

The Climate Adaptation and Resilience Monitoring Alliance: New Technologies for Ecological Monitoring in a Rapidly Changing Environment



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Abstract

Climate Adaptation and Resilience Monitoring Alliance (CARMA) is a team utilizing NASA's STELLA (Science and Technology Education for Land/Life Assessment) device to study the impacts of climate change on plant health in a variety of vulnerable environments. By using this technology, CARMA can determine whether a plant is stressed before it shows visible signs. STELLA can determine the health of the plant by observing the relative levels of twelve unique Near-Infrared and Visible wavelengths. Ideally, a healthy plant should absorb red light for photosynthesis and reflect high levels of Near-Infrared irradiance. An unhealthy plant should reflect higher Visible red light and reflect less Near-Infrared irradiance. STELLA allows researchers to measure the extent to which plants are undergoing stress within their own communities or other areas of interest. By pairing this with Landsat data, general trends can be compared to specific point-based measurements over time to paint a full and detailed picture of plant health in the area. Monitoring plant health allows for investigation of causes of stress including drought, soil health, and agricultural practices. CARMA is testing STELLA in a variety of environments: urban/campus, wildfire impacted areas, state park lands, and rural agricultural lands. An inexpensive handheld spectrometer like STELLA could allow ranchers and farmers to monitor the conditions of the crops and fields that feed their communities, so CARMA is focusing on a rural ranching property devoted to conservation practices. STELLA was originally intended for educational community science purposes, but it has the potential to contribute to professional research and sustainability efforts. NASA's mission to educate the youth about the importance of monitoring climate change would be enhanced by continued support of STELLA's research potential. CARMA is working to provide a variety of datasets in areas and use cases to help guide future use of the STELLA instrument.

Introduction

The Climate Adaptation and Resilience Monitoring Alliance was established with the goal of monitoring the response of plants and their environments to the changing global climate. CARMA is working to develop and enhance cost-effective technologies for monitoring plant health. The CARMA team's current projects include validating NASA's STELLA Spectrometer for use in ecological and agricultural monitoring fields and providing agriculturalists technology that can assess potential causes of plant stress: The Environmental Variance Analyzer Pod (EVA). EVA is a project started by a Senior Design Capstone team for the Colorado Space Grant Consortium. CARMA has been fixing and refining the EVA device.

The NASA STELLA is made with commercial-grade parts and designed to be affordable, with the cost coming in at approximately \$230 as of March 2026. The STELLA device is a handheld spectrometer capable of measuring irradiance at 12 electromagnetic wavelengths ranging from 450nm to 860nm, as well as ambient air temperature, surface temperature, relative humidity, barometric pressure, and altitude. The STELLA displays the current time, date, batch number, surface temperature, ambient temperature, and irradiance values on its display screen. If a micro-SD card is inserted into the STELLA, then the device will automatically create an excel file named data.csv which organizes all data collected. The data is then accessible by reading the micro-SD card using another computer. The STELLA delineates measurements using a batch number that goes by increments of one every time a new measurement is taken and is reset to zero when the device is restarted.

To measure visual light, the STELLA device uses an Adafruit AS7262 visible light sensor, which measures irradiance in $\mu\text{W}/\text{cm}^2$ at 450nm, 500nm, 550nm, 570nm, 600nm, and 650nm each with 20nm full-width half-max detection, 5nm wavelength uncertainty and 12%

irradiance uncertainty. To measure near infrared light, the STELLA device uses a SparkFun AS726x NIR spectral sensor, which measures irradiance in $\mu\text{W}/\text{cm}^2$ at 610nm, 680nm, 730nm, 760nm, 810nm, and 860nm each with 20nm full-width half-max detection, 5nm wavelength uncertainty and 12% irradiance uncertainty. Both sensors have a 40° field of view and operate by using silicon interference filters to isolate desired wavelengths onto photodetectors with bell-curved shaped spectral response functions. The bell-curved shape means that a photodetector will have peak sensitivity at the center of the bandwidth and minimal sensitivity at the edges of the bandwidth. The measurements that the STELLA displays for each wavelength are the integral of the detected incoming radiation weighted by the spectral response function.

To measure surface temperature, the STELLA uses a DigiKey MLX90614 thermal infrared sensor. This sensor has a 35° field of view and has been factory calibrated to measure object temperatures ranging from -70°C to $+380^\circ\text{C}$ with 0.5°C of uncertainty, which far exceeds any temperatures that the STELLA would be used to measure.

To measure ambient temperature, the STELLA uses an Adafruit MCP9808 temperature sensor. This sensor is accurate from -40°C to $+125^\circ\text{C}$ with 0.25°C of uncertainty. While there are other sensors on the STELLA capable of measuring temperature, this sensor is made to provide the most accurate readings.

To measure relative humidity, barometric pressure, and altitude, the STELLA uses an Adafruit BME280 temperature, humidity, and pressure sensor. This sensor can measure humidity with $\pm 3\%$ accuracy, barometric pressure with $\pm 1\text{hPa}$ accuracy, and can use pressure to determine altitude with ± 1 meter accuracy.

The STELLA's ability to identify plant stress before there are visible signs makes it an excellent tool for non-invasive data collection. Devices like STELLA have the potential to technologically advance ecological research, as they enable assessments of plant health in vulnerable systems to be captured efficiently without there being adverse environmental effects.

The second major project being worked on by the CARMA team is the Environmental Variance Analyzer Pod, or EVA for short. The EVA is an autonomous data collection system. It is meant to measure changing variables in the environment to put together a picture of the immediate ecological conditions. EVA Pods contain a suite of sensors collecting soil, gas, light, pressure, and temperature data. The pods come preassembled, and the user picks the location. Farmers, researchers, and civilians can use EVA Pods to understand the effects that environmental factors and decisions have on plant health. For example, a farmer could install one pod along a new irrigation line to understand its effects on soil moisture and composition in that area. Each pod takes measurements at a chosen frequency, such as six times per day. The data is saved to an SD card and can be uploaded to the EVA Pod website by the user. On the website, users can view a map showing the locations of actively used EVA Pods. By clicking on a pod, the user can view its data logs and graphs.

EVA is meant to supplement and elucidate STELLA data. EVA Pods and the associated website allow users to understand the plant health trends they witness. For example, if STELLA readings indicate that a plant on one part of a property is stressed, EVA data could indicate the cause of this stress. If an EVA in that area is showing lower than normal soil moisture or increased sun exposure, the plant is likely dehydrated. Similarly, an EVA Pod may indicate soil nutrient imbalance, concerning soil off-gassing behavior, high surface temperature, or several other factors that could explain a STELLA's readings.

Ongoing Research Efforts

Field Studies

Investigation of Ecological Trends within National Parks

Recently, CARMA has been granted permission to conduct research in Yellowstone National Park. The CARMA team plans to collect data within the park in July of 2026.

CARMA's upcoming research within Yellowstone involves investigation into three main areas of ecological study: drought impacts on wetland species, fungal symbiosis as a means of climate resilience, and the influence of trophic cascades on quaking aspen.

Among the habitats within the park, wetlands are documented as the most susceptible to drought stress. However, *Dichanthelium lanuginosum*, a wetland plant grown near geothermic springs, demonstrates high tolerance when exposed to drought conditions detrimental to other wetland species. This is due to the beneficial relationship it has established with the fungus *Curvularia protuberata*. In hopes of understanding plant adaptations imposed by climate effects, CARMA will directly compare the shift in thermal tolerance across wetland communities with STELLA.

Trophic cascades in Yellowstone, such as the indirect relationship between quaking aspen maturity and grey wolf reintroduction, influence a shift in plant stress tolerance within the park; this applies especially to communities within alpine zones. STELLA can directly assess the health of aspen trees following the reintroduction of grey wolves, reinforcing documentation on the effects an imbalanced ecosystem has upon ecological health.

By applying the unique STELLA technology to past research efforts in Yellowstone National Park, CARMA hopes to cement STELLA as an effective and efficient technology with the potential to innovate ecological monitoring in research fields.

In addition to Yellowstone, The CARMA team has recently submitted a research permit application to Rocky Mountain National Park. In the summer of 2026, CARMA hopes to collect data in Rocky Mountain National Park that will inform three research initiatives: the use of spectrometry in the evaluation of bark beetle presence, the impacts of climate change on alpine species, and the impacts of elk overgrazing on quaking aspen trees.

Bark beetle infestation has become increasingly problematic due to the intensifying effects of climate change, so new ways to stop or at least contain the spread are essential. Aerial surveys taken in 2022-2024 by the Colorado State Forest Service and U.S. Forest Service indicate bark beetle outbreaks throughout Rocky Mountain National Park, with the most prevalent pest being the western balsam bark beetle (Colorado State Forest Service, 2024). By analyzing subalpine firs impacted by western balsam bark beetles, CARMA will determine if the STELLA can detect wavelength differences like those found in past studies between healthy trees and trees in the green stage of beetle infestation.

Climate-sensitive ecosystems like those in alpine zones are especially impacted by climate change and its residual effects. These impacts on alpine plants have been observed as part of the Global Observation Research Initiative in Alpine Environments (GLORIA) (Powers, 2024). To inform future restoration efforts and support GLORIA in understanding the reasons behind these shifts in biodiversity, CARMA will monitor and evaluate the health of three alpine species with respect to elevation and aspect as potential factors.

Elk overgrazing, a long-documented issue in Rocky Mountain National Park, has come to be known as a limiting factor in the maturing of quaking aspen trees. With the STELLA device, the CARMA team can efficiently document the health of aspen stands in elk-frequented areas without need for physical disturbance of the already weakened trees. This study can reinforce existing documentation on the long-term effects that an imbalanced ecosystem has upon ecological health, and it could further inform overgrazing mitigation.

STELLA as an Aid for Local Agriculturalists

Lance Wheeler, a CARMA stakeholder, is the owner of Rafter W. Ranch in Simla, CO, where CARMA has been granted access to conduct experiments. The research CARMA conducts on the ranch gives Lance insight into the state of the plant life on his property, while also informing the CARMA team's decisions on research methods.

CARMA has already investigated plant stress at various locations around the ranch and has used the space to test various research methods, including the point-line method, and various random sampling methods. CARMA has also utilized Landsat data to identify trends in plant health over time, then taken STELLA to areas where vegetation is likely to be under stress.

CARMA plans to investigate a portion of soil that had been received from Rafter W. Ranch which has been keyline treated. Keyline treatment is intended to support plant growth by creating more room in the soil for water filtration and nutrient distribution efficiency. This will be one of the experiments conducted in CARMA's new in-house greenhouse. The comparison between soil from the ranch which has been keyline treated and soil from a place on the ranch with similar soil composition which has not been keyline treated will be conducted with the intent to give Lance insight into the effectiveness of his treatment strategies.

Greenhouse Study

In addition to the experiments CARMA plans on running with Lance's soil, the team is currently preparing to conduct an original in-house greenhouse experiment with native Colorado grasses. CARMA intends to analyze the effectiveness of commercial fungal inoculants in conveying drought resilience to Blue Grama and Buffalo grass. Inoculating plants with mycorrhizal fungi has been explored as a method of enhancing plant resilience in today's changing climate and reinvigorating suffering ecosystems (Evenson, 2003). In addition to assessing the direct influence of mycorrhizal inoculation on dryland species, CARMA hopes to assess the capability of STELLA to identify the presence of mycorrhizal colonies in plants via unique spectral signatures. CARMA's research efforts are guided by professionals in the fields of microbiology and general ecology, namely Dr. Bridget Hilbig from Weber State University and Dr. Lynn Albert from Red Rocks Community College.

The main in-house greenhouse experiment will involve the observation of plants under simulated drought with and without fungal inoculation to determine the effectiveness of mycorrhizal symbiosis in mitigating drought symptoms. Additionally, a portion of the soil used in the greenhouse experiment will be autoclaved to isolate and specifically measure the impacts of the added mycorrhizae to determine the effectiveness of inoculation. In preparation for this experiment, the CARMA team is conducting preliminary experiments to validate the drought simulation, mycorrhizal inoculation, and greenhouse plant growth methods to effectively combine them later. Currently, the CARMA team is developing a plant growth and observation procedure that is appropriate for the specific soil type, pot size, lighting conditions, and grass species that can be applied to all further blue grama greenhouse experiments.

Research Methods

Experiments CARMA plans to run this upcoming summer and fall require both field and lab work, so procedures on how to implement STELLA in both research spaces are necessary. For example, STELLA will be applied to small pots in a controlled indoor greenhouse. STELLA will also be used in sensitive environments like geothermal and alpine zones in Yellowstone National Park and Rocky Mountain National Park, which evidently have different challenges and needs. Nonetheless, the general procedure for utilizing STELLA remains the same:

1. Turn on and run STELLA set up. STELLA has three modes: yellow, blue, and green. Yellow mode takes 1 measurement. Blue mode continuously takes 1 measurement every second. Green mode takes 1 measurement every second, across 20 seconds. Whichever mode is selected will be kept consistent across all plant measurements at a given plot.
2. Define measurement points:
 - i. Determine which part of the plant will be measured. A plant will either have a homogenous or heterogenous structure. This will influence how STELLA is positioned from the plant being measured, including the device's angle of elevation / depression.
 - ii. Record STELLA's angle on the data sheet.
 - iii. Determine the position of the recorder. The recorder should be positioned such that a minimum amount of shadow falls onto the plant being measured.

iv. Position STELLA 10cm, or approximately 4in, from the determined measurement location on the plant. This distance must be maintained across all calibrations and data collections.

3. Calibrate STELLA:

- i. Place a white photography card at the defined measurement point on the plant.
- ii. Push the red button on STELLA to begin calibration. If in blue mode, the calibration will need to be manually ended (by pressing the red button again). Calibrating STELLA accounts for potential errors caused by varying environmental conditions (like changes in light exposure).
- iii. Record time and batch number (located at the top right corner of STELLA's screen) on the STELLA data sheet.
- iv. Remove the white photography card.

4. Collect data on the plant:

- i. Push the red button on STELLA to begin data collection of the plant. If in blue mode, the collection will need to be manually ended (by pressing the red button again).
- ii. Record time and batch number (located at the top right corner of STELLA's screen) on the STELLA data sheet.
- iii. When applicable, record notable environmental influences that may affect measurement such as:
 - Weather conditions
 - Location with respects to any notable landmarks

- Slope of the plot area
- Light exposure (cloud cover and casted shadows)
- Dirt or litter visibility in STELLA's field of view

5. Photograph all recently measured plants.

It is important that all STELLA data is informed by the conditions in which the data was taken. This can be seen in the comprehensive notetaking, and it is also ensured by the calibration with the standard reference white photography card that standardizes all measurements against a sheet of near-100% reflectance. Thus, these steps are consistent in the STELLA procedure. What varies between procedures is how plants are chosen for measurement and experimental set up. In the case of the greenhouse, a final procedure is still being developed. To ensure success and accuracy in data collection, CARMA's research team has developed preliminary experiments to verify some of the methods used in the final experiment. Data currently available on watering requirements for the grasses of interest are designated for large scales such as lawns. Since CARMA intends to grow these grasses in 1.5-liter pots, this data has been interpolated to inform a small-scale procedure as best as possible. CARMA has worked towards developing a watering procedure that keeps the plant healthy over the span of 7 weeks. Thus far, the following procedure has been made:

1. Fill 600 mL of soil and 400 mL of silica sand directly into the pot. The mixture should sit an inch down from the rim of the pot. Mix the soil and sand together with a scoopula.
2. Take 40 mL of soil-sand mixture from the top of the pot to cover the seeds with afterwards.
3. Evenly cover the top of the pot with 1/8 tsp of blue grama seeds.

4. Cover the seeds with 40 mL of soil and mixture.
5. Water the pot with 4 oz of water.
6. Take 3 STELLA measurements (20 measurements per batch) at a 90-degree angle (normal to the soil's surface).
7. Wait every other day to water the plant with 4 oz. Continue this until 10 days after the pot was planted. Do not water the plant on the 12th day.
8. Water the plant with 2 oz on the 13th day. Then, come back on the 15th day to check if the soil is still wet since the previous watering. If the soil is still wet, wait until the 16th day to water with 2 oz, then water 2 oz every 2 days from there on out. If the soil is dry, water 2 oz that day, then water 2 oz every other day.

CARMA continues to experiment with and adjust procedures in preparation for the mycorrhizae and drought stress studies. For example, Step 1 was added to the procedure because the soil we use directly from Rafter W. Ranch is very rich in clay, so the soil is cut with sand to improve root aeration. After further experimentation and preparation, the official experiments are planned to begin in the summer.

For field work, the steps preceding the usage of STELLA are as follows:

1. Travel to a location of interest. This will be based primarily upon prior research documenting a habitat's expected exposure to specific stressors or previous data collection in certain places.
2. Define plot boundaries and plot lines:
 - i. Using field tape, define an origin point and measure axis lines from that point. These axes should define the boundary of four quadrants, with each side length a standard radius measurement of 50 ft. This standard size is

based off the pixel range of Landsat imagery (100ft x 100ft). However, it should be assumed that the plot size will vary dependent on-site accessibility at location of interest to prevent the disturbance of natural land.

- ii. Using field tape, find the origin point (yellow center in **Figure A**) and define an “angle line” with the length of $\sqrt{x^2 + y^2}$ and angles 45° , 135° , 225° , and 315° (as seen in **Figure A**).

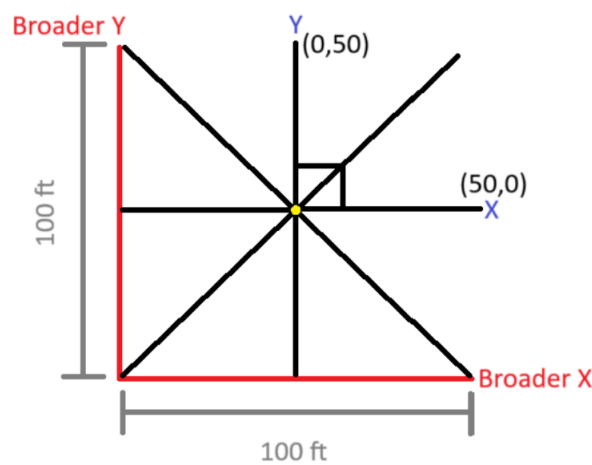


Figure A. Visual Representation of Plot Boundary Area.

3. Collect point source measurements with the STELLA device completing the STELLA data chart created by the CARMA team (**Figure B**) including additional notes.
4. Beginning from the origin point, all field personnel will follow along an angle line, stopping to measure plants of interest that the line intersects.
5. All personnel will proceed down each line at every angle until all plot lines have been covered.

Batch Number	Type of Measurement	Time	Angle	Notes + Species
1	Calibration (C)	11:06am	0°	James' Buckwheat ;
2	Measurement (M)	11:07am		Slight wind
3	C	11:34am	45°	Purple flower ; overcast
4	M	11:34am		
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Figure B. STELLA Data Chart.

When choosing data collection methods for field research, CARMA prioritizes random sampling for point measurements. Once an area of interest is identified, the team follows the procedures above to get an idea of the approximate health of the area without having to measure every member of the species of interest. To get the best estimate of the health of just a single plant, multiple measurements of that plant are necessary (typically 3-5 batches of 20 measurements). CARMA's line and point measurement method allows for a rough evaluation of an area's health to be made efficiently.

To analyze STELLA's data, CARMA's technical team developed MATLAB code that requires the name of the Excel document and the batch numbers in which the data of interest appears in the file to generate Reflectance vs. Wavelength graphs. To generate the reflectance values for the graph, the code first averages the irradiance values taken per batch of measurements, both calibration and respective plant measurements. Once the average irradiances are found for each wavelength (450nm-860nm), the averaged plant irradiance is then divided by its respective averaged calibration measurement to calculate reflectance (%). These values are then graphed for each wavelength as seen in **Figure C**. The shape of the graph, specifically high NIR and green reflectance, indicates a healthy plant.

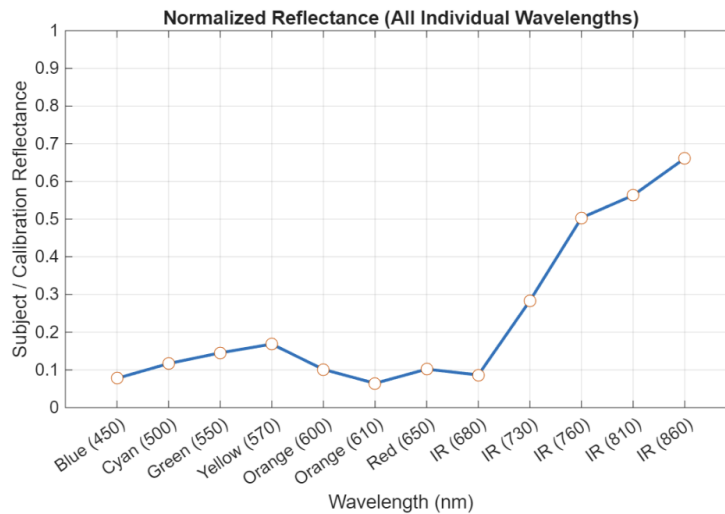


Figure C. Reflectance values (%) for each wavelength (nm) STELLA measures.

Current Challenges

Some current challenges that CARMA is facing are the finalization of research procedures as well as some complications with the functionality of STELLA.

Determining watering procedures for grasses adapted to Colorado's arid environment can be difficult. Luckily, buffalo grass and blue grama are found in similar conditions so the procedures should be similar; however, finding viable online sources on how to germinate and then keep the grasses healthy over a period of 7 weeks is hard to come by at the scale this experiment requires. Because there is so little data available for growing these grasses in about a liter of soil, the CARMA team plans to test different watering procedures until an effective one is found. Thus far, plans to improve the watering procedure include decreasing the quantity and frequency at which the plant is watered. Other environmental conditions, such as light diffusivity

and duration of light exposure, are also being adjusted to determine the optimal experiment set-up.

To test out different watering procedures, CARMA must let a plant grow for at least 2 weeks which takes up a significant amount of time considering the semester is only 16 weeks long. To combat some of these timing issues, CARMA plans to increase the scale of this preliminary experiment to test several watering procedures at once across several pots.

In terms of the STELLA, some issues have been encountered with initial readings taken of plants grown so far. Some of the Reflectance vs. Wavelength graphs display unusual dips in the near infrared range of the spectral signature (610nm-860nm) as well as a jump in visible orange reflectance (600nm).

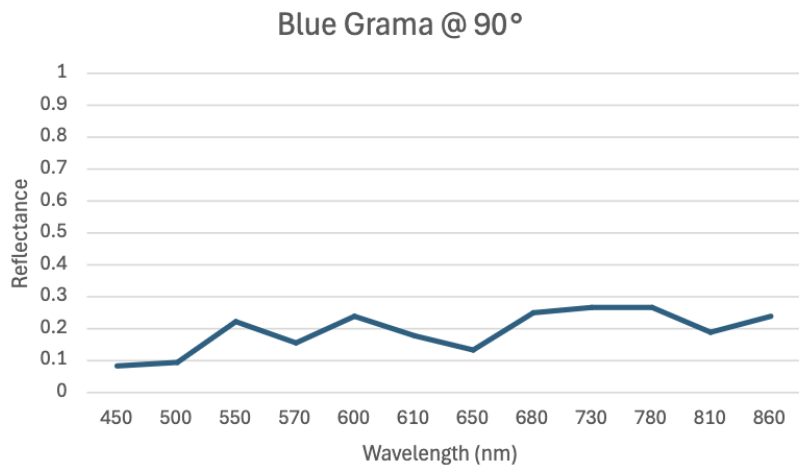


Figure D. STELLA Reflectance vs. Wavelength Graph.

Issues regarding STELLA readings could arise from environmental conditions such as leaf litter and inadequate lighting as well as issues with the device itself. A single STELLA was used for these readings, so future work could include the use of more than one STELLA in

measurements to see if a technical issue is the cause. A potential solution could be transitioning to the STELLA 1.2, a newer version of the STELLA device with improved sensors and increased flexibility.

Future Plans: The STELLA 1.2

An updated iteration of the STELLA 1.1, the STELLA 1.2, has been officially released by the NASA STELLA team. CARMA has been constructing and augmenting this device with the intent to use it for future data collection. The STELLA 1.2 will include the AS7625 Triad Spectroscopy Sensor, which is capable of measuring 18 frequencies of light from 410nm to 940nm. This will allow for additional visible and infrared light wavelengths from the STELLA 1.1 and will reduce the effect of hardware variation in data sets, since all light measurements will be taken using the same sensor instead of two sensors as the STELLA 1.1 currently does. The updated 1.2 STELLA device will enhance the team's technical capabilities and allow for increased efficiency and accuracy of data collection in field and greenhouse settings. In demonstrating STELLA's utility, the CARMA team hopes to enhance environmental monitoring at a low cost in the fields of agriculture and ecological research.

References

- Colorado State Forest Service. (2024). *Common Forest Insects & Diseases*. Colorado State University. <https://csfs.colostate.edu/forest-management/common-forest-insects-diseases/>.
- Evenson, Vera S., et al. “The Use of Mycorrhizal Fungi in Restoration of Highly Disturbed Soils in Boulder Country Open Space Lands.” Denver Botanic Gardens, 2003, <https://assets.bouldercounty.gov/wp-content/uploads/2017/03/research-report-2002GrantDeprenger.pdf>. Accessed 4 Dec. 2025.
- Powers, C., E. Borgman, and D. F. Doak. 2024. Climate and species traits shape responses of alpine flora in the US Rocky Mountains to a changing world: Analysis of five GLORIA sites across the southern Rockies. Science Report NPS/SR—2024/221. National Park Service, Fort Collins, Colorado. <https://doi.org/10.36967/2306920>
- STELLA. (2025, July 2). Spectral STELLA. <https://science.gsfc.nasa.gov/stella/instruments/spectral/>