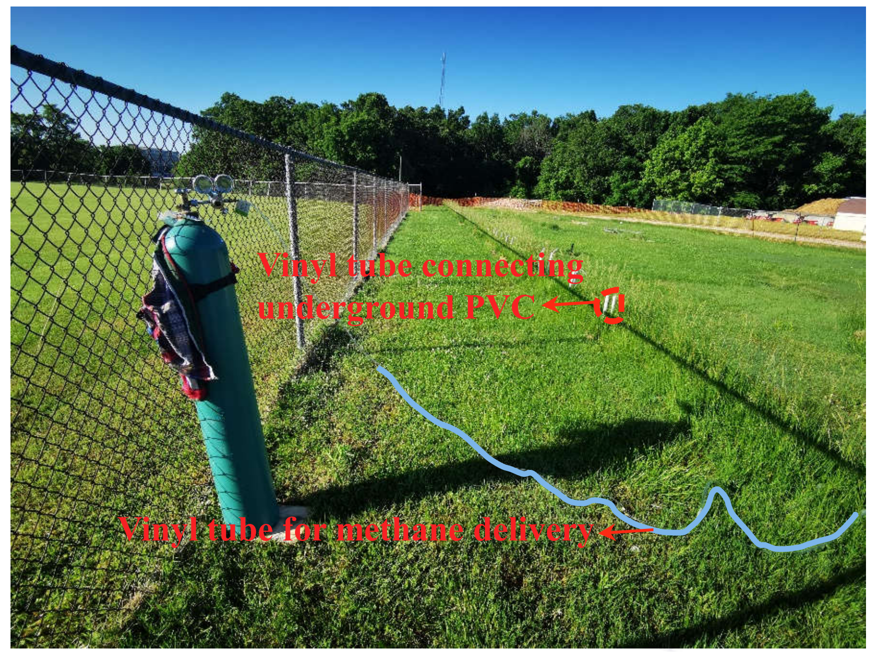
Construction of the tested trenches in field

Underground natural gas leak

- Perforated PVC pipes are buried underground at 1 m deep;
- Methane is used as a substitute for natural gas;
- Methane is delivered through preset vinyl tubes.



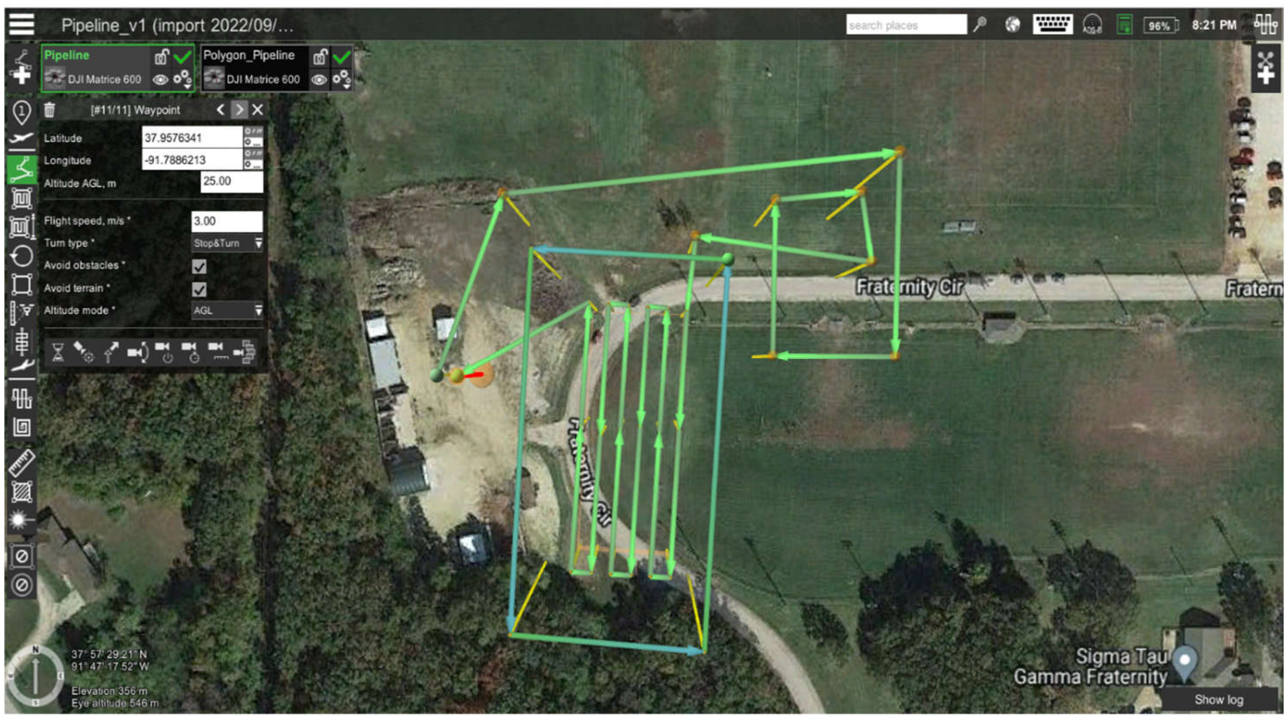
Underground methane delivery and methane leak monitoring



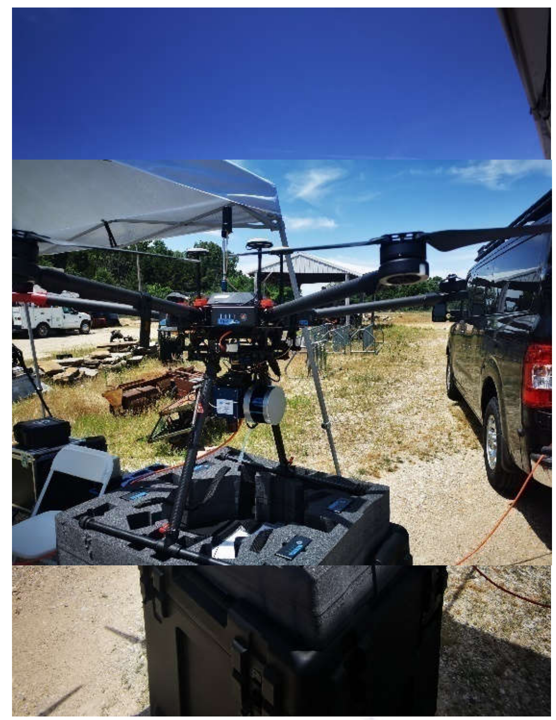
Methane delivery setup in field

Routine hyperspectral data collection

- Hyperspectral imaging is collected weekly.
- Headwall VNIR sensor + DJI M600.
- Scanning route planned in UgCS.
- 1m/s speed, 40% parallel overlap, 24 m altitude.



Flying route in UgCS for remote sensing of the test field



Headwall VNIR sensor + DJI M600

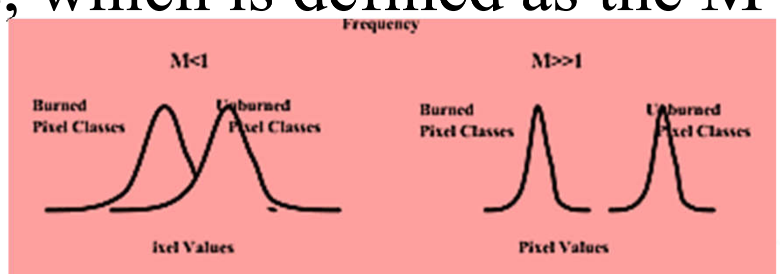
Methane leak detection in field

Different methods are considered in the study to detect the earliest methane leak in a more robust way. Two criterion are emphasized, time efficiency and separability.

- Red edge position shift (REP) (widely used);
- Four physiology-based vegetation indicators;
- Four natural gas specialized vegetation stress indicators;
- Deep neural network (DNN) to distinguish the ethane stressed vegetation from the unstressed.

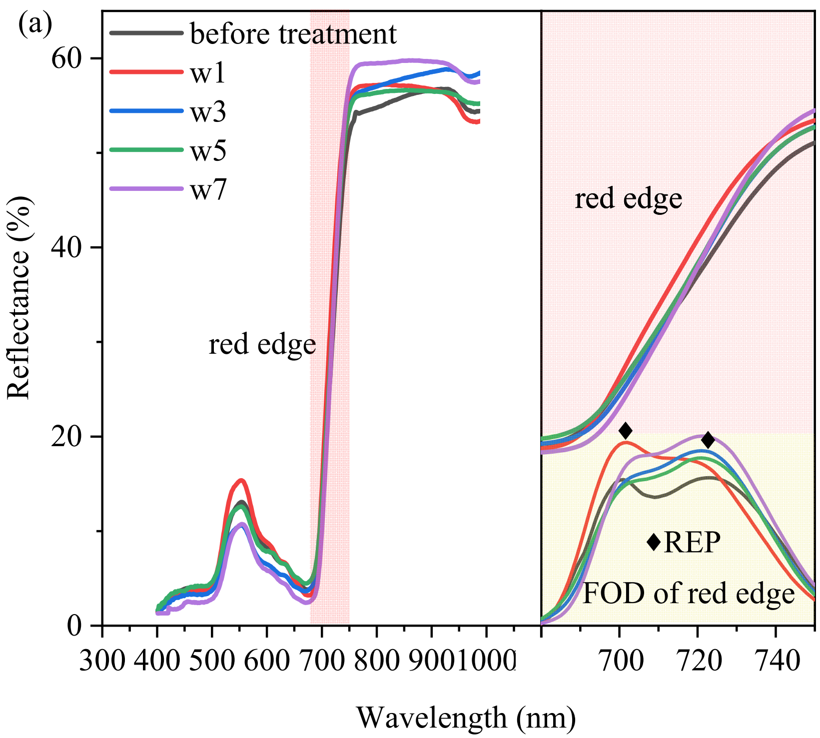
Separability measures the distinguishability of the vegetations with and without methane stress, which is defined as the M-estimator (ME) from statistics.

$$M = (\mu_1 - \mu_2) / (\sigma_1 + \sigma_2)$$

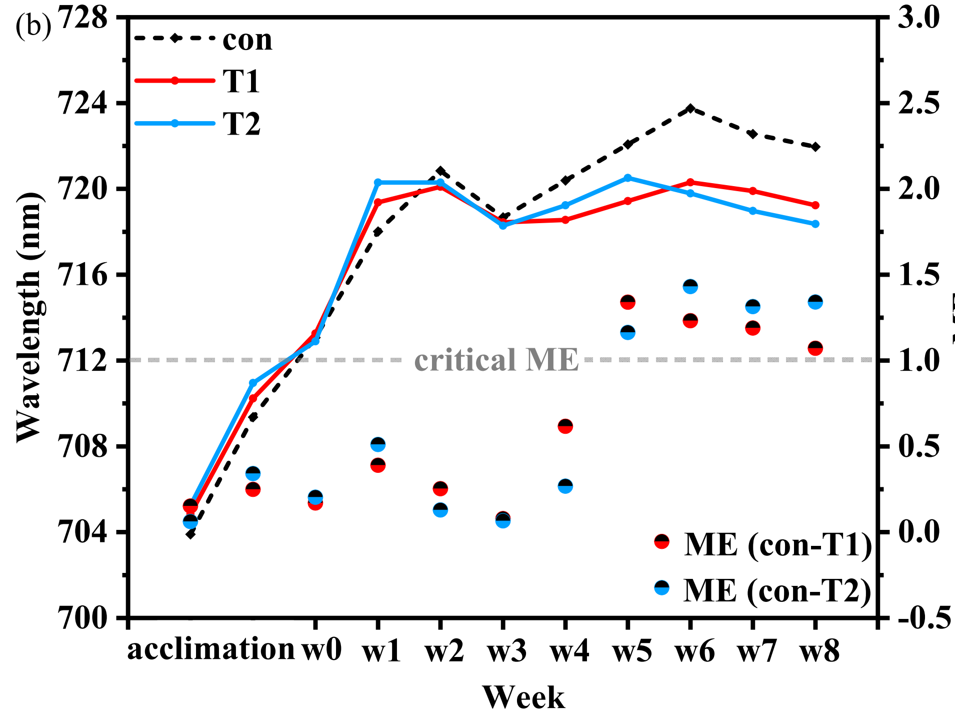


Methane stress demonstration-REP shift

- Red edge position shift has been widely used to indicate the stress presence from different stressors.



REP demonstration in spectral signature

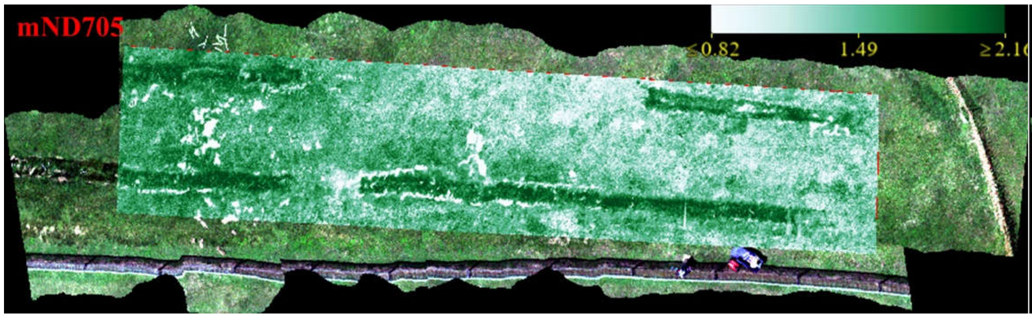


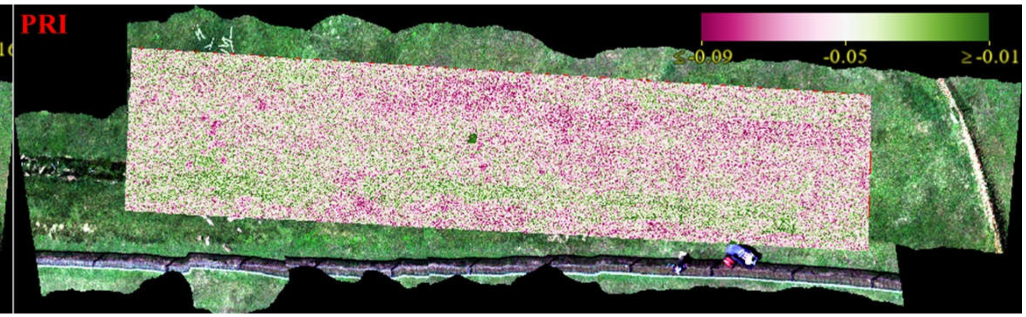
REP position between vegetation with and without methane treatment

Results: REP starts to show difference from the control at w4. ME indicates that the methane stress can be separated from w5 till the end of the field test.

Methane stress-physiology indicators

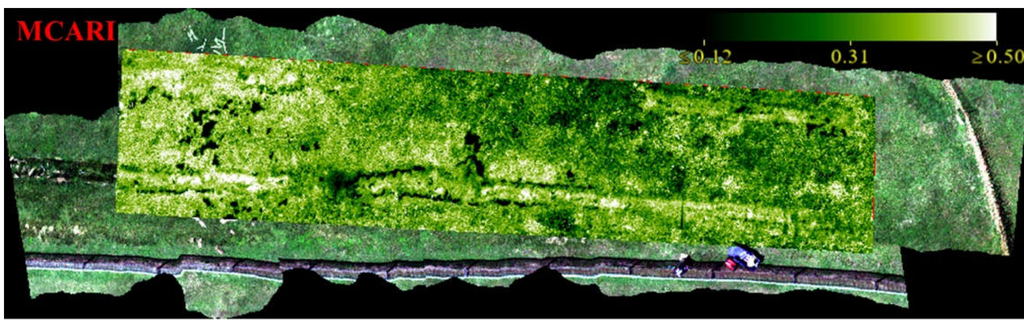
- Stress indicators are mapped in the view of test field to detect the potential leaks.

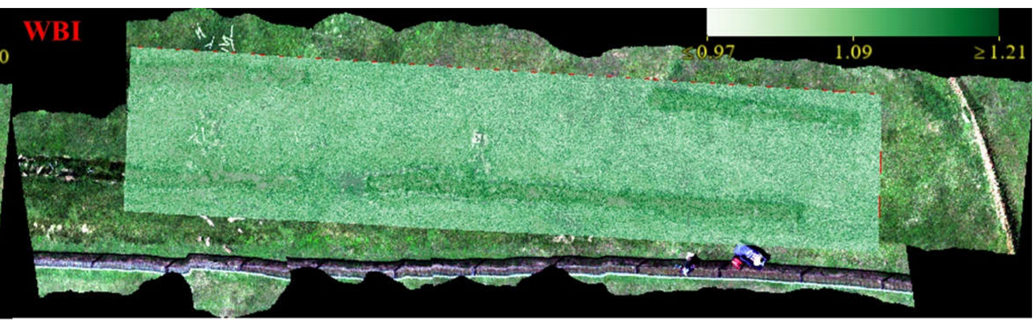




$$mND705 = \frac{(R_{750} - R_{705})}{(R_{750} + R_{705} - 2 \times R_{445})}$$

$$PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}$$





$$MCARI = (R_{700} - R_{670}) - 0.23 \times (R_{700} - R_{550}) \frac{R_{700}}{R_{670}}$$

$$WBI = \frac{R_{900}}{R_{970}}$$

Methane stress-physiology indicators

- Four indicators about the physiological response of vegetation are used to show the methane stress presence

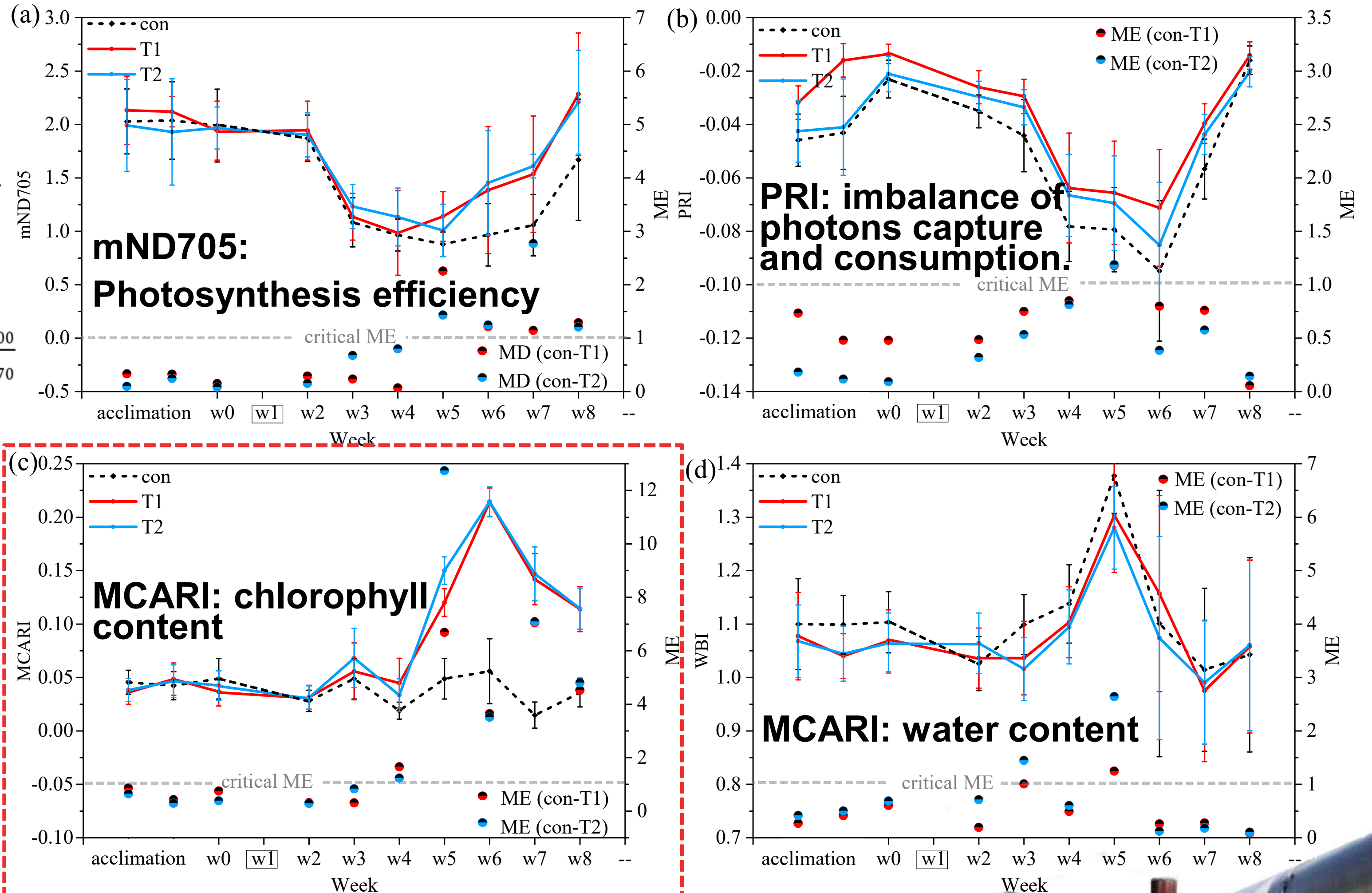
$$mND705 = \frac{(R_{750} - R_{705})}{(R_{750} + R_{705} - 2 \times R_{445})}$$

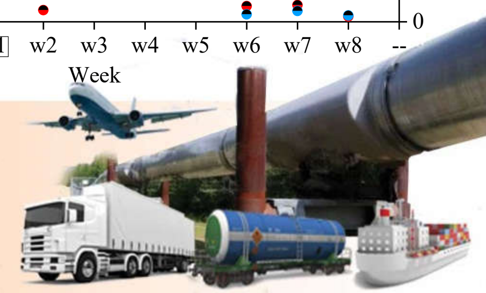
$$MCARI = (R_{700} - R_{670}) - 0.23 \times (R_{700} - R_{550}) \frac{R_{700}}{R_{670}}$$

$$PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}$$

$$WBI = \frac{R_{900}}{R_{970}}$$

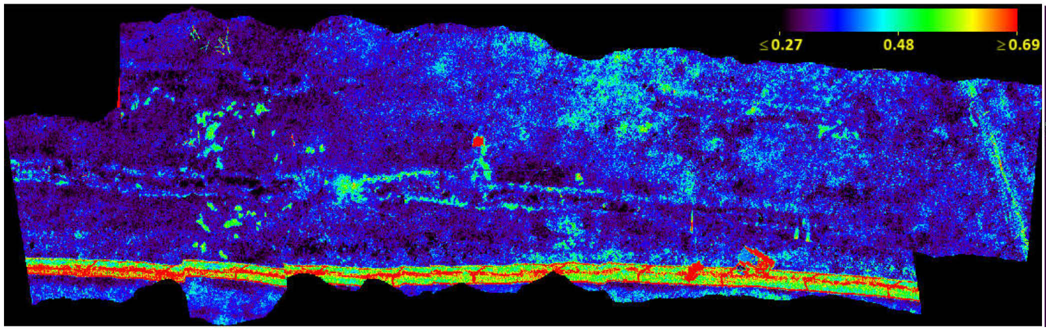
Where, R_i denotes reflectance at wavelength i.

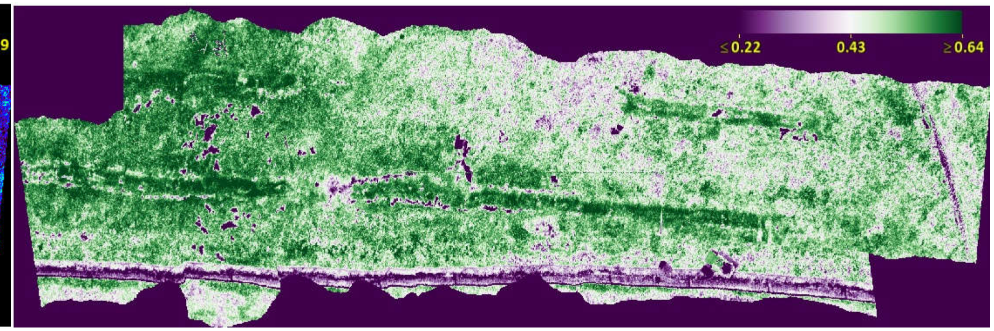




Methane stress-specialized indicators

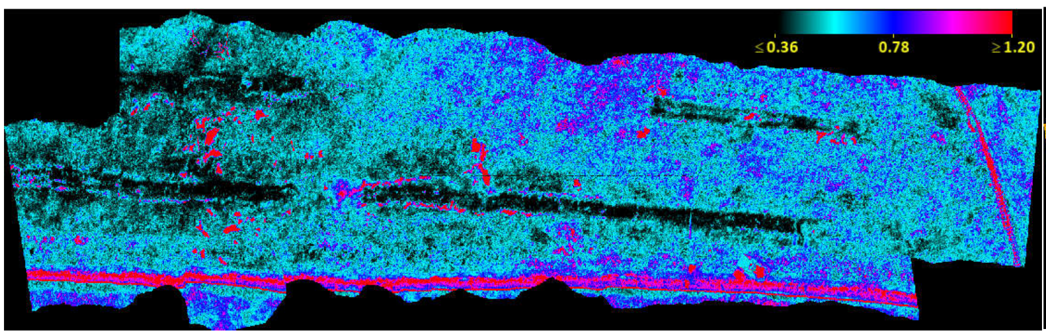
- Four indicators derived from natural gas detection study.

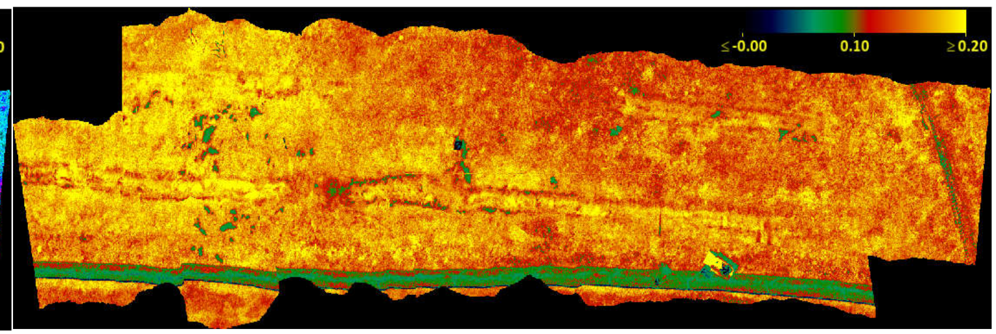




LIC (Lichtenthaler index)	$\frac{R_{440}}{R_{760}}$

OSAVI (Optimized Soil-Adjusted Vegetation Index)	$\frac{(1+0.16)*(R_{800}-R_{670})}{R_{800}+R_{670}+0.16}$





NGSI (Natural Gas Stress Index)	$\frac{(R_{645}+R_{690})}{R_{800}}$

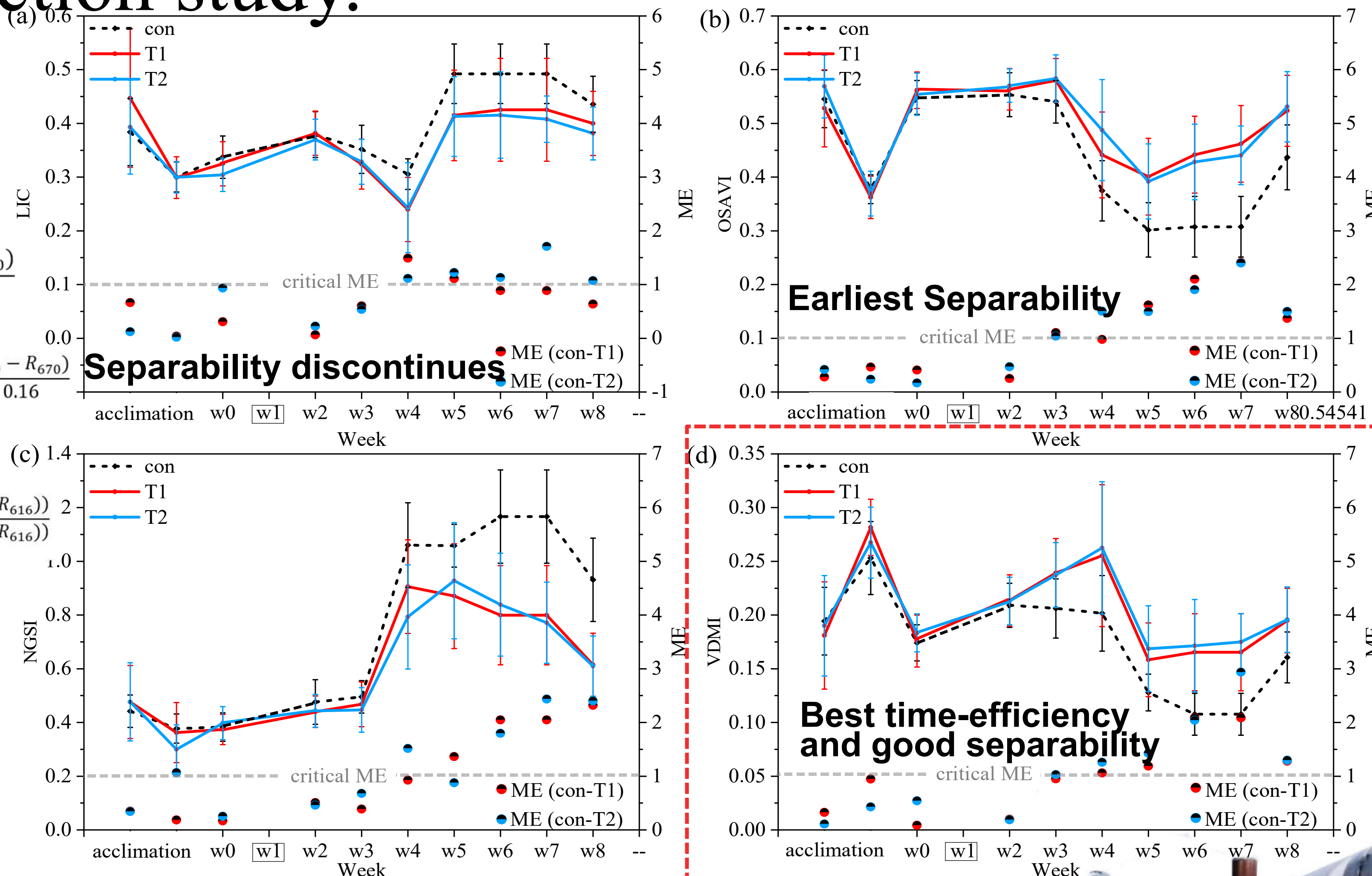
VMDI (Variational Mode De-composition Index)	$\frac{(exp(R_{829})-exp(R_{616}))}{(exp(R_{829})+exp(R_{616}))}$

Methane stress-specialized indicators

- Four indicators derived from natural gas detection study.

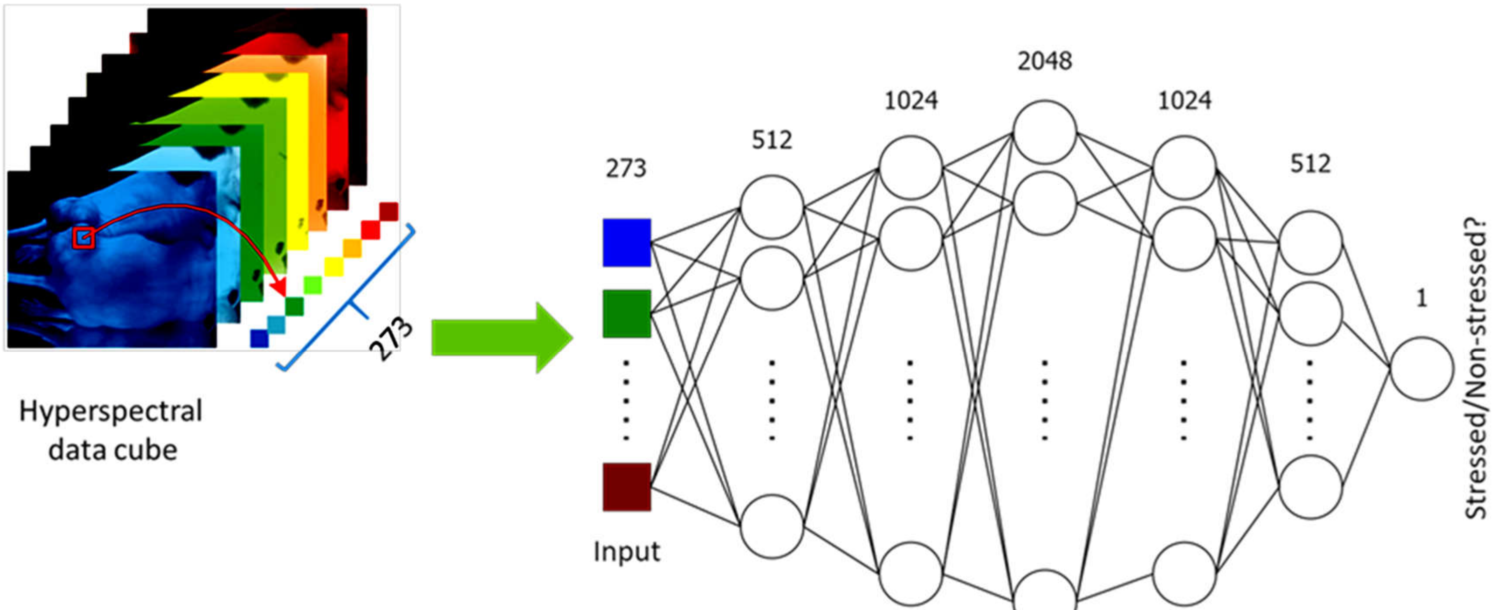
LIC (Lichtenthaler index)	$\frac{R_{440}}{R_{760}}$
NGSI (Natural Gas Stress Index)	$\frac{(R_{645}+R_{690})}{R_{800}}$
OSAVI (Optimized Soil-Adjusted Vegetation Index)	$\frac{(1+0.16)*(R_{800}-R_{670})}{R_{800}+R_{670}+0.16}$
VMDI (Variational Mode De-composition Index)	$\frac{(exp(R_{829})-exp(R_{616}))}{(exp(R_{829})+exp(R_{616}))}$

Where, R_i denotes reflectance at wavelength *i*.



Methane stress detection- DNN

- DNN is used to group the vegetations exposed with and without methane treatment.



DNN for classification

2000 random pixels per trench, 4 trenches;
7 scans after methane treatment;
2,000*4*7=56,000 pixels

50% training
50% test

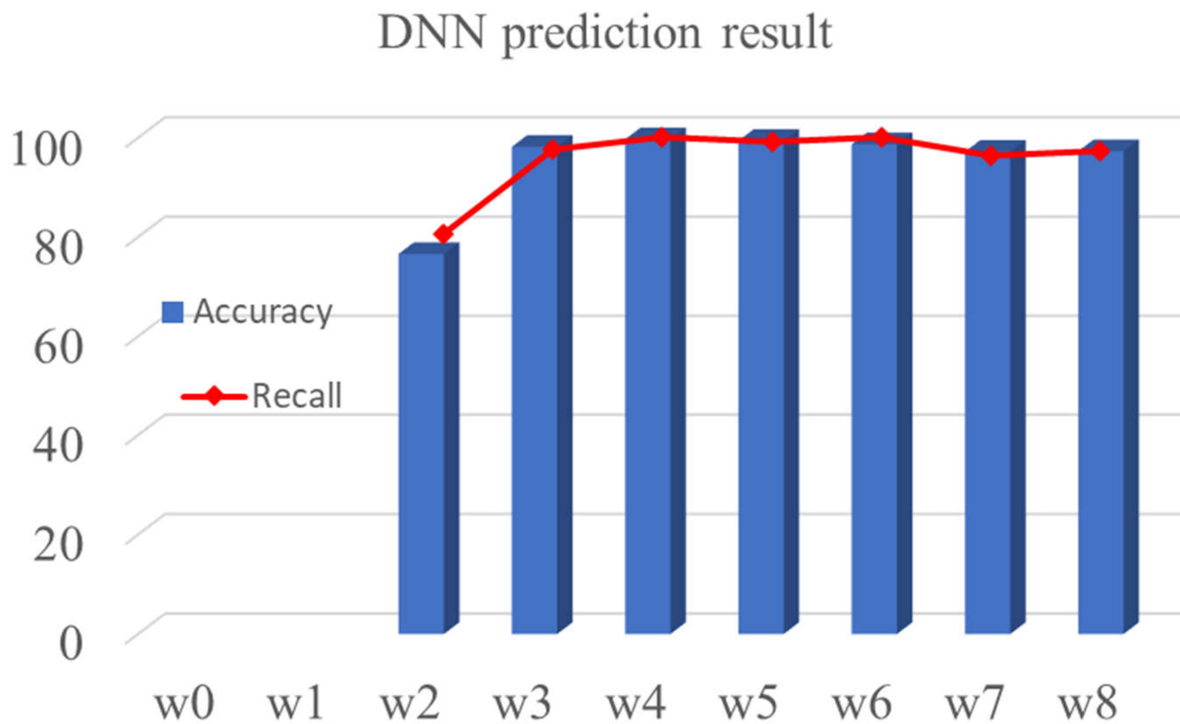
DNN model

output

Stressed？
Unstressed？

DNN stress detection results

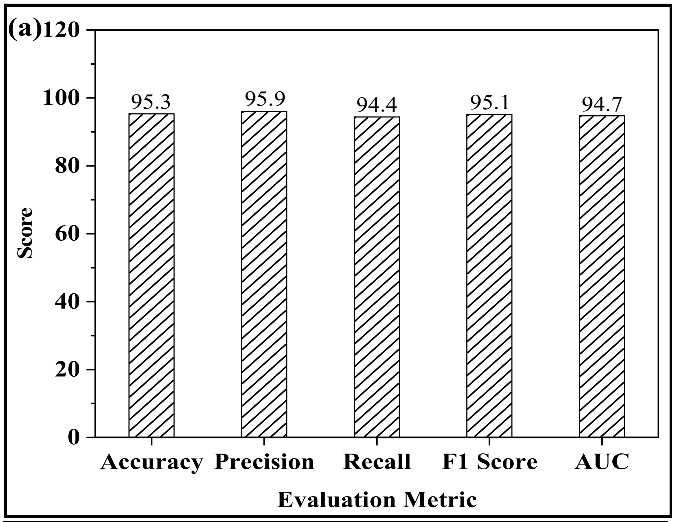
- Methane stress detection by DNN in time series to find the early methane leak.

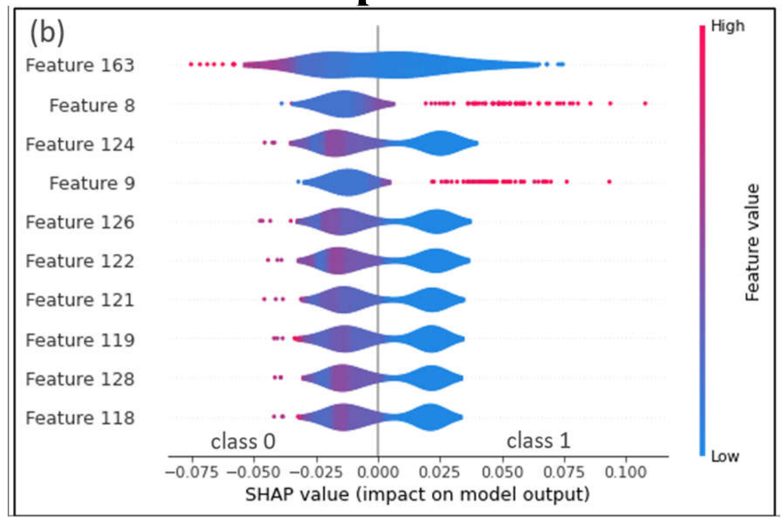


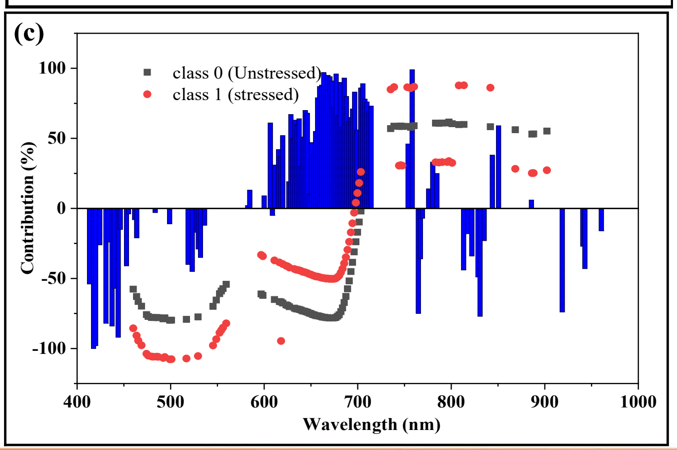
Results: DNN predicts a >80% methane stress at w3 on the vegetations according to the difference on the spectral signature. The probability decreases at the last two week due to the more rainfall.

DNN indication of the spectral change

- DNN takes each wavelength equally in the range of VNIR and calculates its significance and indication for methane stressed plants.







Results: DNN yields an overall >90% methane stress considering all dates after methane treatments.

1. SHAP show the most sensitive wavelengths are in 600-730 nm, and 420-480. only few presents in NIR.
2. SHAP indicates increase in VIS and decrease in NIR, consistent with previous natural gas detection results.

Project Summary Findings

- Methane stress can be identified across different plant species with different sensitivities based on greenhouse tests.
- Methane stress can be detected after 34, 49 and 56 days of treatment for grass, shrub-southern and Gembox.
- Saline soil effect is similar to the methane leak effect on vegetation while drought is the most separable stressor.
- Physiology based stress indicator, MCARI, can identify the methane stress in 4 weeks of treatment in field.
- Natural gas specialized stress indicator, VDMI, can detect the methane stress in 3 weeks in field;
- DNN can predict the methane stress in field in 3 weeks of the treatment.
- Methane stress will increase the reflectance in VIS and decrease in NIR.

Next Steps

- More biochemical experiments are needed to determine the mechanism of stressing and then guide the stress detection by vegetation indicators.
- More techniques can be integrated in natural gas leak detection by hyperspectral imaging to improve the accuracy of detection.

Public Page

- The final report is posted on the PHMSA CAAP website at the following link: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=843
- This presentation is available now.

The Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Pipeline Safety Research Program

An Unmanned Aerial System of Visible Light, Infrared, and Hyperspectral Cameras with Novel Signal Processing and Data Analytics

Objective: The project objectives are to:

1. Develop and integrate a robust and stable, semi- or fully automated unmanned aerial system with multiple sensors for multi-purpose pipeline safety data collection;
2. Explore and develop novel signal and image processing techniques for data analytics, damage assessment, and condition classification; and
3. Evaluate and validate field performance of the integrated unmanned aerial system for pipeline safety inspection.

Project page and final reporting are available: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=843

Meeting Information:

Tuesday, May 9, 2023, 10:00 a.m. to 11:00 a.m. ET

Microsoft Teams Meeting:

https://teams.microsoft.com/l/meetup-join/19%3ameeting_NzcxZWZlMjktNjI2NC00NmIyLWFhZmQtMzRhOTgyYzIzOWJh%40thread.v2/0?context=%7b%22Tid%22%3a%22c4cd245b-44f0-4395-a1aa-3848d258f78b%22%2c%22Oid%22%3a%2234c0cacb-d46c-4db0-8318-2afeee3536d9%22%7d

Agenda:

Welcome and PHMSA Introduction

Summary Slideshow of Project Results

Open Q&A and Discussion

Adjourn

Please contact Nusnin Akter (839-273-0528 or nusnin.akter2@dot.gov) with any questions.

Closing Remarks

- Researcher Name
  - Genda Chen, Ph.D., P.E., Fellows of ASCE, SEI, ISHMII, and SPIE
- Email Contact Information
  - gchen@mst.edu

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