Risultati del Progetto STOPP

Un approccio multidisciplinare al monitoraggio ambientale multi-scala attraverso bioindicatori vegetali

Telerilevamento multi-scala dei bioindicatori a livello di chioma

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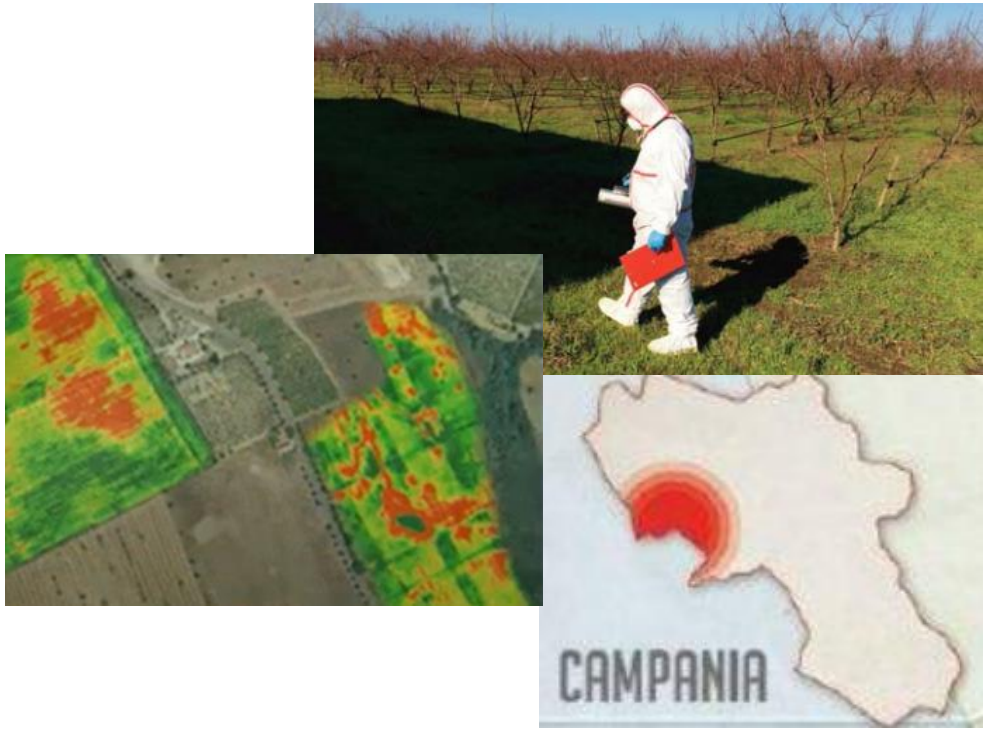
ASI, Roma, 22 maggio 2025

Contesto: Selezione Bioindicatore

- **<u>Obiettivo del Progetto</u>**: sviluppare tecnologie per l'osservazione di sistemi biologici al fine di valutare lo stato di salute dell'ambiente.



Criteri

- Alterazioni dei processi fisiologici noti o presumibili
- Diffusione nella regione d'interesse
- **Osservabilità** in remote sensing

Scelta

- Colture cerealicole
- Grano, erba medica→ **Mais**

Set – up sperimentale: open field lab 2024

Semina in bin (1050x1050x445 mm**): 06/05/24 – Contaminazione con Cr, Zn e Pb + Benzopirene**

- Controllo --> C1, C2, C3 ---> Tra la 7° e 8° Foglia – **C** piante non trattate
- Contaminato con dose x4 --> T1, T2, T3 ---> Tra la 6° e 7° Foglia – **T4** piante trattate con un mix di metalli 3 volte superiore al limite di legge Decreto Nazionale (152/2006, Annex 5, Parte IV, Tabella 1, 2006).

Date delle Acquisizioni: Novembre 2023 - **Luglio 2024**

Monitoraggio Multi-scala

Foglia

Chioma

UAV

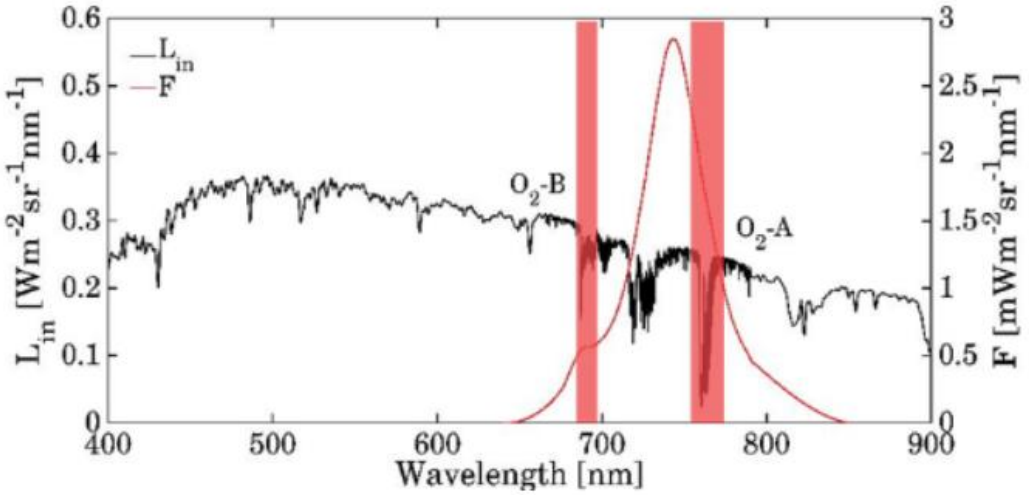
Minori tempi di acquisizione

Maggiore Precisione

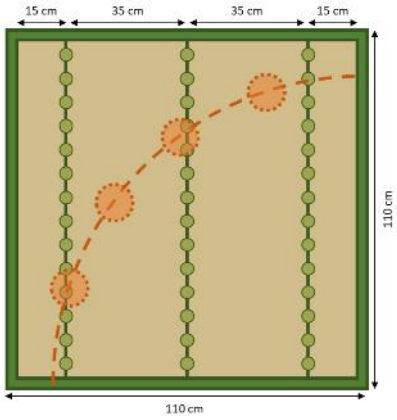
Fluorescenza passiva a livello di canopy

- **FloX** è un dispositivo di spettroscopia da campo automatizzato, progettato per raccogliere dati iperspettrali continui.

Spectrometer	FWHM (nm)	Sampling interval (nm)	Spectral range (nm)	Application
FLUO	0.3	0.14	650 - 800	Sun-induced fluorescence at O_2-B and O_2-A bands
FULL	1	0.3	400 -1000	Irradiance, Radiance, Reflectance and VIs



4 punti di acquisizione ripetuti **3 volte** per **ogni bin.**

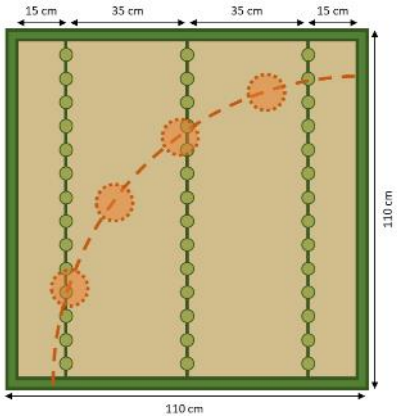


- **Strumentazione**: Spettroradiometro

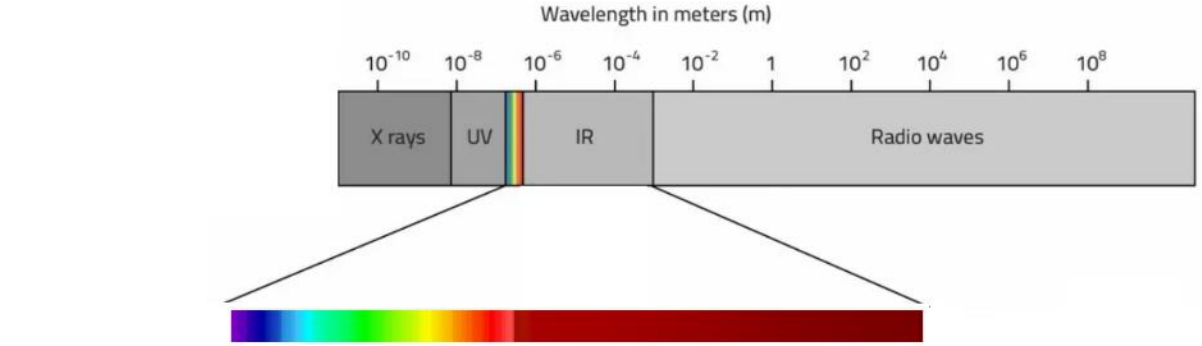
- **Tipologia di misura**: riflettanza di foglia e di chioma (*400 – 2500 nm*)

  - Frazione della radiazione elettromagnetica riflessa dalle superfici
  - Dipende dalle caratteristiche chimiche e fisiche della superficie
  - Firma spettrale – andamento della riflettanza a diverse lunghezze d'onda

4 punti di acquisizione ripetuti **3 volte** per **ogni bin.**



Camera Multispettrale e Iperspettrale



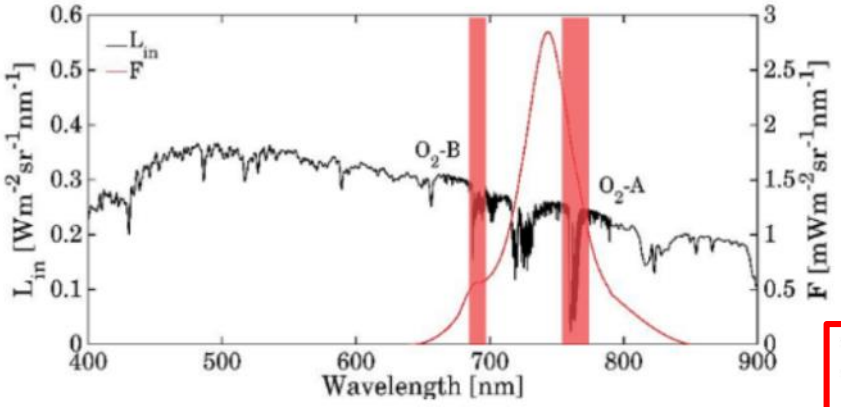
Multispettrale (MS)

Iperspettrale (HS)

	Micasense Altum	Cubert Ultris 5
# Bands	5	51
Wavelengths [nm]	475 - 842	450 - 850
Max Resolution	2064 × 1544	295 × 270

Analisi effettuate

- **FloX**:
  - SIF_A e SIF_B



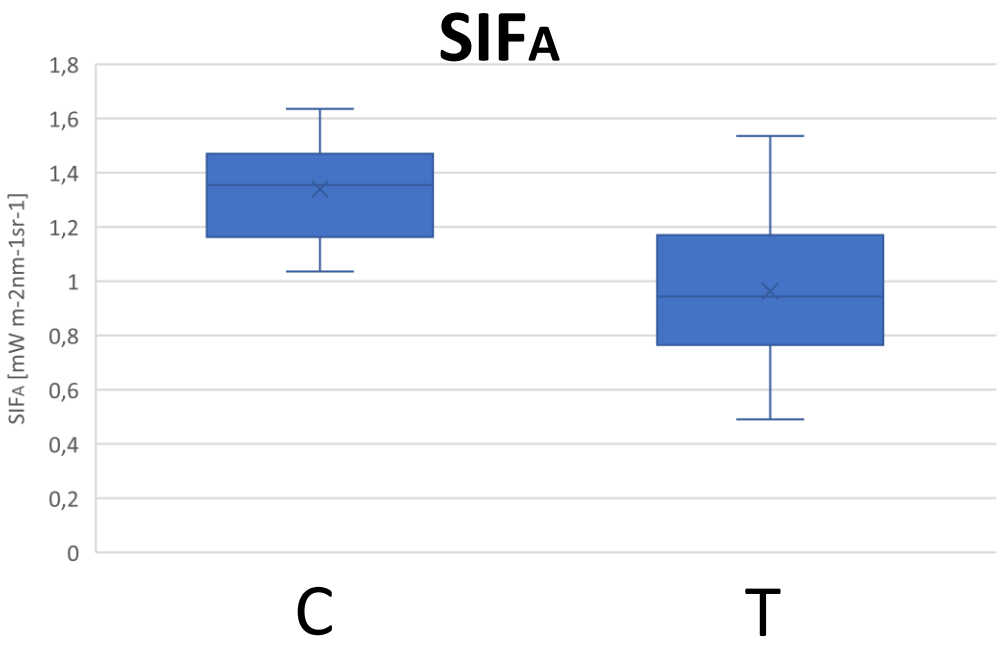
- **Spettroradiometro**:
  - Firme spettrali (400 – 2500 nm → 450 – 850 nm)
  - Indici di vegetazione
  - **ANOVA**

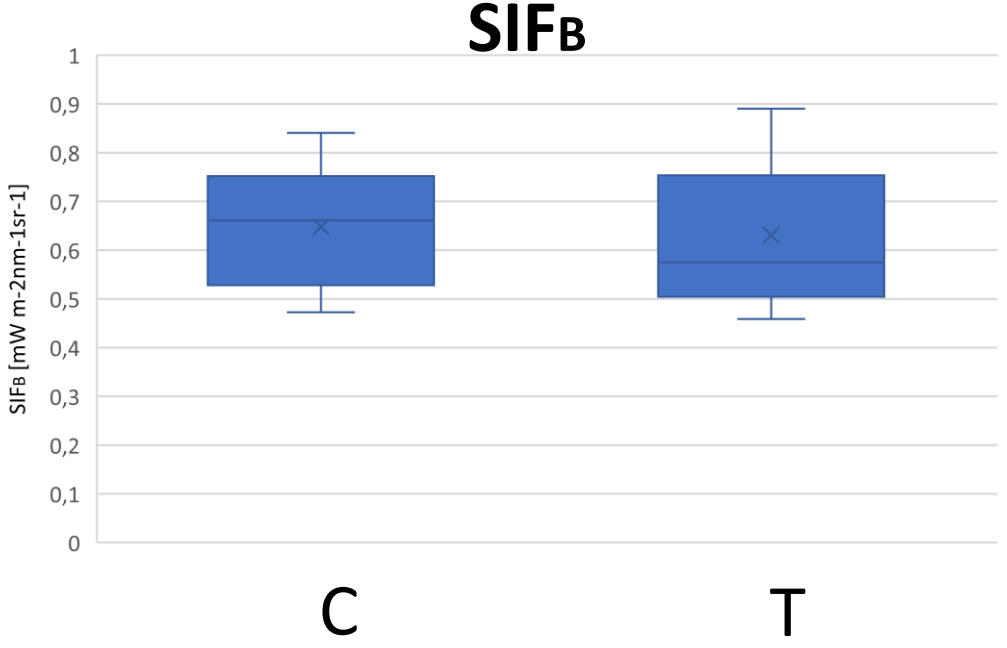
- **UAV**:
  - Indici di vegetazione e **ANOVA**
  - Analisi visiva
  - Classificazione supervisionata

Index	Formula
Chlorophyll Absorption Ratio Index	$CARI = R_{700}\lvert(R_{670}a + R_{670} + b\rvert/R_{670}(a^2+1)^{0.5}$ with $a = (R_{700} - R_{550})/150$ and $b = R_{550} - R_{550}a$
Chlorophyll/Carotenoids Index	$CCI = D_{720}/D_{700}$
Carter Index 1	$CTR1 = R_{695}/R_{420}$
Carter Index 2	$CTR2 = R_{695}/R_{760}$
Gitelson & Merzlyak Index 1	$GM1 = R_{750}/R_{550}$
Gitelson & Merzlyak Index 2	$GM2 = R_{750}/R_{700}$
Lichtenthaler Index 1	$LI1 = (R_{800} - R_{680})/(R_{800} + R_{680})$
Lichtenthaler Index 2	$LI2 = R_{440}/R_{690}$
Lichtenthaler Index 3	$LI3 = R_{440}/R_{740}$
modified Chlorophyll Absorption Ratio Index 1	$mCARI1 = 1.2[2.5(R_{800} - R_{670}) - 1.3(R_{800} - R_{550})]$
modified Chlorophyll Absorption Ratio Index 2	$mCARI2 = \frac{1.5[2.5(R_{800}-R_{670})-1.3(R_{800}-R_{550})]}{\sqrt{(2R_{800}+1)^2-(6R_{800}-5\sqrt{R_{670}})-0.5}}$
modified Simple Ratio 705 nm	$mSR705 = (R_{750} - R_{445})/(R_{750} + R_{445})$
MERIS Terrestrial Chlorophyll Index	$MTCI = (R_{754} - R_{709})/(R_{709} + R_{681})$
Normalized Difference 705 nm	$ND705$ or $NDVI705 = (R_{750} - R_{705})/(R_{750} + R_{705})$
Normalized Pigment Chlorophyll Index	$NPCI = (R_{680} - R_{430})/(R_{680} + R_{430})$
Optimized Soil-Adjusted Vegetation Index	$OSAVI = (1 + 0.16)(R_{800} - R_{670})/(R_{800} + R_{670} + 0.16)$
Photochemical Reflectance Index 1	$PRI1 = (R_{528} - R_{567})/(R_{528} + R_{567})$
Photochemical Reflectance Index 2	$PRI2 = (R_{531} - R_{570})/(R_{531} + R_{570})$
Photochemical Reflectance Index 3	$PRI3 = (R_{570} - R_{539})/(R_{570} + R_{539})$
Plant Senescence Reflectance Index	$PSRI = (R_{678} - R_{500})/R_{750}$
Pigment Specific Simple Ratio a	$PSSRa = R_{800}/R_{680}$
Pigment Specific Simple Ratio b	$PSSRb = R_{800}/R_{635}$
Pigment Specific Simple Ratio c	$PSSRc = R_{800}/R_{470}$
Structure Intensive Pigment Index 1	$SIPI1 = (R_{800} - R_{445})/(R_{800} + R_{680})$
Structure Intensive Pigment Index 2	$SIPI2 = (R_{800} - R_{505})/(R_{800} + R_{690})$
Structure Intensive Pigment Index 3	$SIPI3 = (R_{800} - R_{470})/(R_{800} + R_{680})$
Simple Ratio 705 nm	$SR705 = R_{750}/R_{705}$
Transformed CARI	$TCARI = 3[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})(R_{700}/R_{670})]$
Transformed CARI/OSAVI	$\frac{TCARI}{OSAVI} = \frac{3[(R_{700}-R_{670})-0.2(R_{700}-R_{550})(R_{700}/R_{670})]}{(1+0.16)(R_{800}-R_{670})/(R_{800}+R_{670}+0.16)}$
Vogelmann Index 1	$VOG1 = R_{740}/R_{720}$
Vogelmann Index 2	$VOG2 = (R_{734} - R_{747})/(R_{715} + R_{726})$
Vogelmann Index 3	$VOG3 = (R_{734} - R_{747})/(R_{715} + R_{720})$
Disease Water Stress Index	$DWSI = (R_{800} - R_{550})/(R_{1660} + R_{680})$

Fluorescenza passiva a livello di chioma: SIF_A e SIF_B

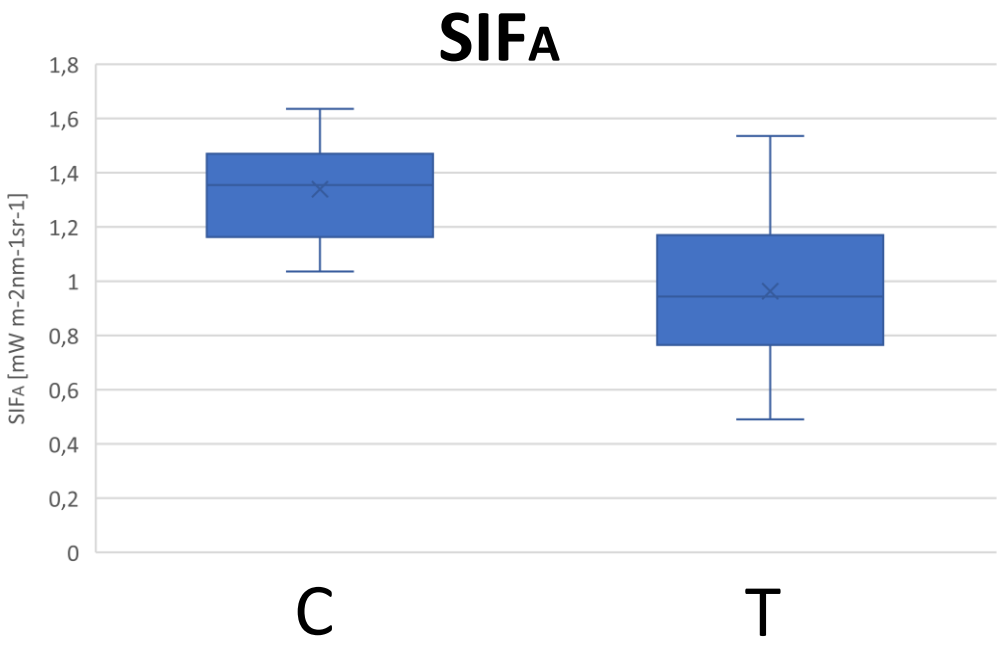
C: Controllo
T: Trattato (x3 e x4)



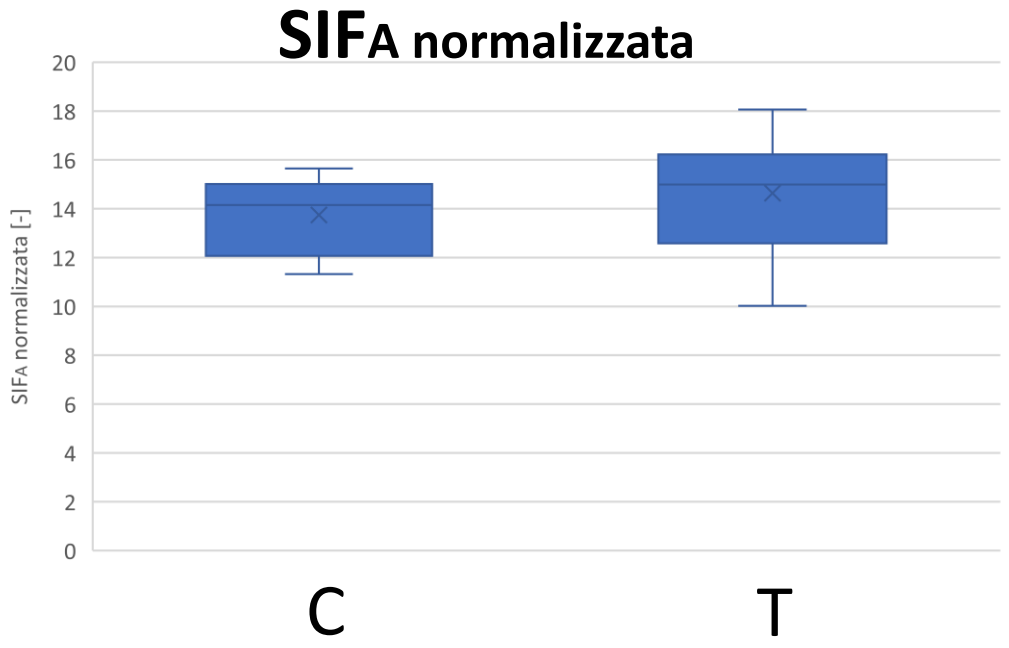


Fluorescenza passiva a livello di chioma: SIF_A

C: Controllo
T: Trattato (x3 e x4)



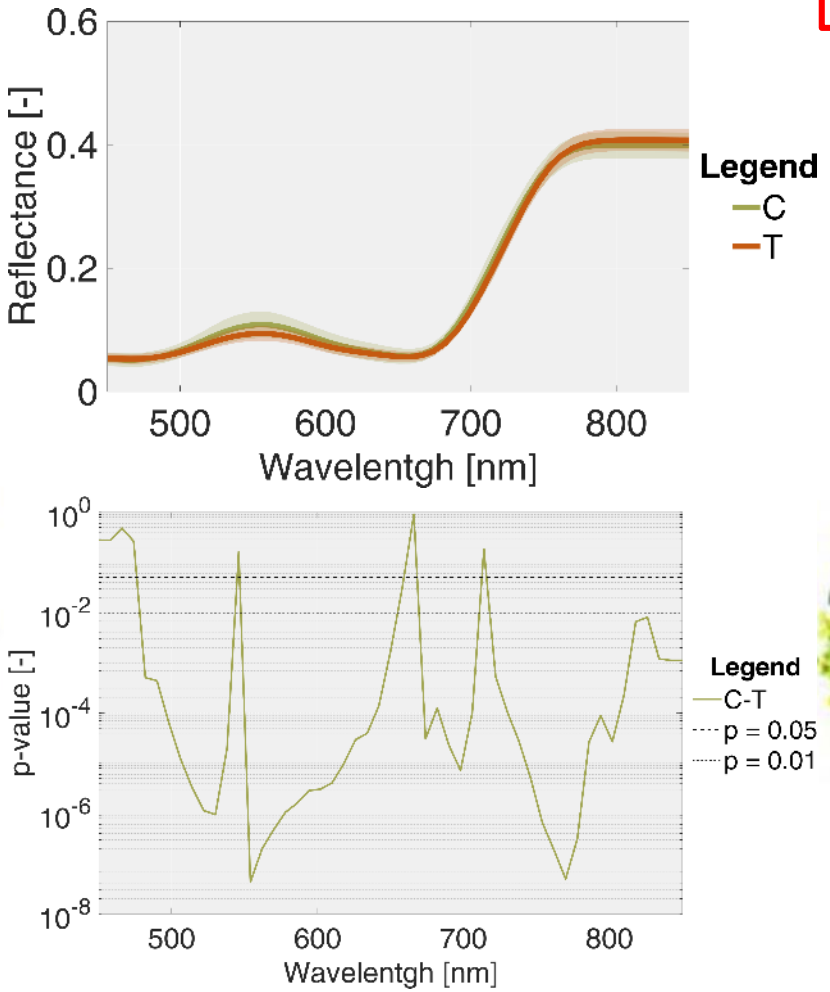
normalizzazione per la **biomassa**

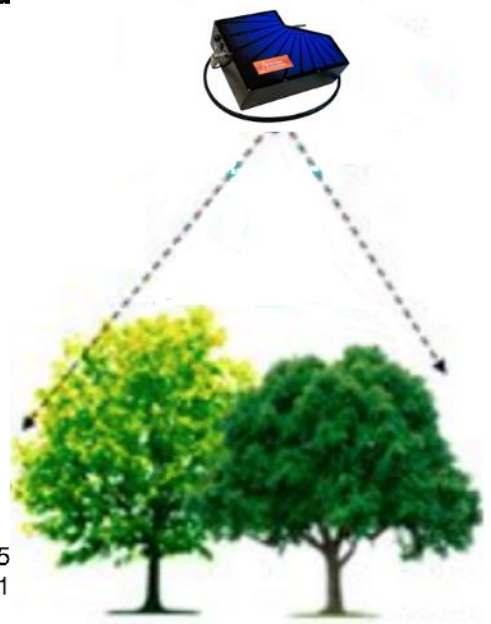


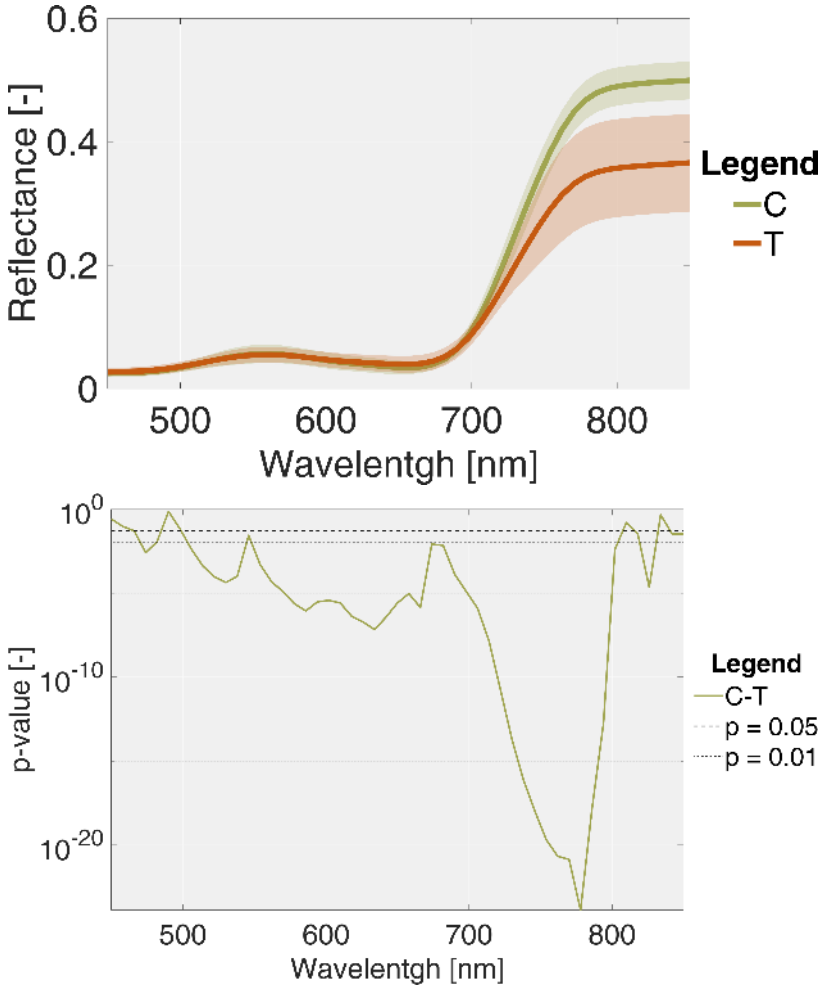
Separabili prima della normalizzazione → dovuto alle differenze strutturali.

Firme spettrali e significatività (ANOVA)

C: Controllo
T: Trattato (x3 e x4)





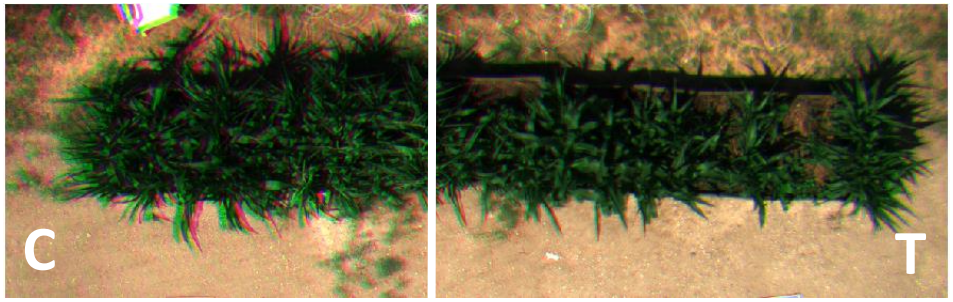


Dati Iperspettrali e Multispettrali: Analisi Visive

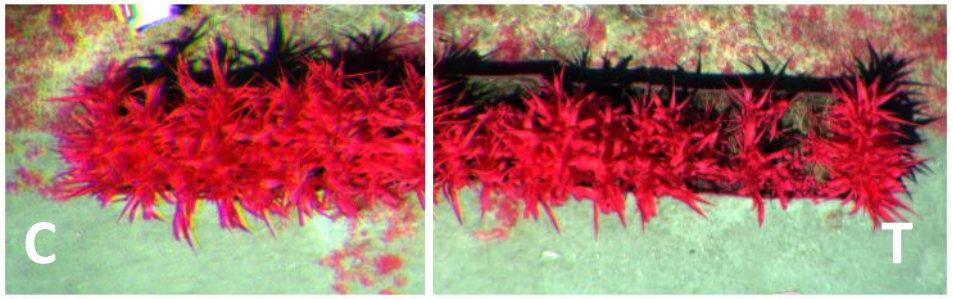
RGB (Red, Green, Blue)

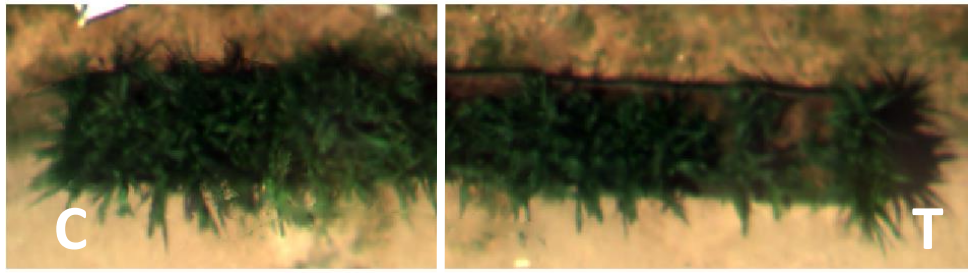
C: Controllo
T: Trattato (x3 e x4)

NRG (NIR, Red, Green)

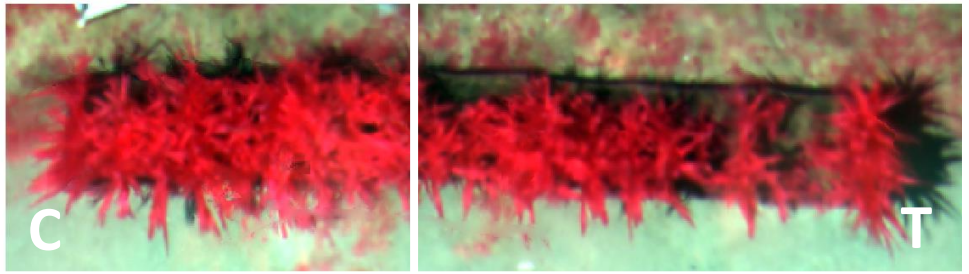


Multispettrale (MS)





Iperspettrale (HS)



C1 C2 C3 T1 T2 T3 T4

x4 x3

C1 C2 C3 T1 T2 T3 T4

x4 x3

Indici di vegetazione e ANOVA

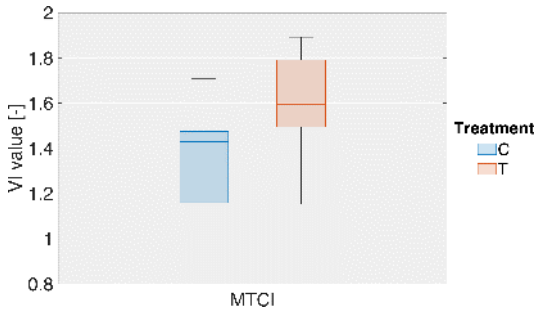
VIs	Significance		
	Foglia	Chioma	UAV
MTCI	**	**	*
ND705	**	**	ns
VOG1	**	**	ns
mCARI1	*	**	**
mSR705	ns	**	*

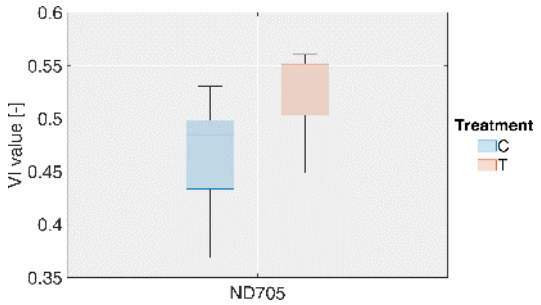
Legenda	
**	$p < 0.001$
*	$0.001 < p < 0.05$
ns	altrimenti

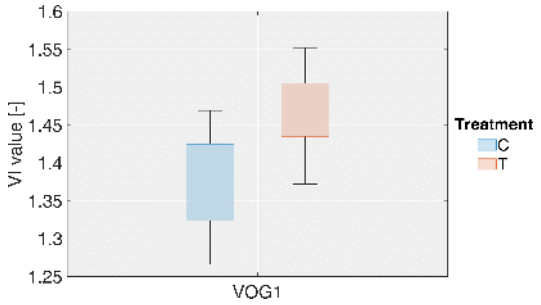
Indici di vegetazione e Significatività

C: Controllo
T: Trattato (x3 e x4)

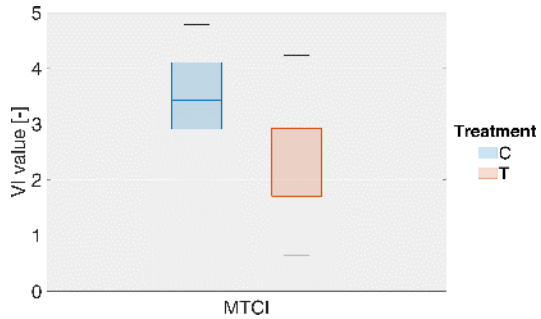
Foglia

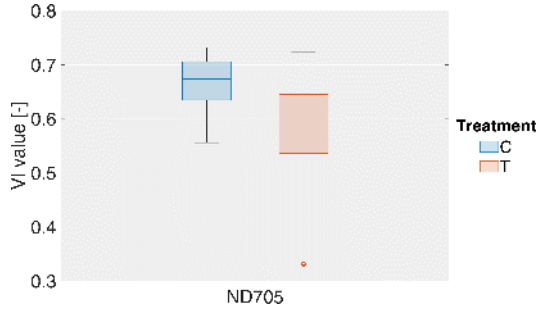


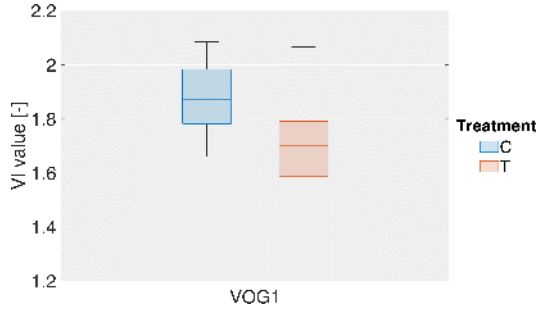




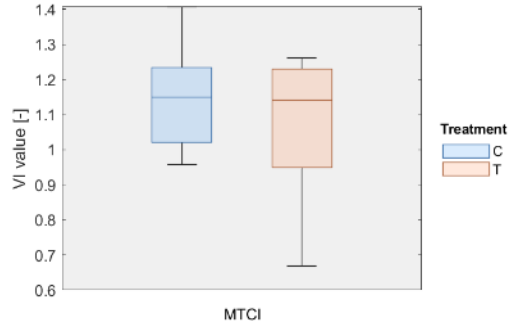
Chioma

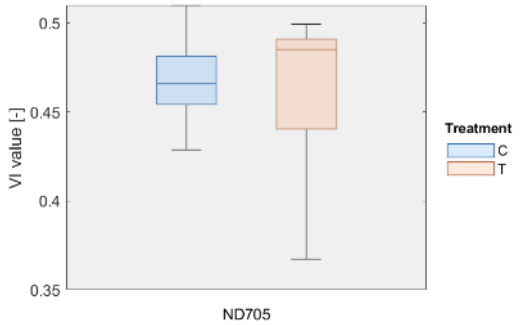


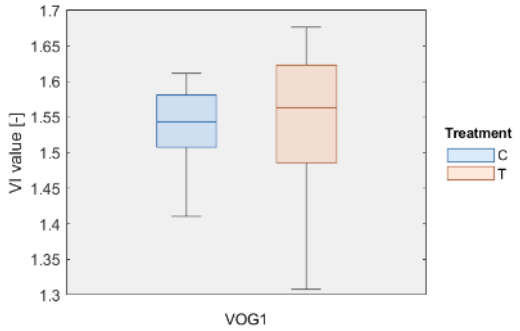




UAV







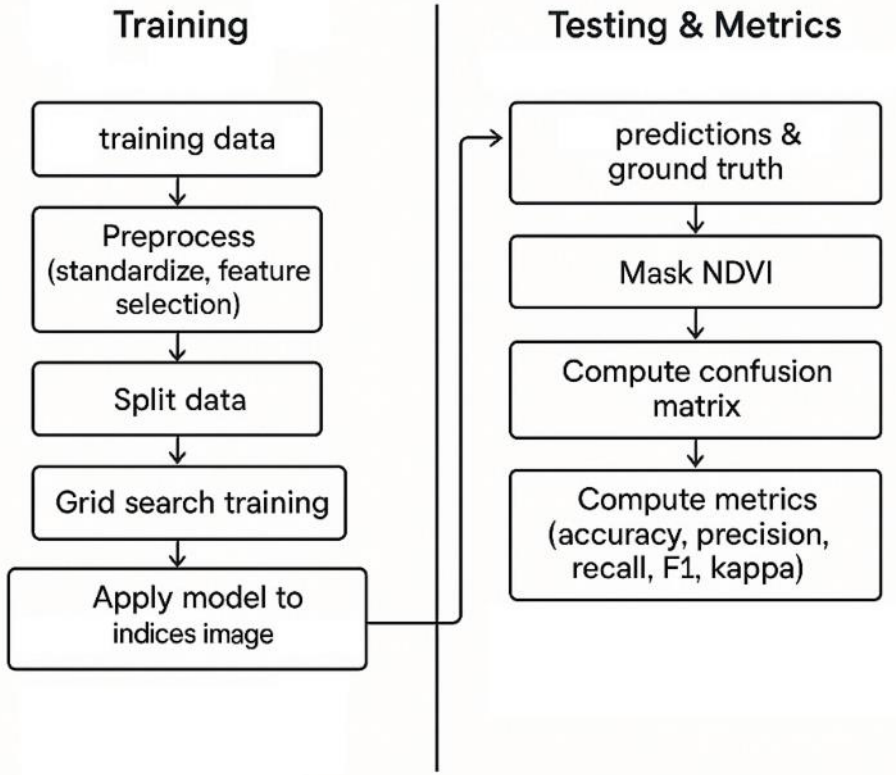
Classificazione Supervisionata

C: Controllo
T: Trattato (x3 e x4)

- **Input dati**: vettori di dimensioni pari al numero N di indici selezionati
  - **N multispettrale < N iperspettrale**

- **Pre-processing:**
  - Standardizzazione **z-score** delle feature
  - **Feature selection**: Random Forest
- **Split**: 80% training / 20% validation
- **Training**: *Classificatori*
  - *Iperparametri ottimizzati*
  - 5 fold, accuracy
- **Inferenza immagine**:
  - Stesso preprocessing & NDVI mask,
  - predizione pixel-wise → mappa contaminazione
- **Metriche finali:** accuracy globale e matrice di confusione

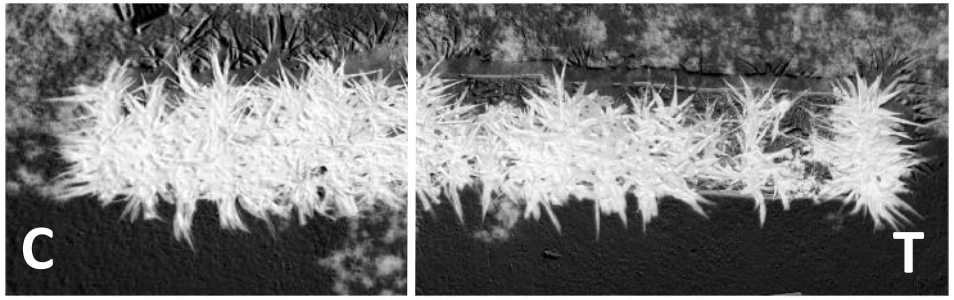
- **Random Forest (RF)**
- **Support Vector Machine (SVM)**
- **MultiLayer Perceptron (MLP)**
- **XGBoost**



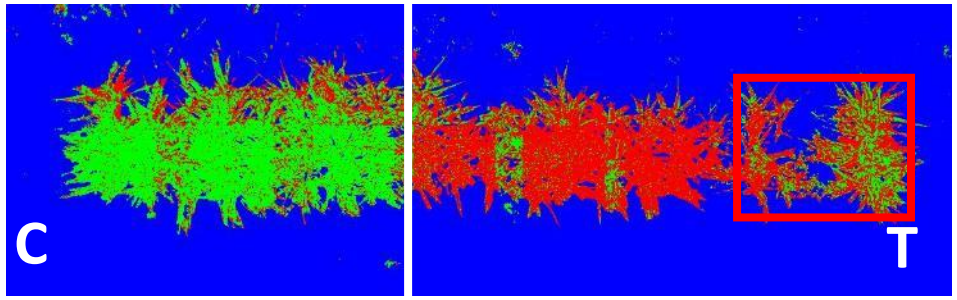
NDVI

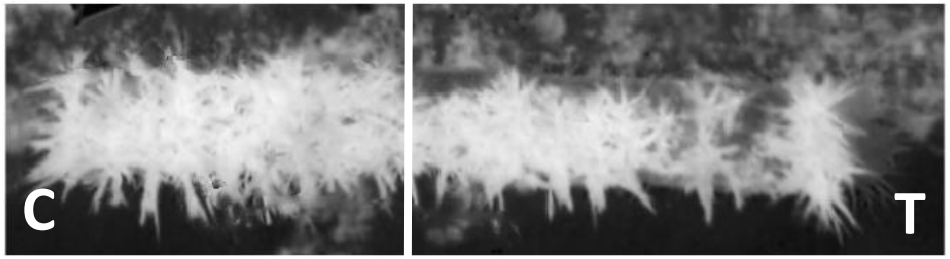
C: Controllo
T: Trattato (x3 e x4)

Classificazione

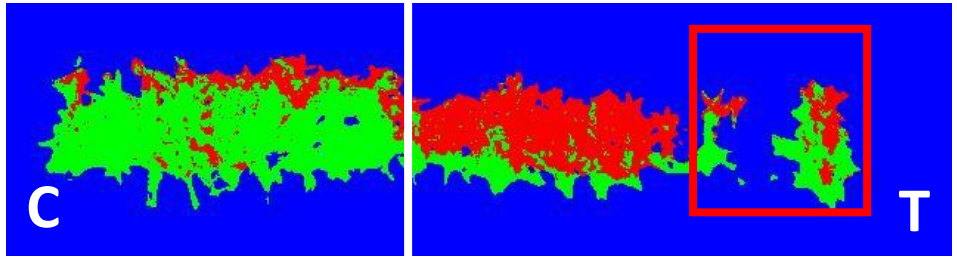


MS





HS



C1 C2 C3 T1 T2 T3 T4

x4 x3

C1 C2 C3 T1 T2 T3 T4

x4 x3

Risultati Numerici

		Accuracy	
		2023	2024
SVM	MS	0,710	0,676
	HS	0,813	0,805
RF	MS	0,737	0,723
	HS	0,772	0,781
MLP	MS	0,717	0,657
	HS	0,730	0,802
XGBoost	MS	0,720	0,682
	HS	0,781	0,784

Confusion Matrix (SVM-HS) 2024

		True	
		P	N
Predicted	P	**13389**	2791
	N	2377	**7948**

Conclusioni

- **FloX:**
  - Fluorescenza **SIFA** significativa a livello di chioma e **non dopo la normalizzazione**;

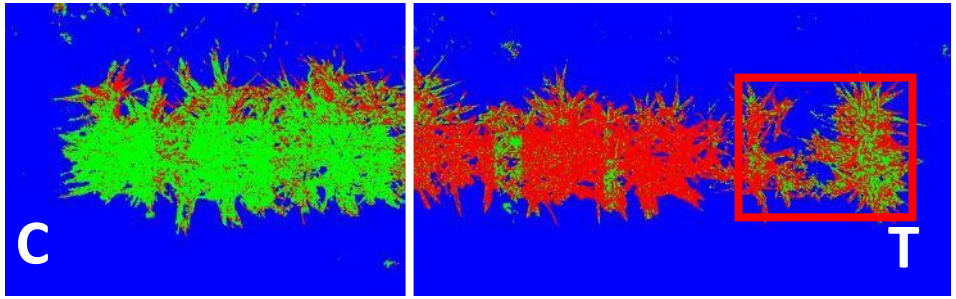
- **Spettrometro**:
  - firme spettrali a livello di foglia → fasi fenologiche diverse;
  - firme spettrali a livello di chioma nettamente distintive → biomassa → sensori iperspettrali e multispettrali;

- **UAV:**
  - **Analisi visiva**: diversa biomassa → differenze strutturali e morfologiche;
  - Indici iperspettrali **significativi** *(ANOVA);*
  - **Classificatori** con ottimi risultati.

Sviluppi futuri

- Disponibilità di **Piattaforma stratosferica**

- Differenti coppie **bioindicatori-contaminanti**



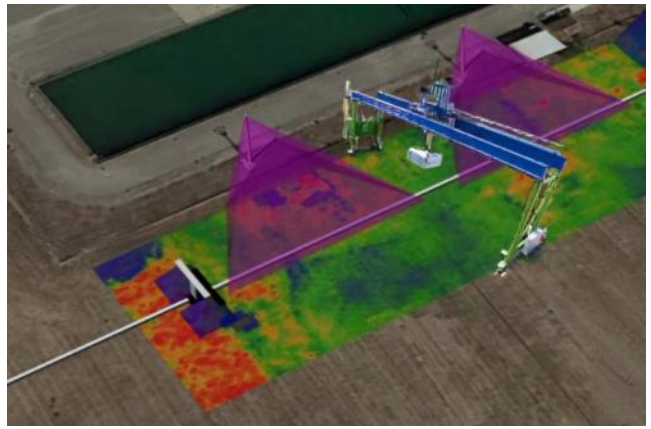
- **Algoritmi di Machine Learning più evoluti**

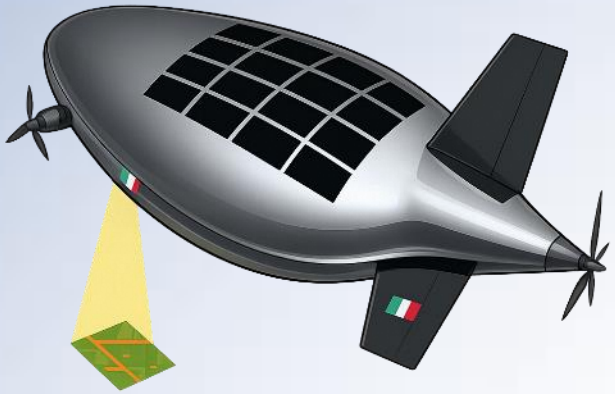
↓

Necessità di Dati

↓

Facility di **Plant Phenotyping**.





STOPP

Grazie per l'attenzione!

CIRA
Centro Italiano Ricerche Aerospaziali

Massimiliano Gargiulo