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*__RadSCape__: radiative transfer simulation of the dynamic structural and spectral properties of the vegetation of the Cape

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South African Collaborators

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DIRSIG Simulation Team

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**Assumption: Cape region's ecological importance has been explained*

May 28, 2025

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What We Proposed

Improve remote **FYNBOS** measurement & monitoring via a combination of

Fynbos trait measurements

+

Radiative transfer modeling in a biophysically- and physics-robust simulation environment

Validated using NASA imaging spectroscopy and LiDAR remote sensing data from the BioSCape airborne campaigns

- To improve our ***understanding of light interactions within the context of fynbos biophysical traits, at different spatial scales, spectral resolutions, and other system parameters***
- A ***mechanistic linking of structure/spectra-to-traits*** & assess approaches to ***track biodiversity as a function of post-fire recovery time***

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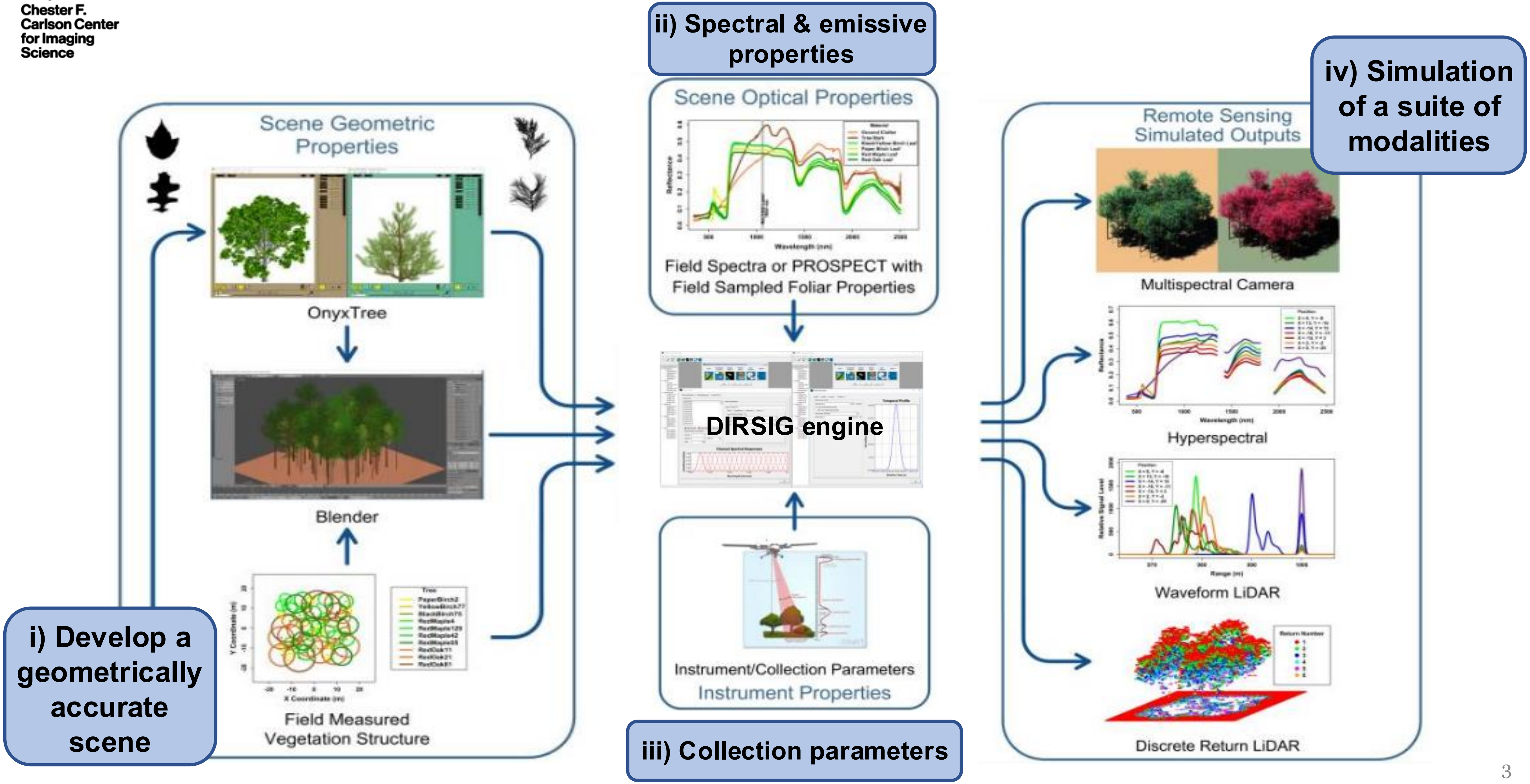
The Simulation Backbone - DIRSIG



Field Sampling

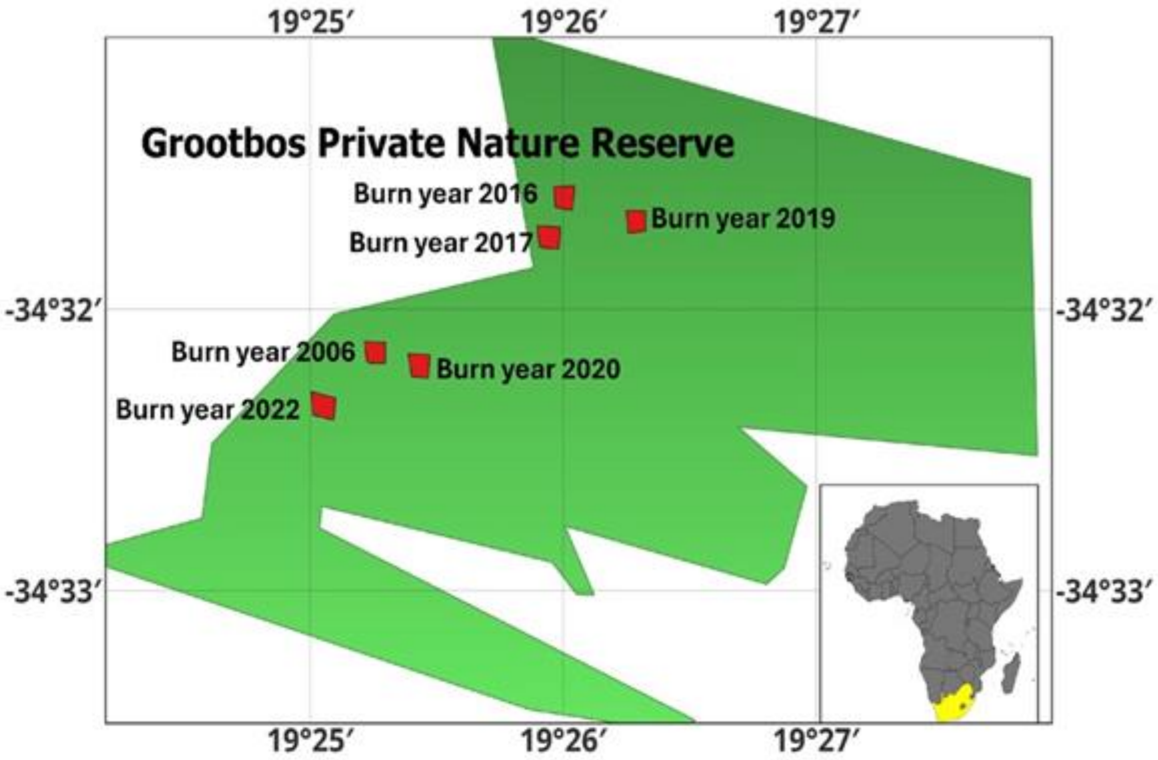
BioSCape regions-of-interest: **Grootbos Private Nature Reserve**

- Goal: Capture variability in fynbos species composition and structure for virtual scene development

Dimension: 5m x 5m & 5 x 10 m releves

Data Collected:

- Leaf spectra per species
- Background spectra (soil, dead wood, burned wood)
- Plant species fractional cover, mean diameter
- Six drone survey plots across six **time-since-last-fire** gradients per site (burn year- 2006, 2016, 2017, 2019, 2020, 2022)



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Utilizing UAS to ***Differentiate Fynbos Vegetation of Different Post-fire Ages*** and ***Alpha Diversity Mapping***

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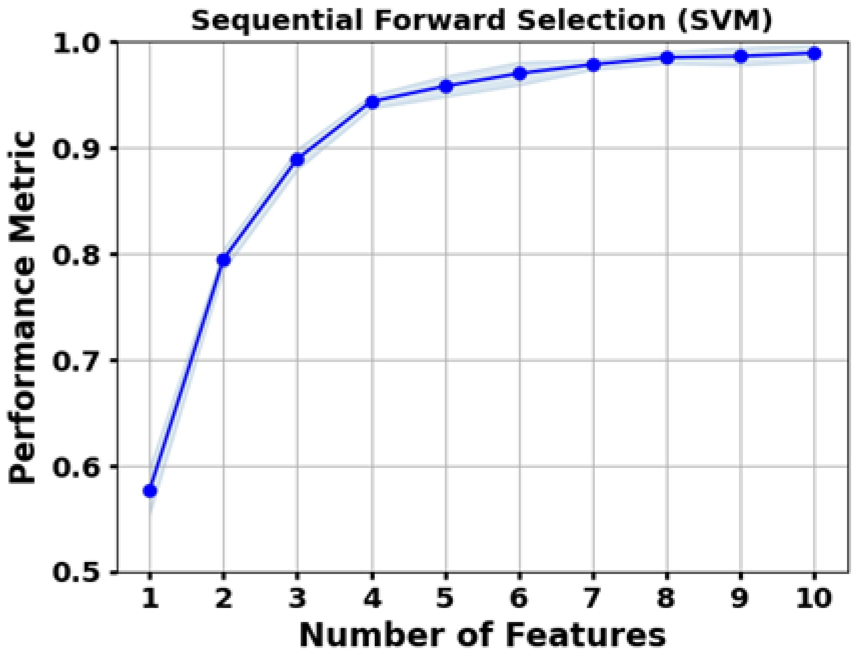
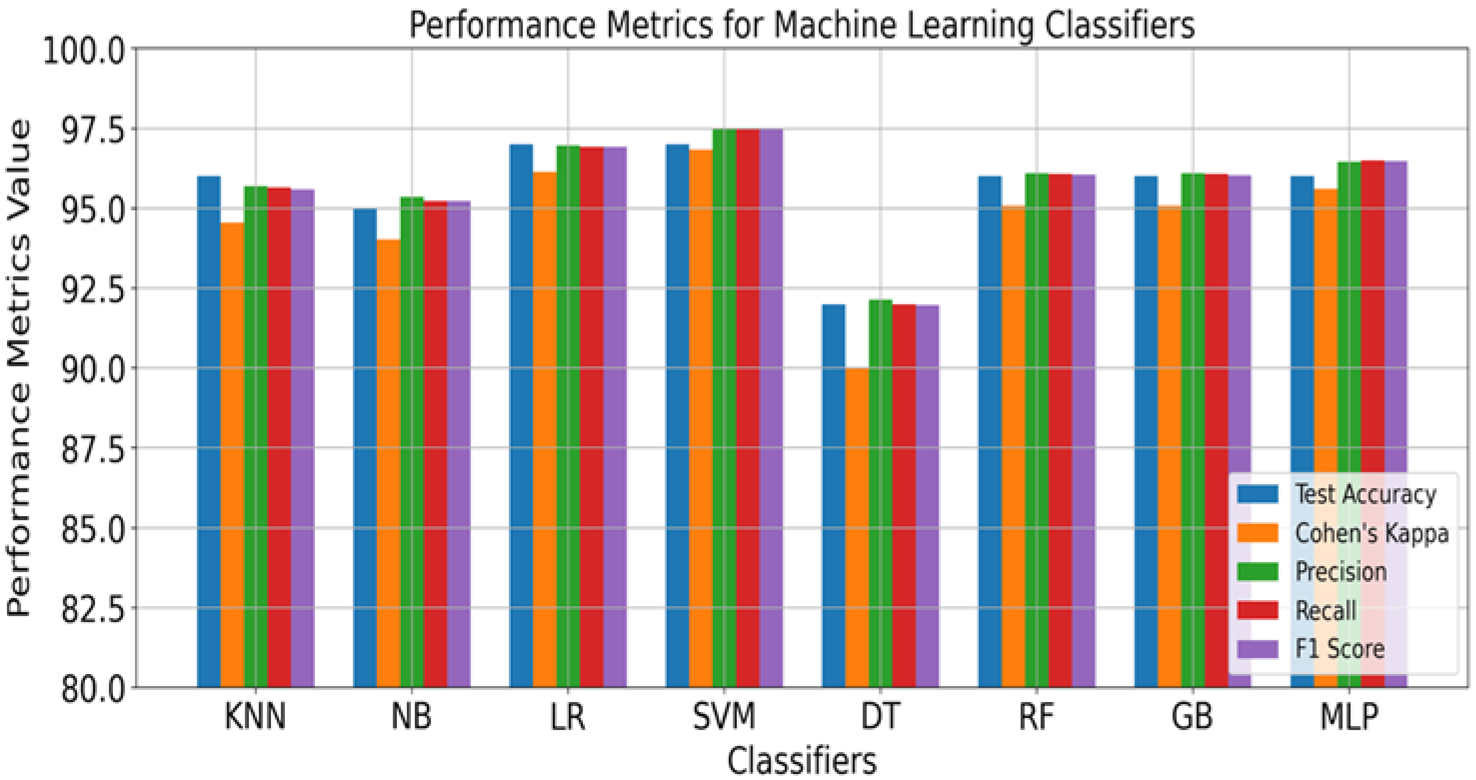
Classification Results

Best Results: **SVM**





Seven Features:

- Five spectral: Mean of NIR, CV of RE, mean of CVI, CV of LCI, CV of ratio1
- Two textural: Mean of dissimilarity in red band, mean of homogeneity in NIR band

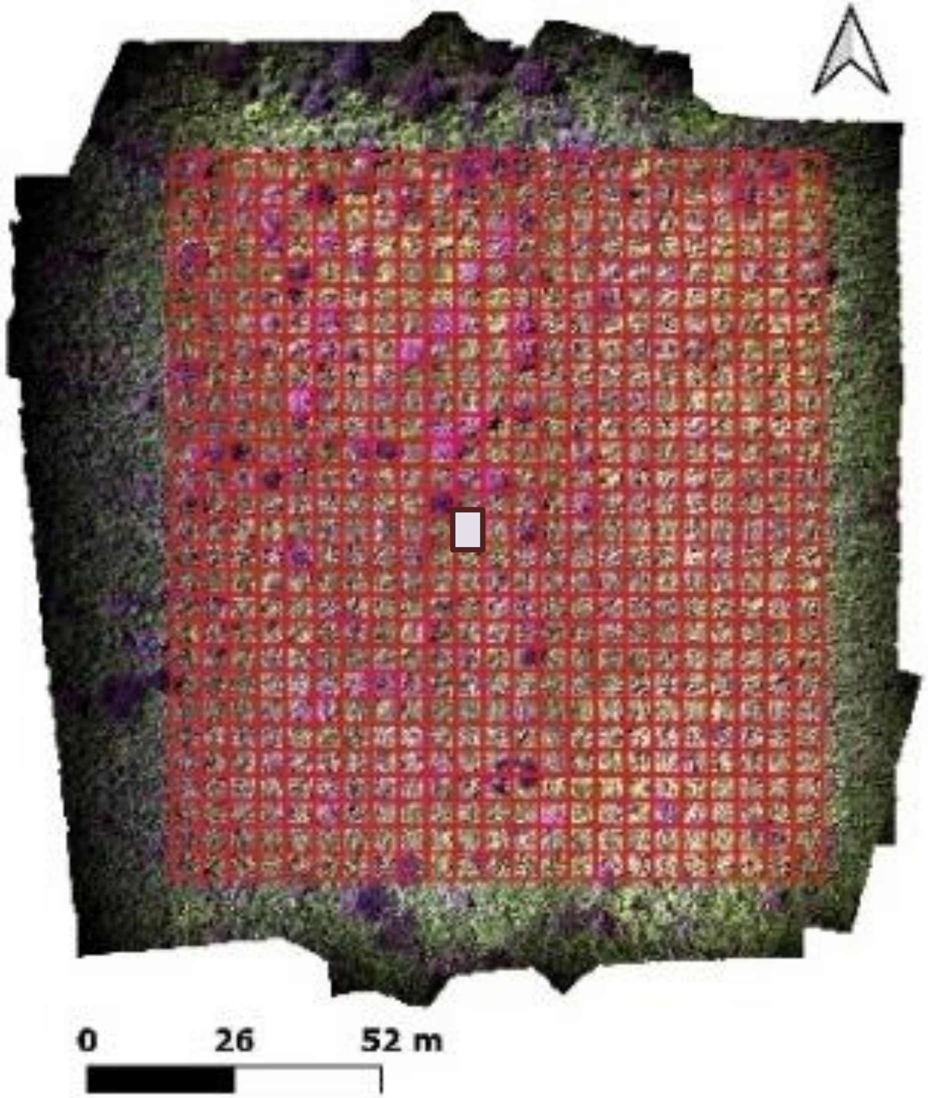
The bar plot to compare overall performance metrics such as accuracy, Cohen's kappa, precision, recall and F1 score for eight different machine learning classifiers in test data

Most Common Feature Across All Classifiers: Mean of CVI

Alpha diversity estimation

Assumption: The reference alpha-diversity represents the average diversity of each post-fire plot

- Previously-selected **spectral and textural features** for each subplot
- Computed **Euclidean distance** between each test subplot and the **reference subplot** with known alpha diversity
- Assigned **weights to test samples** based on similarity
- **Higher similarity = higher weight**



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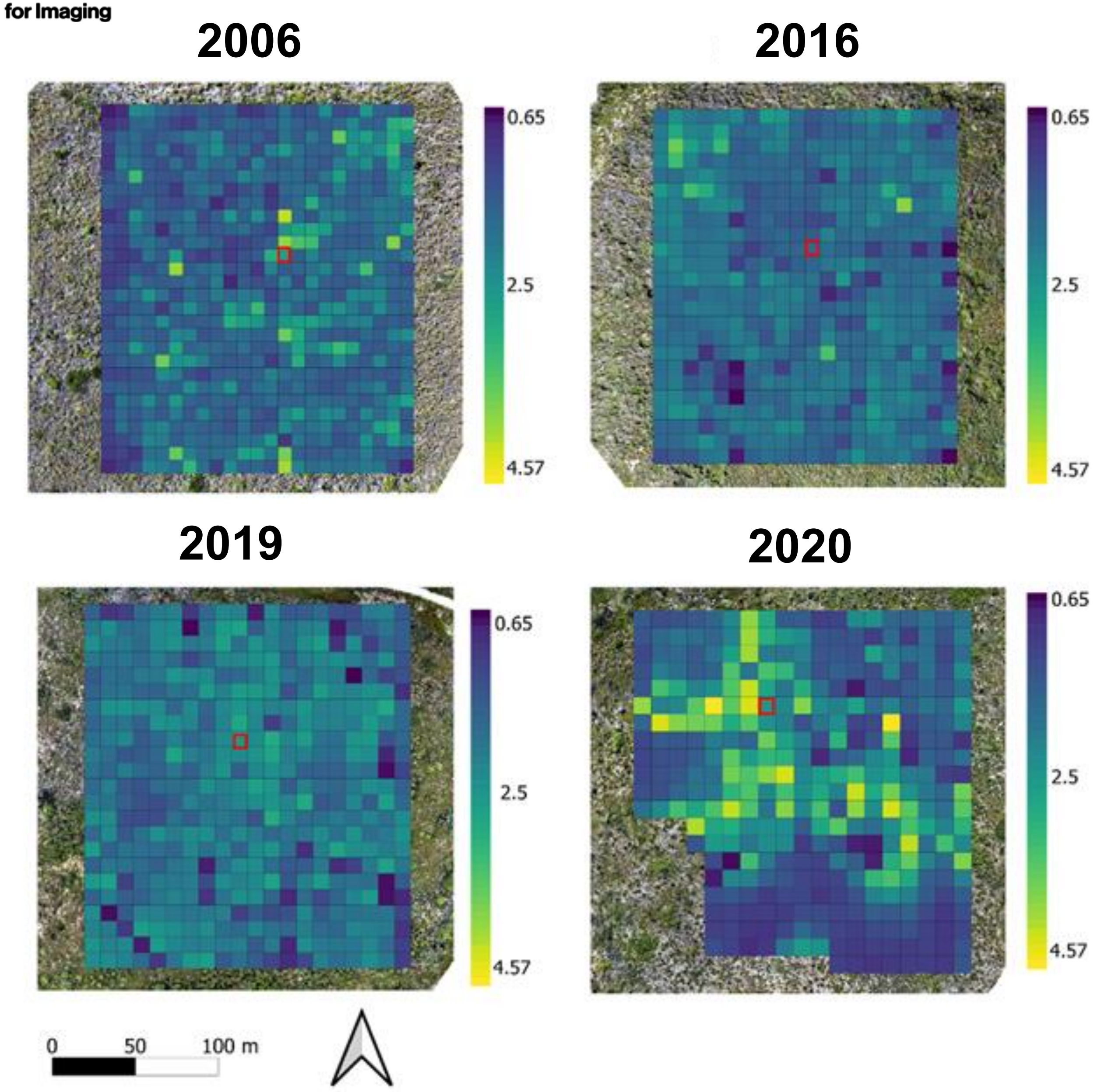
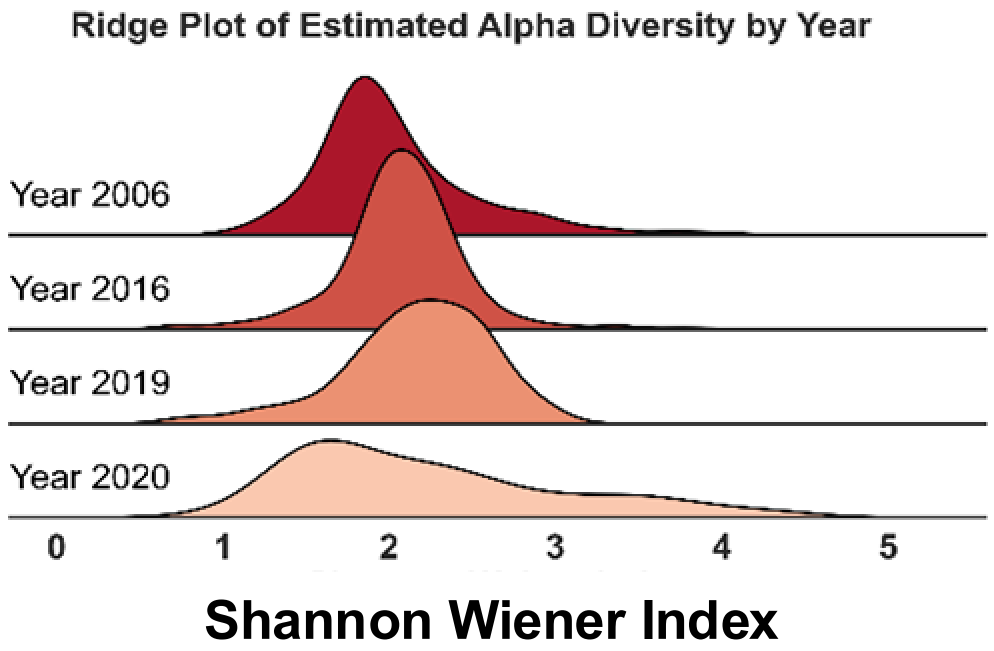
Alpha diversity mapping





Alpha diversity tends to decrease in old Fynbos (2006, 2016) vs. young fynbos sites (2019,2020). The decline in biodiversity over time in fynbos ecosystems is attributed to the site aging process

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Structure-from-motion (SfM) UAS Approach

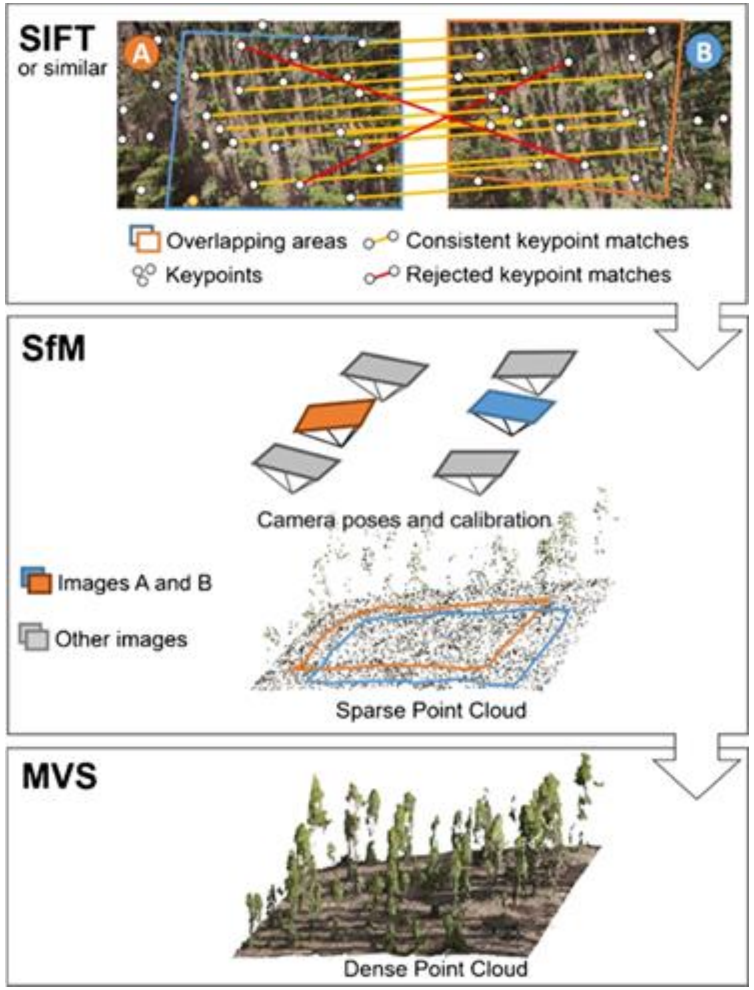
SfM: Generates **3D** models **from** sequence of overlapping **2D** images.

Basic Steps:

1. **Keypoints Matching**
   - SIFT (scale invariant feature transform)

2. **Bundle Adjustment**
   - Computes camera pose and parameters and a sparse point cloud

3. **Multi-view stereo matching (MVS)**
   - Generates densified point clouds



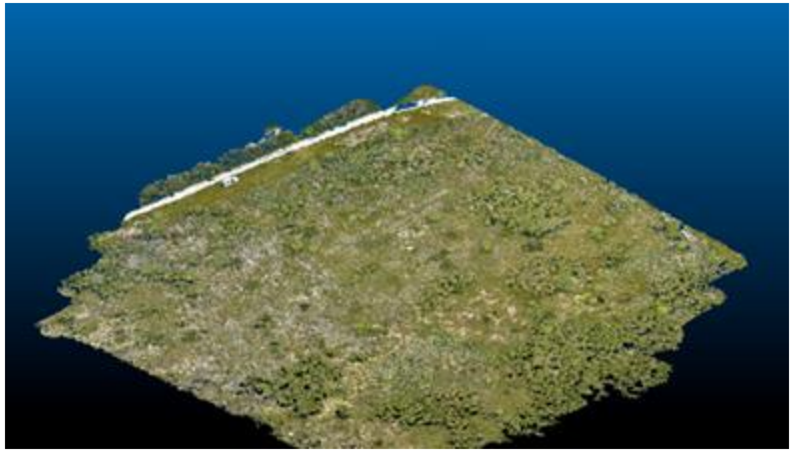
Three key stages in generating SfM point cloud (Iglhaut *et al.*, 2019)

Drone Imagery

↓

Pix4D

↓

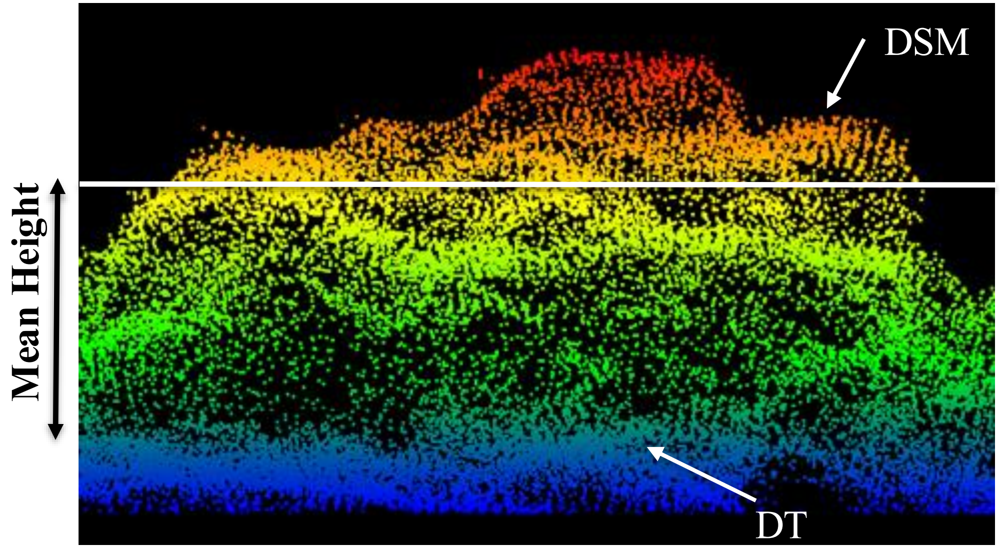


Dense point cloud example

SfM - Metrics

1. Canopy Height/Shrub Height

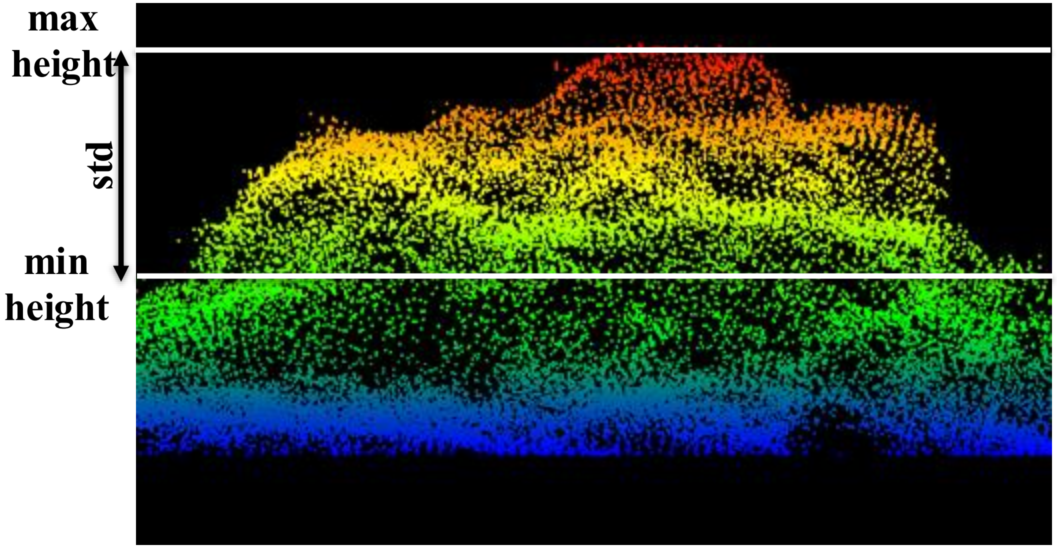
- Canopy Height Model (CHM) = Digital Surface Model (DSM) – Digital Terrain Model (DTM)



Mean Canopy Height

2. Top Rugosity (External Heterogeneity)

- **Standard deviation** of maximum canopy heights within kernel
- Characterizes the differences in canopy heterogeneity



External Heterogeneity

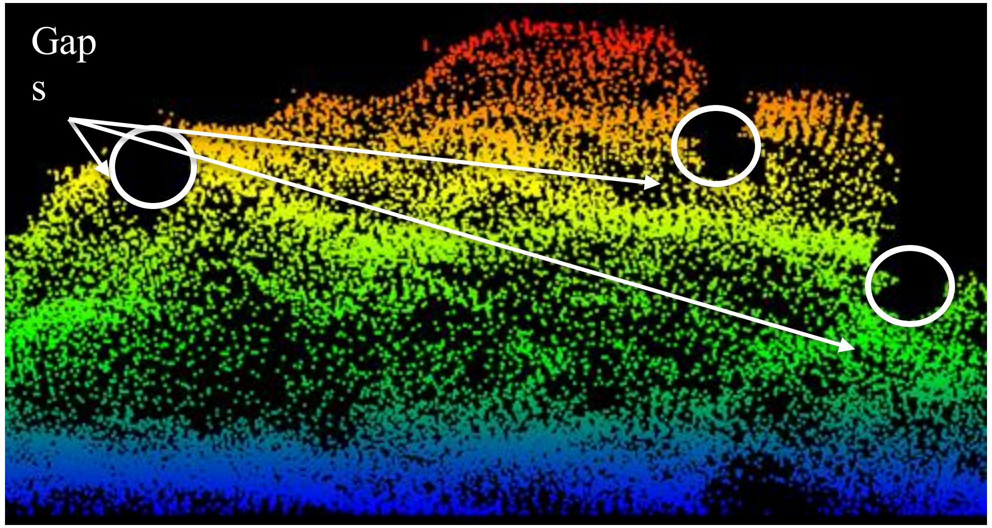
SfM - Metrics

3. Surface Gap Ratio

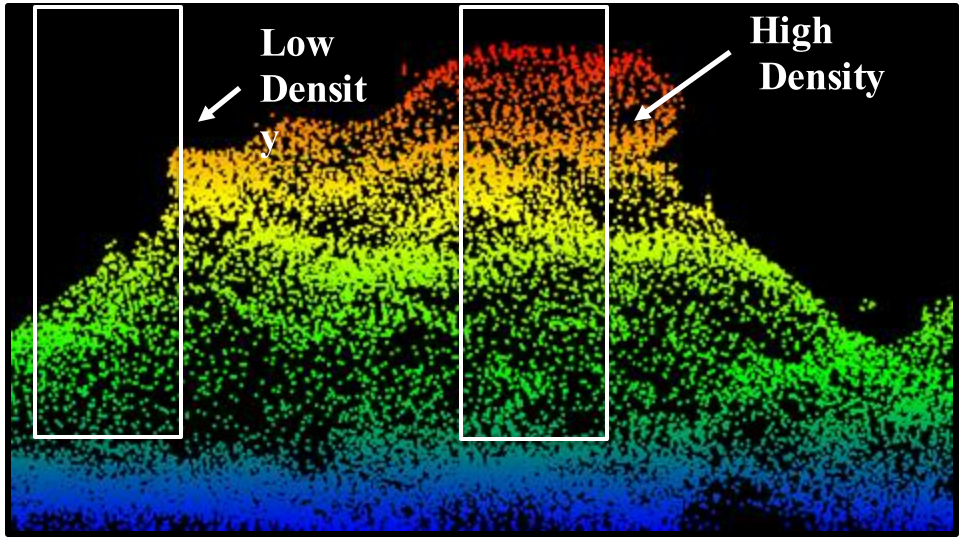
- Represents **proportion of gaps** within the surface containing vegetation (**gap fraction proxy**).
- Ratio of number of points in the kernel column that are at lower heights than mean point height within kernel to the total number of points in kernel

4. Surface Point Density

- Represents surface **density**
- Number of non-ground points (surface points) within a kernel



Surface Gaps



Surface Point Density

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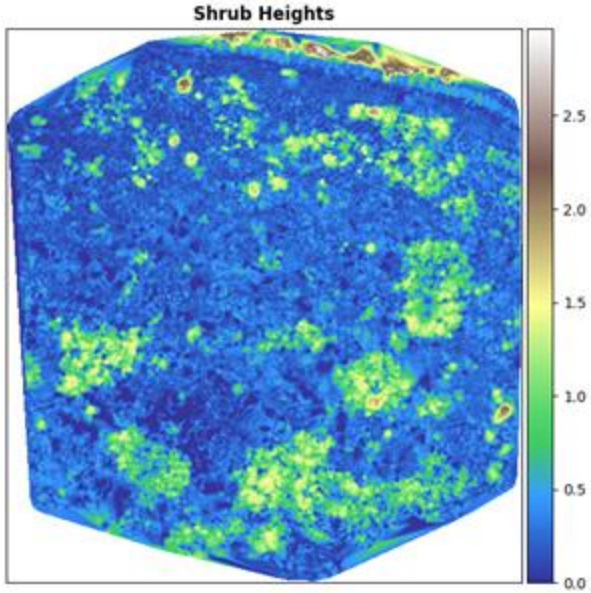
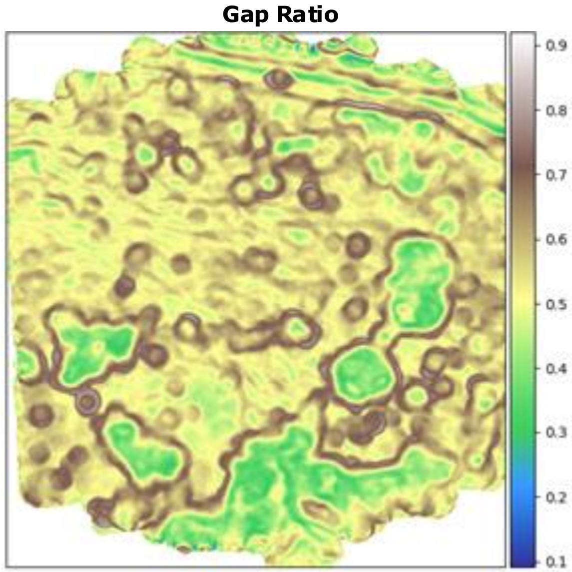
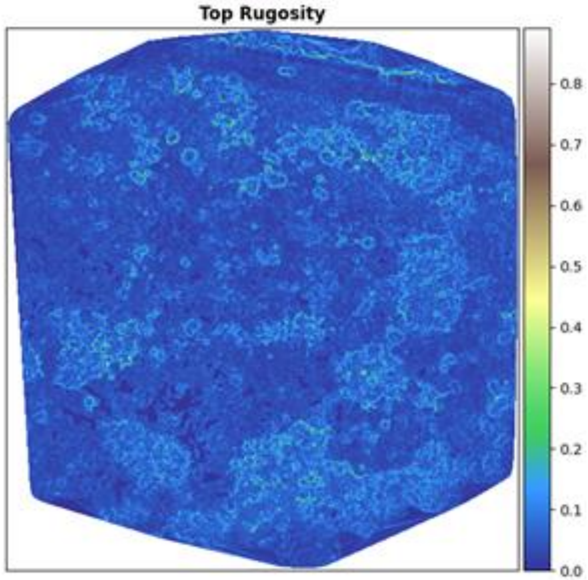
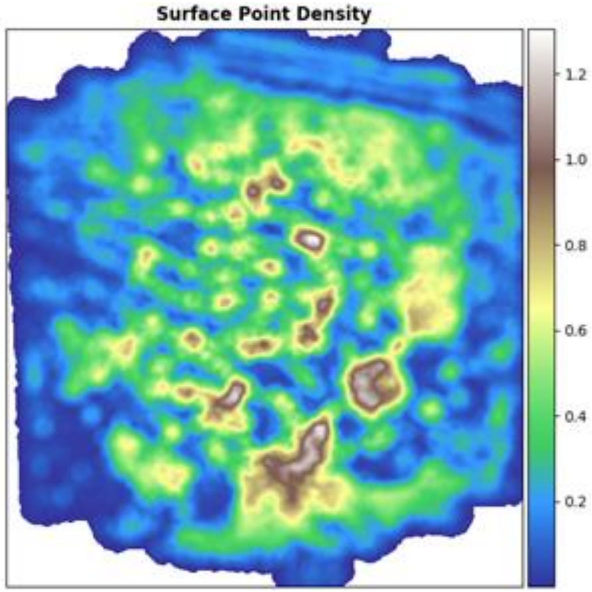
SfM – Feature Maps





Burn Plot 2019





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SfM – Burn Year Classification

"Can we predict the burn year of a particular subplot (5m x 5m) using the structural metrics?"

Classifiers	Burn Year Prediction on Test Data (429 samples) [F1-Scores]						Overall Accuracy
	2006	2016	2017	2019	2020	2022	
Random Forest	1.00	0.85	0.60	0.78	0.78	0.83	85%
1D CNN	1.00	0.82	0.54	0.74	0.75	0.81	83%
SVM	1.00	0.80	0.56	0.76	0.80	0.80	83%
KNN	1.00	0.80	0.56	0.78	0.77	0.74	82%
Naïve Bayes	1.00	0.76	0.50	0.72	0.79	0.78	81%
Des-Tree	1.00	0.75	0.44	0.72	0.73	0.72	80%

Easiest to predict

Difficult to predict

- *"Burn year"* = label & structural metrics = features; **predict burn year** of unseen subplots
- **SMOTE** *(Synthetic Minority Oversampling Technique)* was used to generate samples for the minority class during training
- **Most confusion** in classification **between** burn **year 2016 vs. 2017** and **year 2019 vs. 2020**

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DIRSIG Scene Simulation

Fynbos

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Workflow

Field Data & Traits

↓

3D Scene Construction
(vegetation structure, materials)

↓

DIRSIG Simulation
(radiative transfer modeling, sensor config)

↓

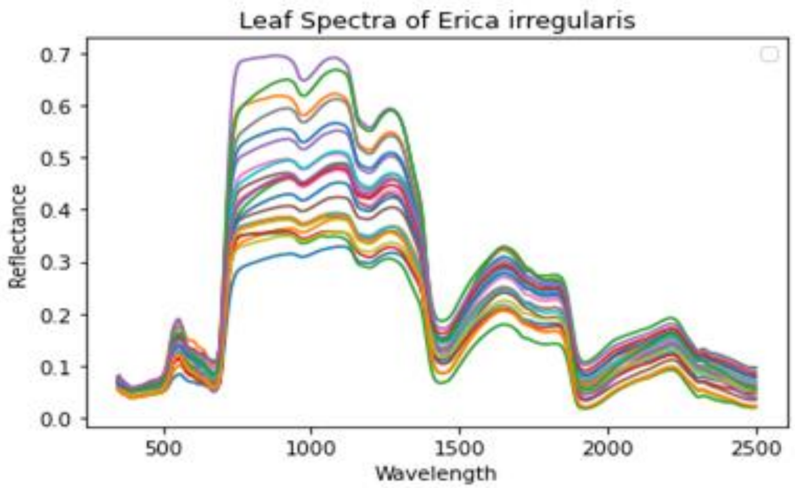
Synthetic Imagery
(multi/imaging spectroscopy outputs)

↓

Analysis
(Validation, biodiversity detectability)

Spectral attribution

- Field measurements of each species were used to fit Prospect parameters to get the transmittance curve
- Each species has multiple spectra which are picked randomly for each instance



iPad *.ply scan of *Cliffortia ilicifolia*

Workflow

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3D Scene Construction

Errica irregularis

Ficinia rigida

Ilex cassine

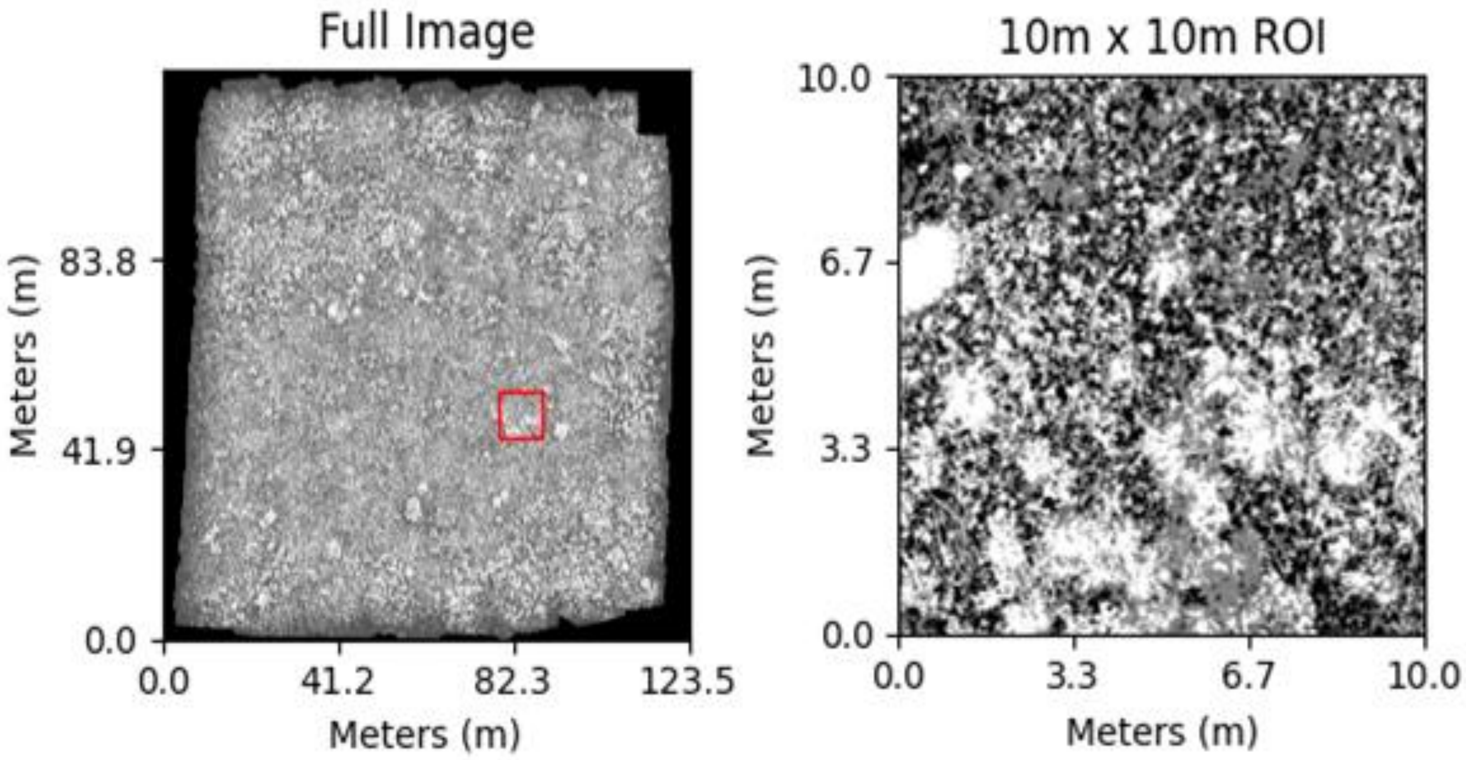
These example 3D models were created by taking real-world examples of each species for reference and recreating each one with as much accuracy as possible by mirroring the structure of plants from the leaves to the stems. The DIRSIG simulation team used *Maya* and *Blender* to create these 3D models

Species Instantiation

Distribute species throughout the scene in a pseudo random manner…

- **Blue Noise Algorithm** (Poisson Disk Sampling) **+**

- **Probability map** derived from UAS imagery ensures even spacing



Workflow

Field Data & Traits

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↓

Analysis
(Validation, biodiversity detectability)

DIRSIG Simulation - Example

1. Instrument information
2. Platform position data
3. Atmosphere information

Multispectral Imager	DJI MAVIC-3 MSI
Spectral Bands	5
Spectral Sampling	Green: 560 ± 16 nm Red: 650 ± 16 nm Red Edge: 730 ± 16 nm NIR: 860 ± 26 nm
Pixel Array	640 x 460
Pixel Size	2 microns
Focal Length	4 mm
Flying Height	50 m
GSD	2.5 cm

Workflow

Field Data & Traits

↓

3D Scene Construction
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↓

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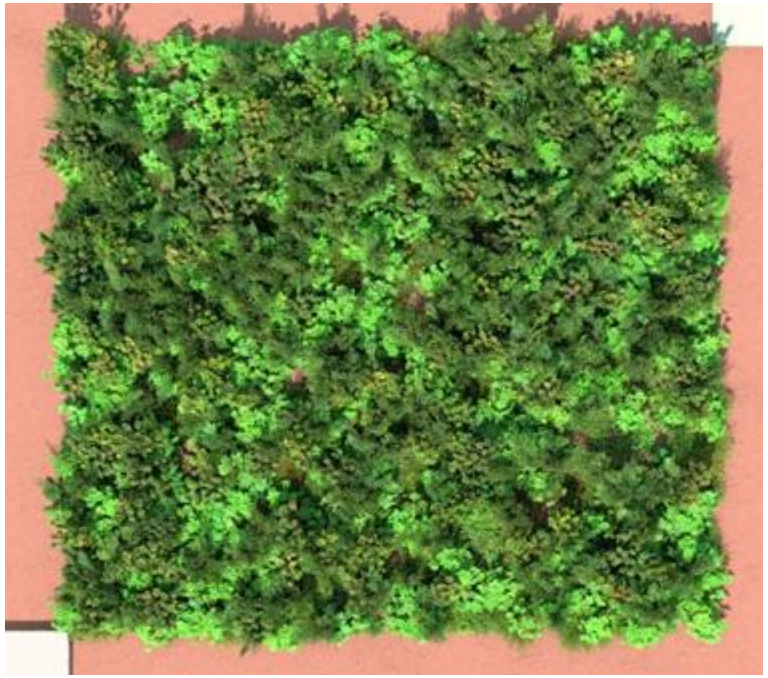
↓

Analysis
(Validation, biodiversity detectability)

Synthetic Imagery

Burn Year **2006**

Burn Year **2016**



Burn Year **2019**

Example of plot-level simulated scenes of fynbos that were burned in 2006, 2016, and 2019 in Grootbos Private Nature Reserve. The scenes are dimensions of (10 x 10 m) captured using a DJI MAVIC-3 multispectral camera at 50 m altitude with 2.5 cm GSD

Workflow

Field Data & Traits

↓

3D Scene Construction
(vegetation structure, materials)

↓

DIRSIG Simulation
(radiative transfer modeling, sensor config)

↓

Synthetic Imagery
(multi/imaging spectroscopy outputs)

↓

Analysis
(Validation, biodiversity detectability)

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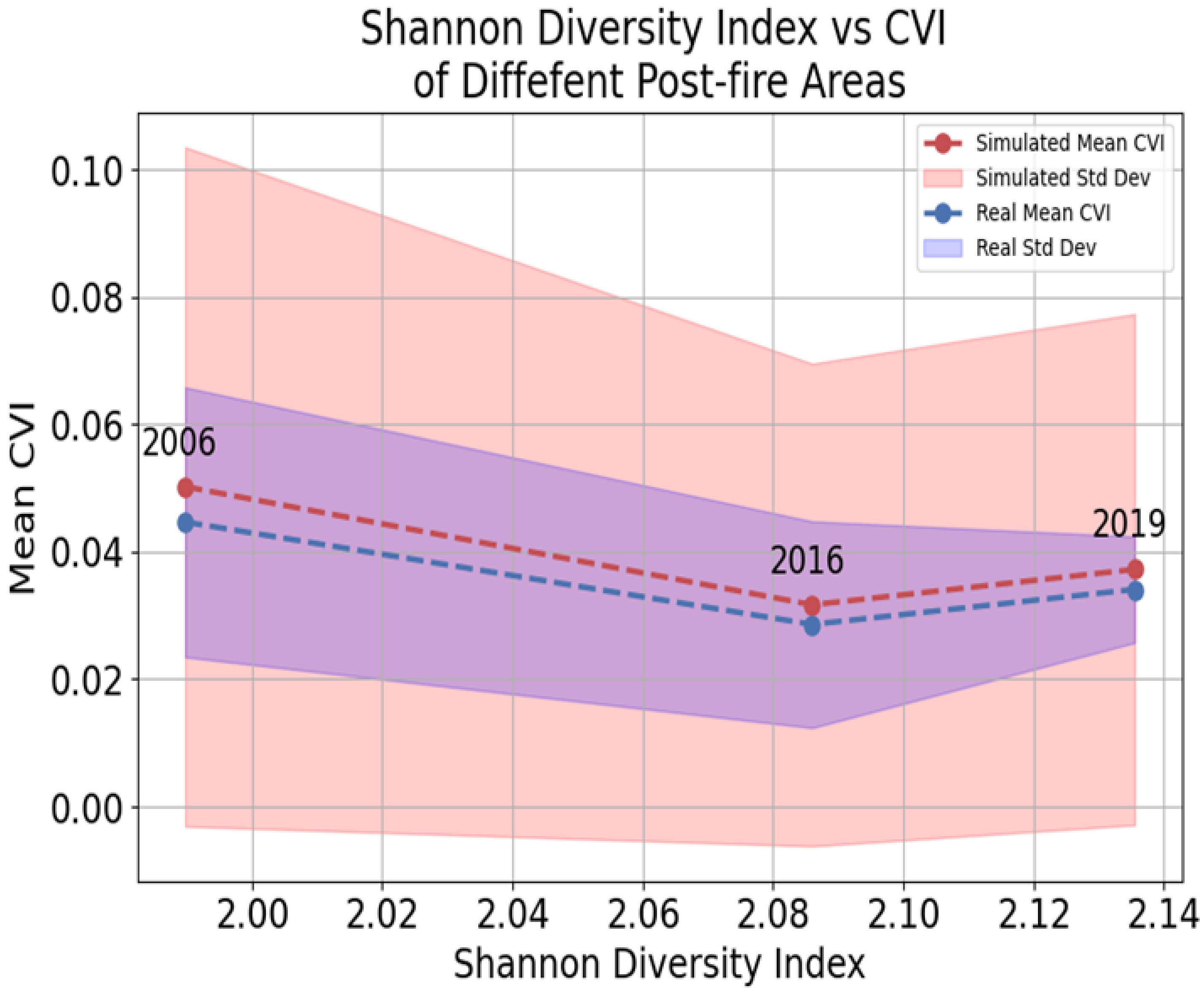
Scene Validation: Real vs. Simulated MSI

- Simulated post-fire vegetation areas follow the same distribution pattern, with a 2-10% difference in NIR band compared to real data across different years

- Simulated Chlorophyll vegetation index (CVI) aligns with real CVI patterns falling within the mean ± std of the real CVI



Scene Validation: Real vs. Simulated IS

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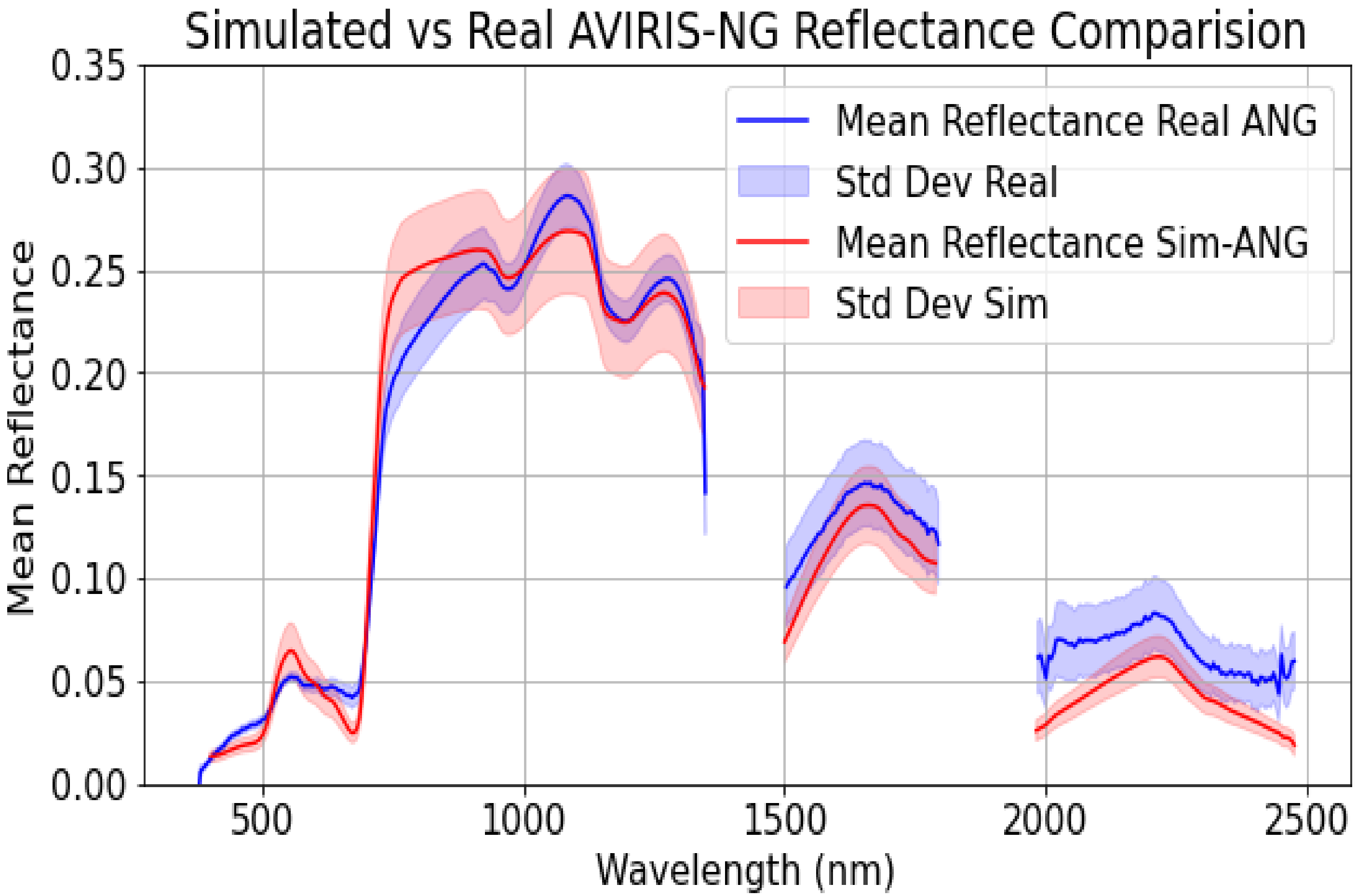
System specification AVIRIS-NG

- GSD: 6 m
- Spectral band: 450-2500 nm
- Spectral Bandwidth: 5 nm

Visually, simulated imaging spectra fall within the mean ± std of the real spectra



Simulation – (active) Structure Modalities

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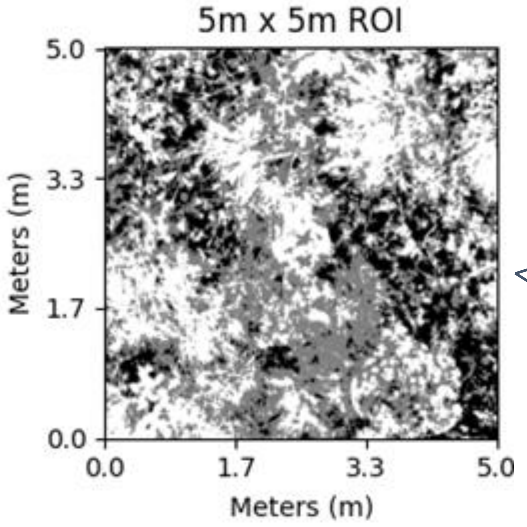
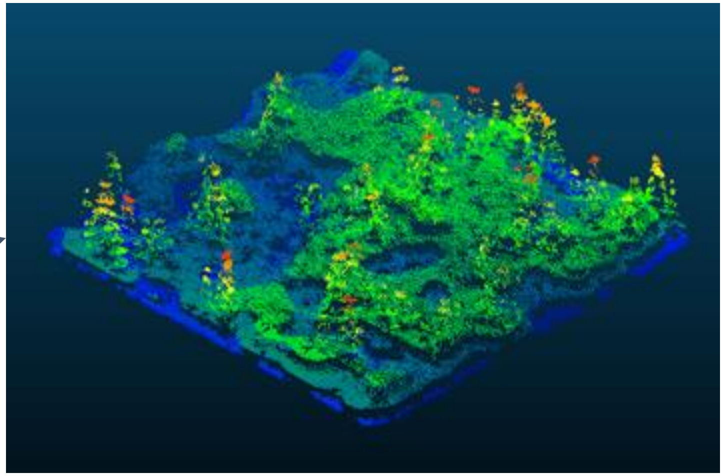
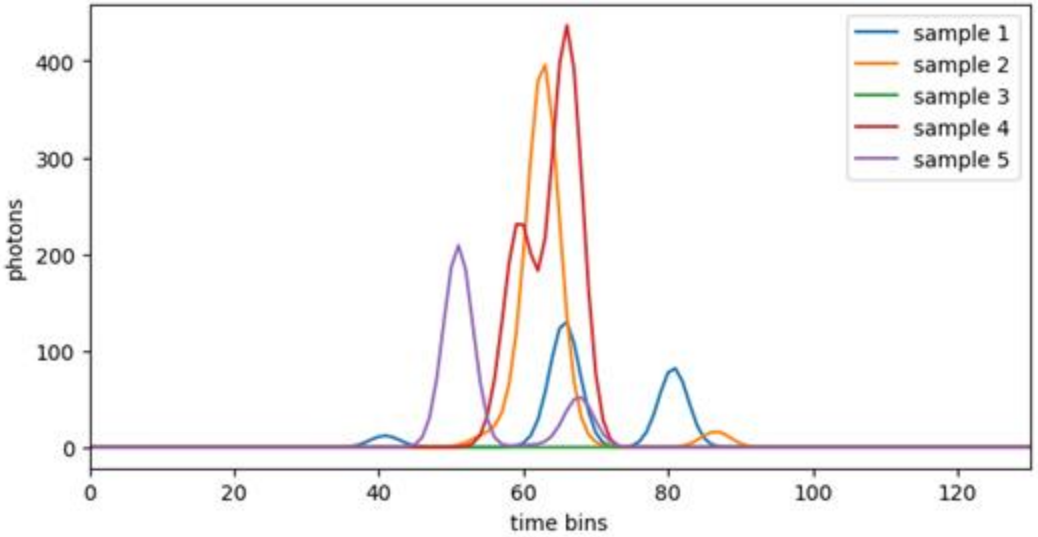


Drone based VLP16 LiDAR Simulation

ALS waveform LiDAR simulation





DIRSIG based simulation of a 5m x 5m plot of **2019 burn year** scene

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Next Steps

- Linking ***spectral diversity*** and biodiversity using synthetic imagery
    - evaluate novel deep learning-based spectral metrics
    - understand how scale impacts the spectral diversity and biodiversity link (e.g., varying pixel sizes, from a few centimeters to meters)

- Simulate (***structure***) to
    - assess "next generation" system parameters for burn year structure detection and classification
    - identify best set of structural metrics for burn year classification for each modality of data
    - evaluate the correlation of structural diversity and species diversity through time and space