Long-term Biomonitoring of Coal Ash Impoundments Using Plants and Unmanned Aerial Vehicle (UAV)-Deployed Remote Imaging Platforms

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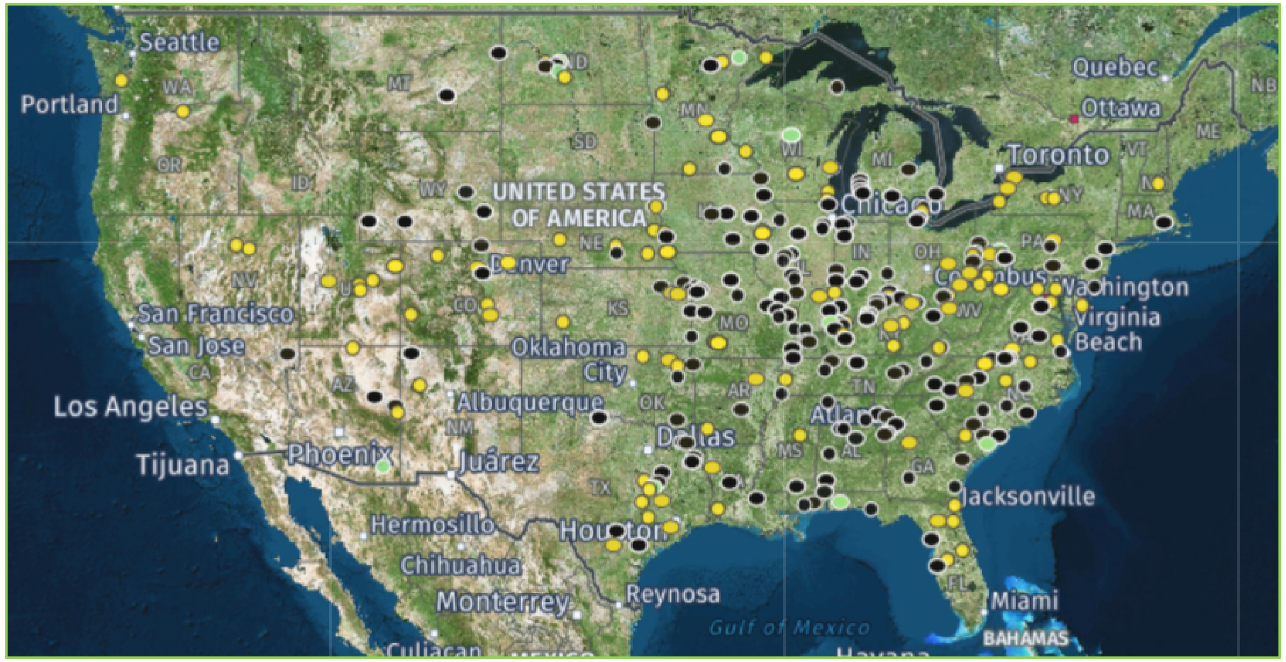
Background

- Coal-fired power plants produce a wide variety of coal combustion residuals (CCR) in their waste streams that are typically disposed of in landfills and surface impoundments.

- CCR waste streams contain metals and other inorganics that may be persistent, bioaccumulative, or toxic and pose potential human and ecological health risks should leakage or rupture of the impoundment occur.



Locations of coal ash disposal units in the US. Image from Source: https://earthjustice.org/features/coal-ash-contaminated-sites-map

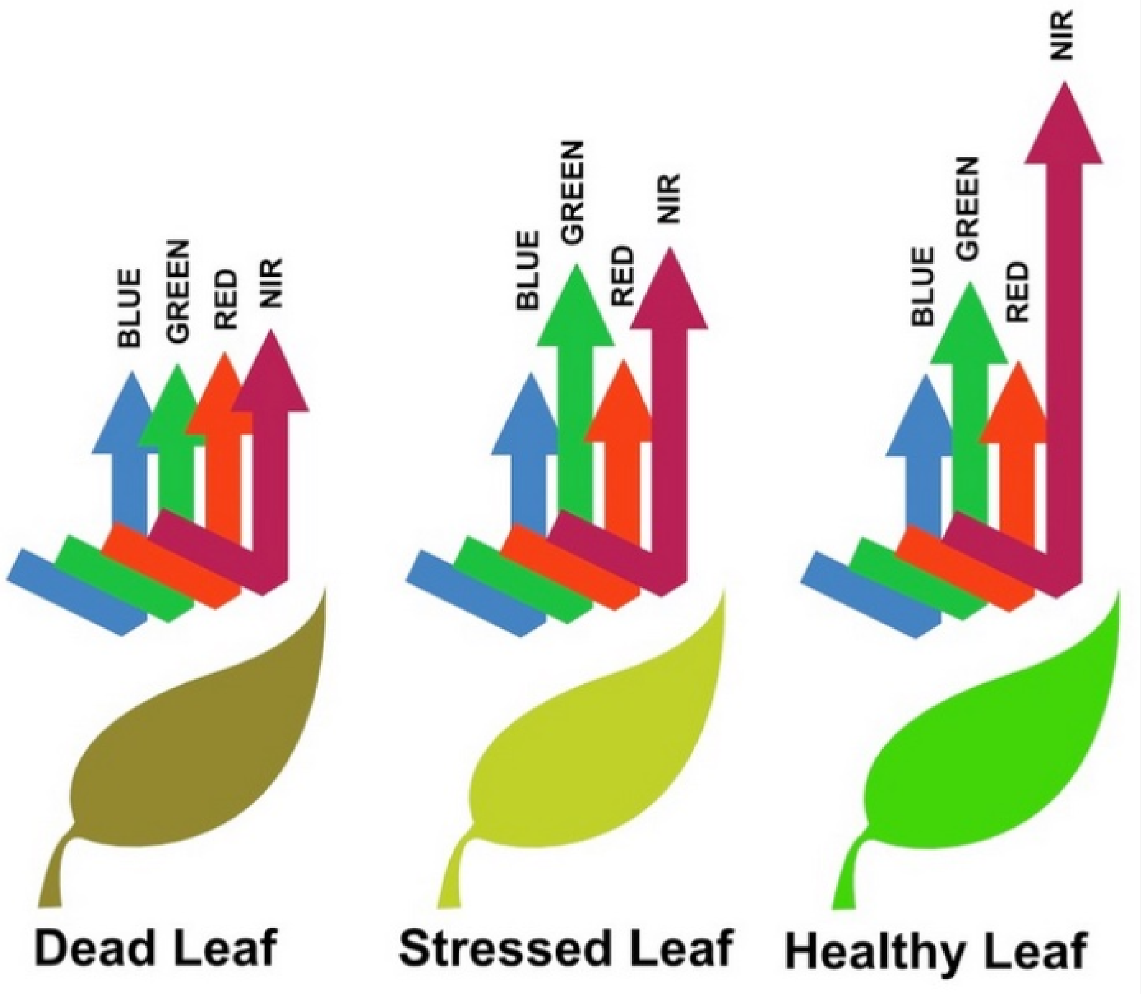
Background cnt...

- Long-term monitoring of coal ash impoundments is resource-intensive and largely manual.

- Significant advances in remote imaging using unmanned aerial vehicles (UAVs) are occurring in the precision agriculture domain which can be directly leveraged for more autonomous and efficient long-term risk monitoring of coal ash impoundments (and other contaminated areas).

Objective

- **The objective of this study was to investigate the feasibility and value of collecting indicator data for measuring plant responses at contaminated sites and inferring changes in site contamination profiles.**
- Fly ash can contain levels of metals, metalloids, and other trace elements that are toxic to plants.
- Metals and metalloids like Cd, Pb, Ni, and As present in soil can enhance the formation of reactive oxygen species (ROS), which generate oxidative stress in plants.
- Many plants will exhibit signs of stress when exposed to heavy metals. Elevated concentrations of heavy metals in soil can inhibit photosynthesis, which can hinder plant growth.

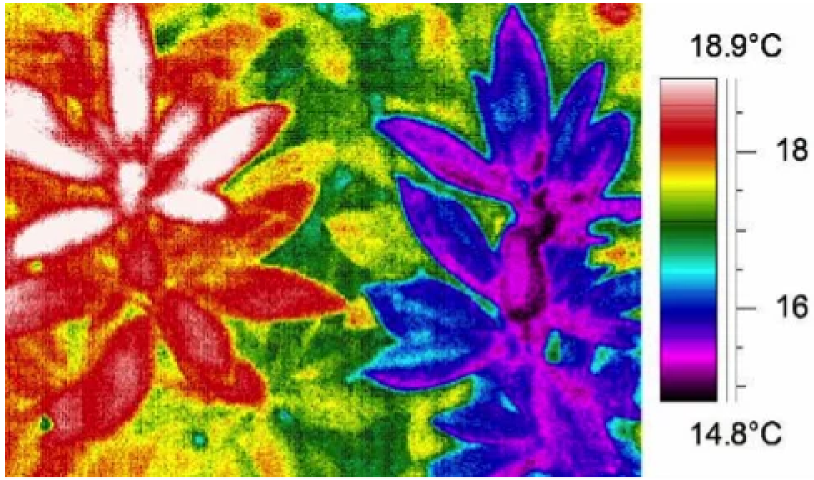


(Qadir et al., 2020), (Yang et al., 2020), (Lakshmi et al., 2018)

Literature Review of Plant Stress Indicators

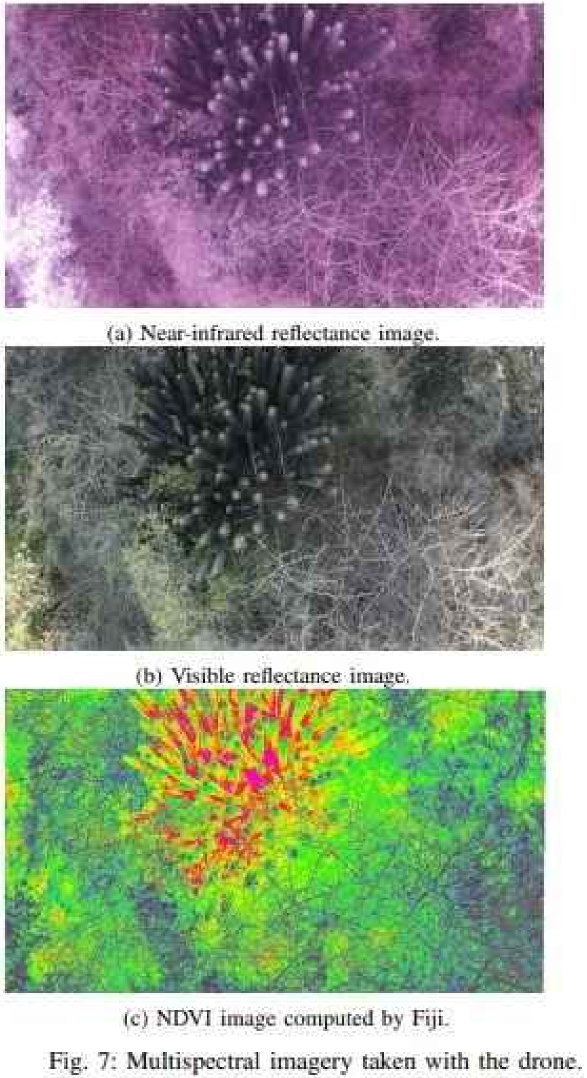
- A comprehensive literature review using a Web of Science search led to a total of 96 papers which were separated into four categories:

1. Hyperspectral/Multispectral/Infrared imaging of plants (N = 32 papers),
2. Aerial visual analysis of changes in plant health (N = 44 papers),
3. Aerial visual analysis of changes in plant diversity (N = 3 papers), and
4. Aerial visual analysis of changes in plant density (N = 17 papers).



Thermal Imaging (Quibit Systems Inc., 2020)

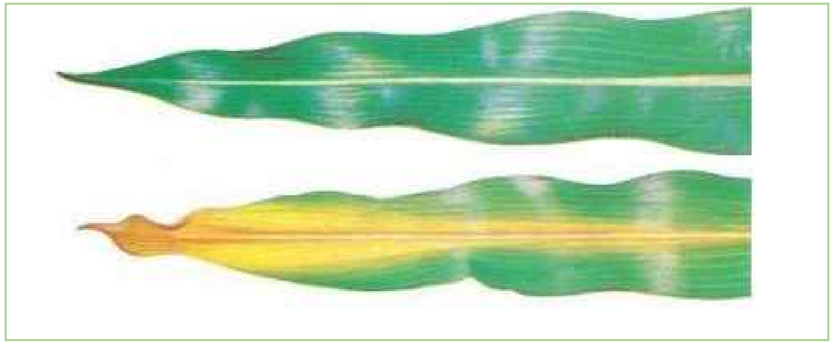
Hyperspectral image of whole plant (Moghadam et al., 2017)



(Montes de Oca et al., 2018)

Literature Review of Plant Stress Indicators cnt…

- Physical stress indicators
  - Morphological changes
  - Deviations in normal leaf development / external structures
  - Changes in height
- Chemical indicators
  - Pigment composition
  - Moisture content
  - Nutrient uptake / retention



Samples of healthy (top) and N-deficient (bottom) leaves; taken from (Zermas et al., 2015).

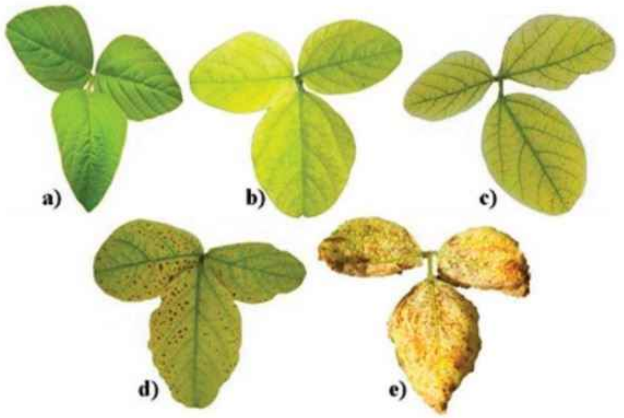


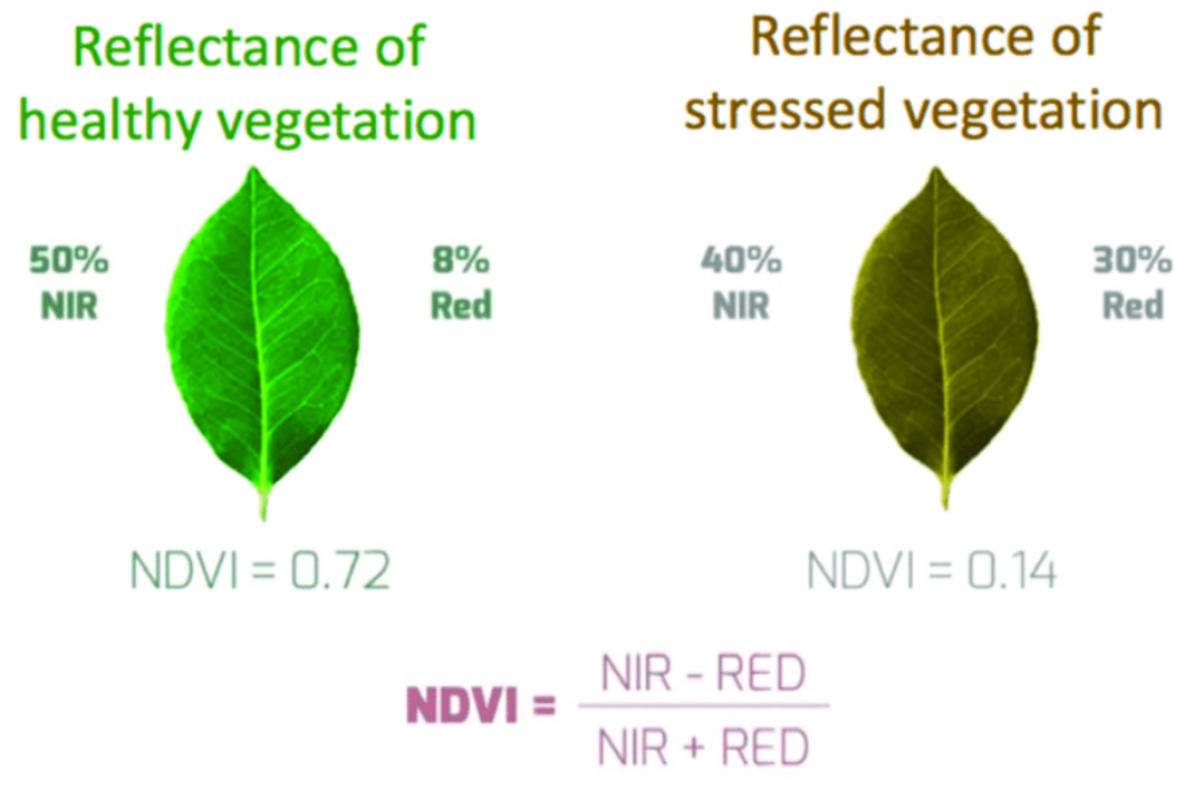
Figure 3. Evolution (25 days) of increased symptoms on soybean leaves (a, b, c, d and e).

Figure 4. Difference in growth between the plants in the most contaminated soil (Soil 1) and less contaminated (Soil 7), sixty days after the seeding.

Phytotoxicity in soybean plants; taken from (Lígia de Souza Silva et al., 2014)

List of Indicators

- Red Edge Index (REI) (~700-750 nm)
- **Leaf Chlorophyll Concentration (LCC)**
- Chlorophyll *a* and Chlorophyll *b*
- **Normalized Difference Vegetation Index (NDVI)**
- Leaf Area Index (LAI)
- Above Ground Biomass (AGB)
- **Plant Nitrogen Concentration (PNC)**
- Air Pollution Tolerance Index (APTI)
- **Crop Water Stress Index (CWSI)**
- Soil Adjusted Vegetation Index (SAVI)
- Optimized Soil Adjusted Vegetation Index (OSAVI)
- Optimal Vegetation Index (Viopt)
- Normalized Difference Texture Index (NDTI)



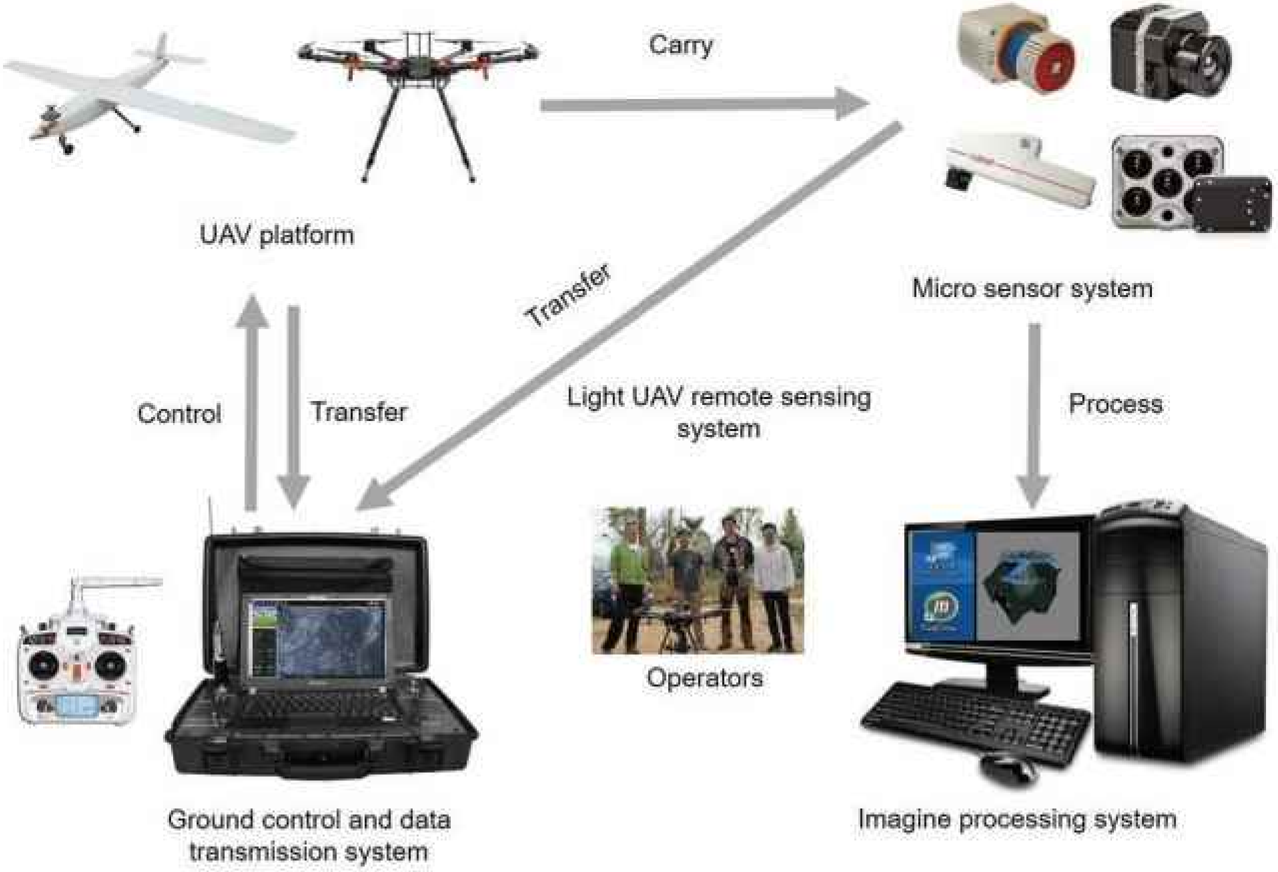
Example of the use of a normalized difference vegetation index (NDVI).

(Loures et al., 2020)

Remote Sensing System

Fig. 3. Rotary-wing UAVs.

Fig. 2. Fixed-wing UAVs.



- (Sun et al., 2021), (Radoglou-Grammatikis et al., 2020)

Multispectral Imagery

- **Multispectral camera**
  - Mainly used in plant research and precision agriculture for estimating the **vegetation state**
    - Normalized Difference Vegetation Index (NDVI)

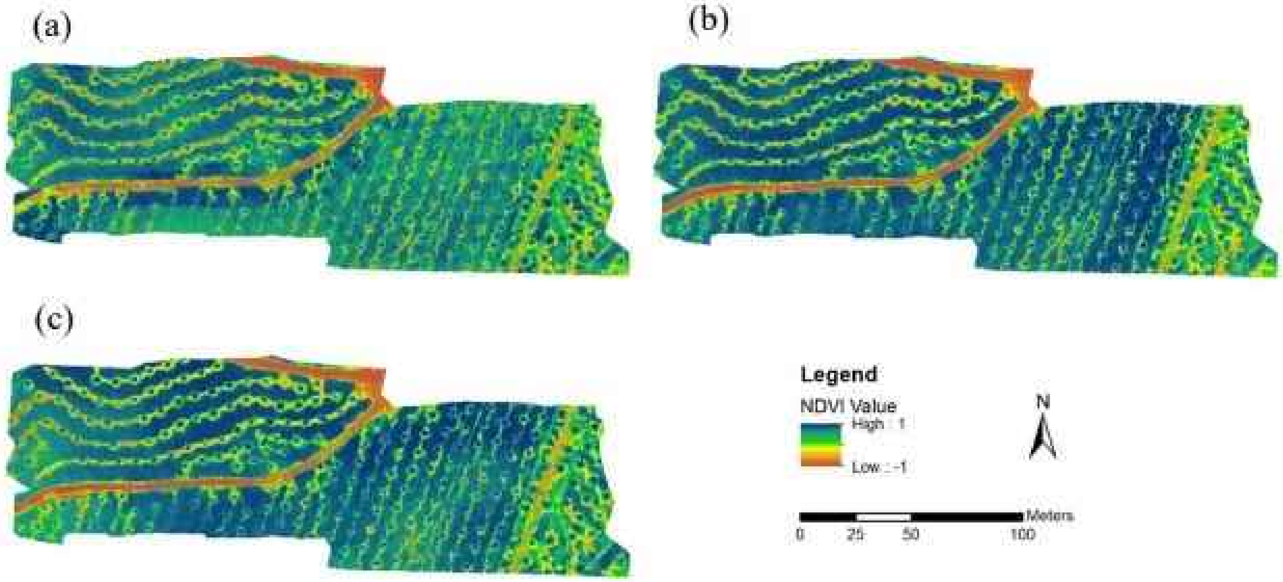


Figure A3. Normalized Difference Vegetation Index (NDVI) for (**a**) 20 m, (**b**) 60 m and (**c**) 80 m altitude.

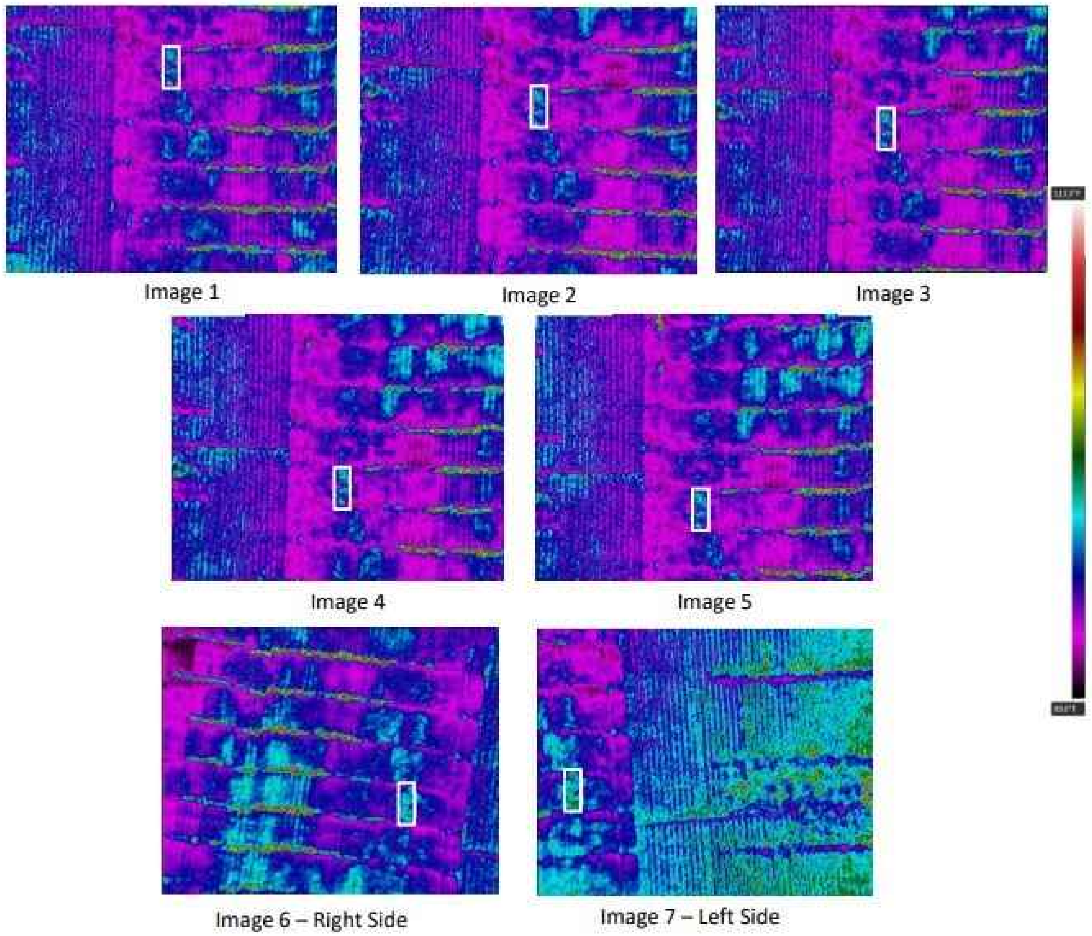
- DJI Phantom–4 mounted with a MicaSense RedEdge multispectral sensor
- Biophysical parameters were extracted to monitor health conditions and growth of oil palm trees in precision agriculture practices

(Avtar et al., 2020)

Thermal Imagery

- **<u>Thermal camera</u>**
  - Mainly used in plant research and precision agriculture for evaluating **<u>water stress</u>**
    - Crop Water Stress Index (CWSI)

- FLIR VUE Pro R 10 mm thermal camera
- Canopy temperatures were recorded to identify unhealthy soybean plants that had been infected with a fungal disease that causes sudden death syndrome



(Hatton et al., 2020)

Hyperspectral Imagery

- **Hyperspectral camera**
  - Mainly used in plant research and precision agriculture for calculating chemical attributes, such as **nitrogen state** and **chlorophyll density**
    - Plant Nitrogen Concentration (PNC)
    - Leaf Chlorophyll Concentration (LCL)

- Micro-Hyperspectral imager (VNIR model)
- Estimating leaf carotenoid content in vineyards

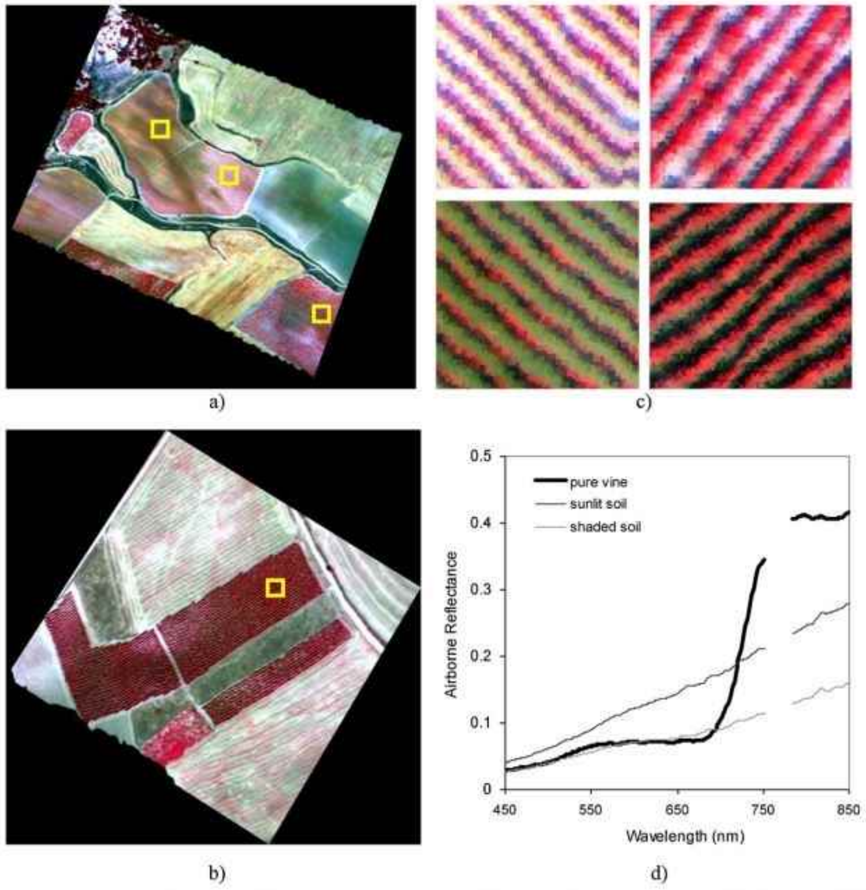


Fig. 1. Hyperspectral scene (a) obtained with the micro-hyperspectral imager on board the UAV platform at 40 cm resolution, enabling pure vine identification (b). The imagery enabled the separation of pure vine from shaded and sunlit soil reflectance (c), observing the scene components and the pure vine reflectance later used for index calculation (d). Yellow squares (a and b) shown in detail in (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(Zarco-Tejada et al., 2012)

Use of Multiple Imaging Systems

- Multiple imagery systems are sometimes used simultaneously to complement one another and draw out a specific vegetation index or combination of indices.
- A micro-hyperspectral imager and a thermal camera.
- Extract pure crown temperature, radiance and reflectance spectra to estimate chlorophyll fluorescence, visible ratios and structural indices for water stress detection.

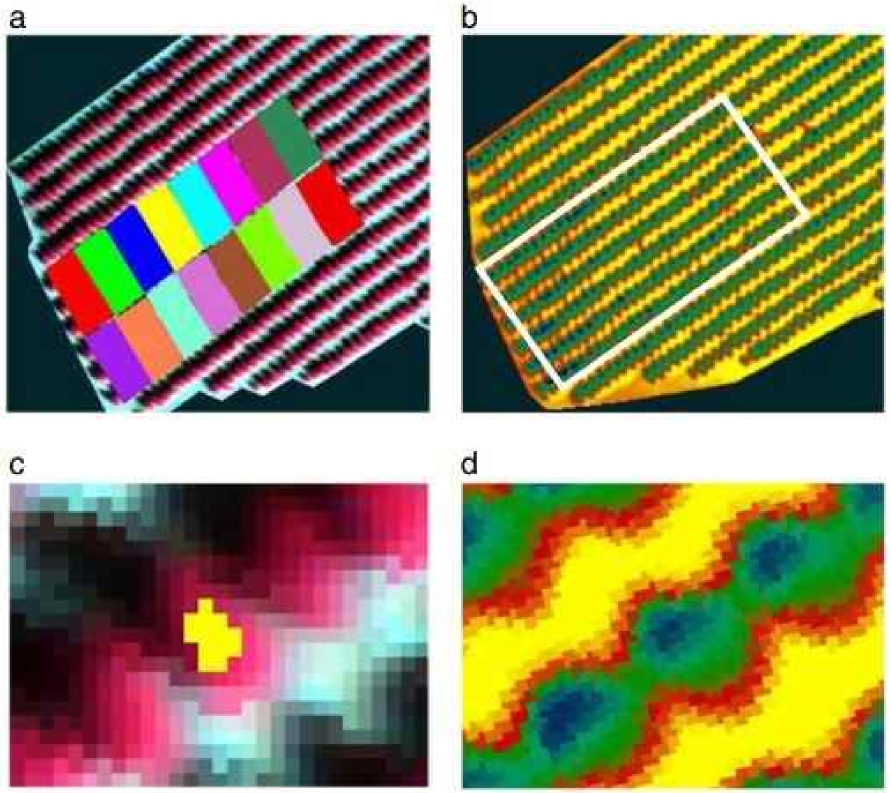
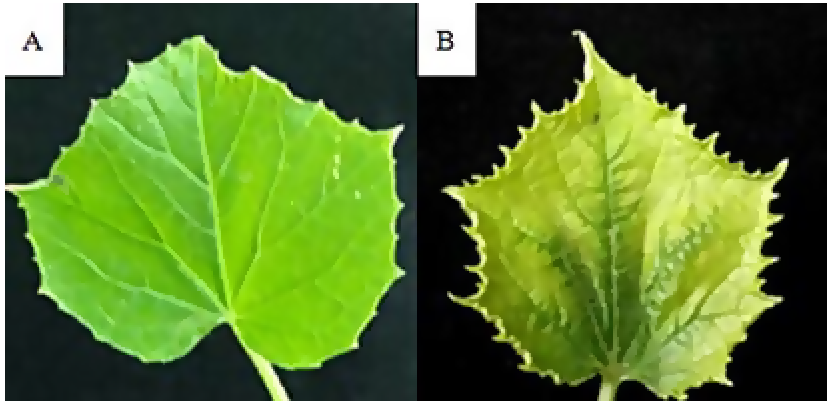


Fig. 3. Sixteen experimental irrigation blocks designed for well-watered (100%ET) and regulated deficit irrigation (RDI) schemes used for pure crown radiance and reflectance extraction (a) from the micro-hyperspectral imagery acquired at 40 cm resolution and 260 bands at 6 nm FWHM (c). The same experimental field was imaged using a high resolution thermal camera acquiring at 40 cm pixel size (b), enabling the extraction of pure tree crown temperature from each irrigation block (d).

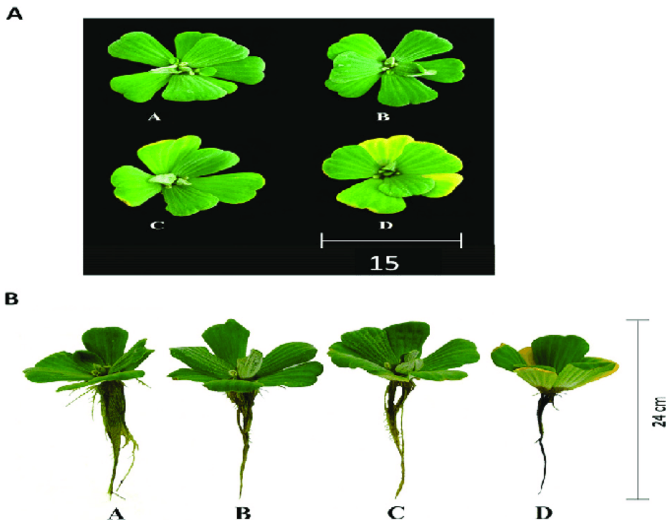
(Zarco-Tejada et al., 2011)

Findings

- Even minor shifts in plant reflectance, health, diversity, and density can provide an early warning to site managers that the risk profile of the site is changing.
- The literature shows that stress in plants can be detected and monitored efficiently and effectively using UAV-deployed remote imaging platforms.
- For monitoring plant responses on or around coal ash impoundments, the mentioned indices would provide the information needed to determine if plant stress is occurring due to heavy metal contamination



A. Healthy leaf B. Cadmium exposed leaf; taken from (Sun et al., 2015)



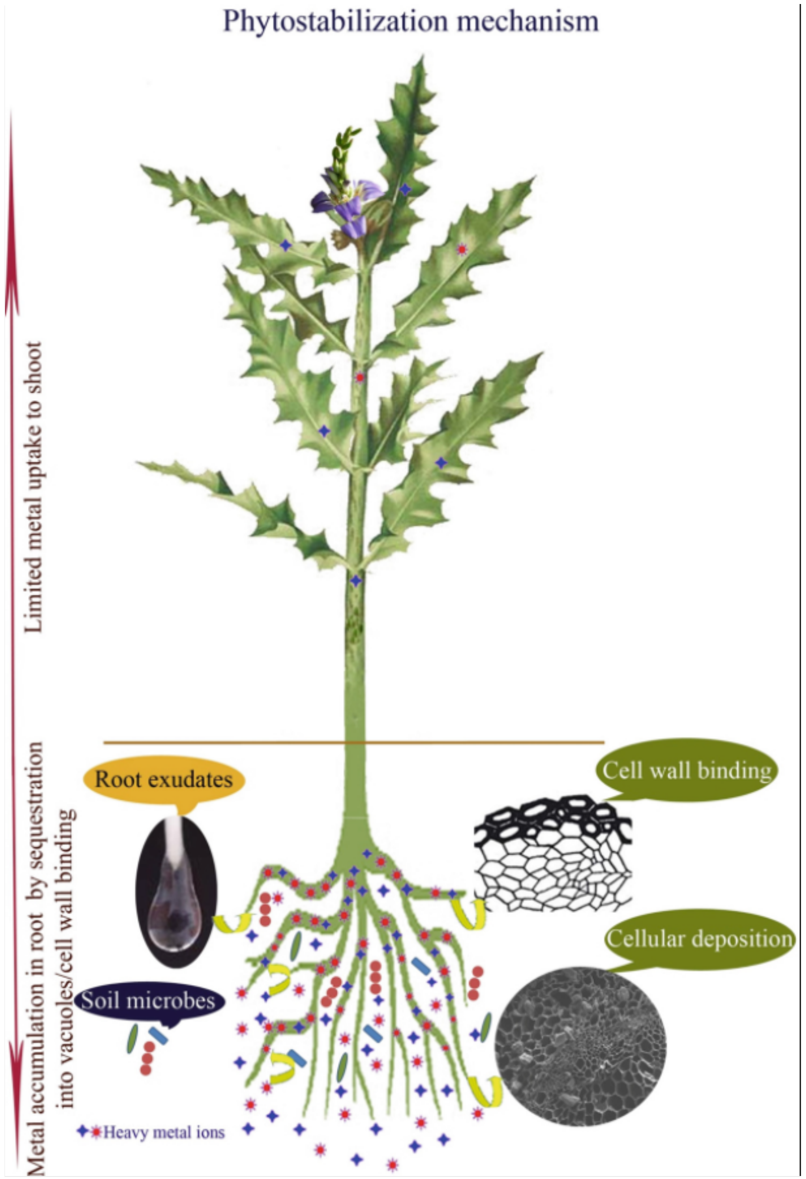
Visual symptoms of leaf (A) and root (B) exposure to Arsenic; taken from (Isiuku & Ebere. 2019)

Challenges

- Weather plays a large role in the ability to use drones for aerial imaging.
    - Strong winds / cloud coverage
        - Maintaining stability and altitude
    - Battery efficiency / life
    - Short flight duration
    - Limited communication distance
    - Weight / payload restrictions
- Inability to quantify the concentration of the target metal.
- Detection of heavy metal contamination is often qualitative and binary (present/absent) rather than quantitative, where quantification requires further soil testing by ground personnel.

Parallel Study

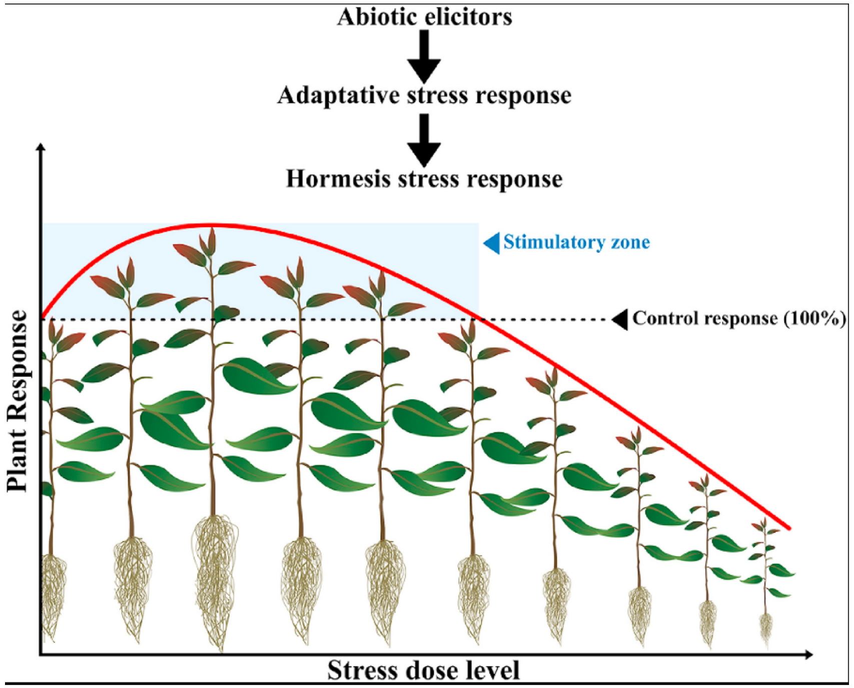
- **Grasses and Legumes**
- Grasses are considered for initial vegetation cover as they are drought tolerant and can grow in poor conditions.
- Grasses gradual growth to develop massive root systems helps to slow down erosion, increasing soil shear strength and conserving moisture.
- At dormancy, dried shoots form mulches which also prevents erosion, facilitates water infiltration, improves soil moisture, ameliorates soil temperature and enhances nutrient supply.
- Legumes exhibit rapid growth as well as enhance substrate characteristics by increasing organic carbon and total nitrogen content.

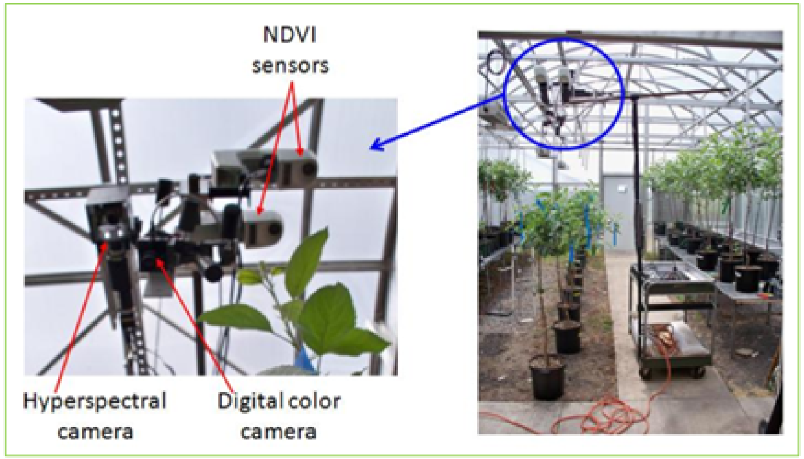


Schematic of contaminant stabilization in the soil by plants (image from Shackira and Puthur, 2019)

Next Steps

- Conduct greenhouse studies to capture aerial imagery (multispectral, hyperspectral, thermal infrared) of plants exposed to contamination at ash impoundments and identify/interpret stress-response relationships.
- Identify specific spectral bands that detect change as the sentinel plant responds to contaminant fluctuations in soil.
- Determine which camera types and stress-response indicators (e.g., temperature, NDVI, etc.) are best suited for larger scale field demonstration at a CCR landfill.
- Examine each sentinel species' phytostabilization potential of As and Se in CCR contaminated soil.





(Jalal et al., 2021)

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