Polyploid Breeding

PRIN 2022

Computer vision for plant phenotyping: the Polyploidbreeding 4.0 project and the AGRI-VISION initiative

Filippo Biscarini

(And the Polyploidbreeding Core Team)

CNR-IBBA, Milan, Italy

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Overview

1. Neural Network models for **Computer Vision**:
   - CNN
   - Self-attention and transformers vs RNN
2. The **Polyploidbreeding** project
   - drone phenotyping
   - rhizotron
   - genotyping & sequencing
3. **drone2report** (software) + **vegetation indices**
4. **AGRI-VISION**: a proposal for a new COST Action (submitted)

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Filippo in one slide

- **Roma** (*born*)
- **Perugia** (*MSc degree*)
- **Cork, ICBF** (*Web-design & Database*)
- **Cremona, ANAFI** (*Quantitative Genetics*)
- **Guelph, CGIL** (*Visiting Scientist*)
- **Wageningen, WUR** (*PhD*)
- **Göttingen University** (*post-doctoral researcher*)
- **Lodi, PTP** (*'omics in animals, plants, humans*)
- **Caldes de Montbui, IRTA** (*Visiting Scientist*)
- **Milan - CNR** (*tenured researcher*)
- **Cardiff University** (*biostatistician*)
- **Milan - CNR** (*senior researcher*)
- **Bruxelles - ERC** (*seconded national expert*)
- **Milan - CNR** (*senior researcher*)

Currently coordinating:
- Polyploidbreeding (more on this later)
- Sheep-TreeSeq (UK)
- DeepMicroCore (Serbia)

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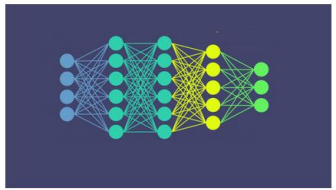
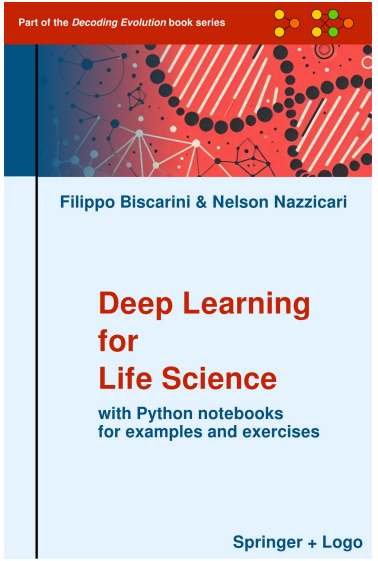
Neural Networks and I



INTRODUCTION TO DEEP LEARNING FOR BIOLOGISTS

Physalia Courses

course (5th edition)



scientific reports

scientific articles

OPEN

Check for updates

Stacked kinship CNN vs. GBLUP for genomic predictions of additive and complex continuous phenotypes

Nelson Nazzicari[1,3] & Filippo Biscarini[2,3]✉

book

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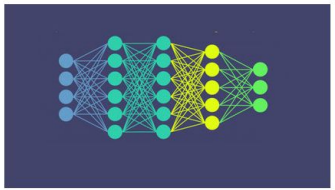

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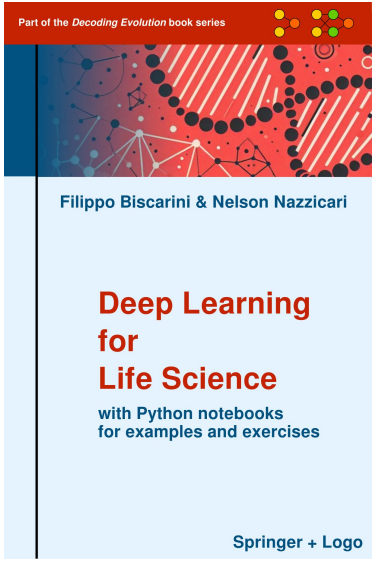

+ workshops, projects, conferences, etc.

scientific reports

scientific articles

OPEN

Check for updates

Stacked kinship CNN vs. GBLUP for genomic predictions of additive and complex continuous phenotypes

Nelson Nazzicari[1,3] & Filippo Biscarini[2,3]✉

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Part 1:

Neural Network models for Computer Vision

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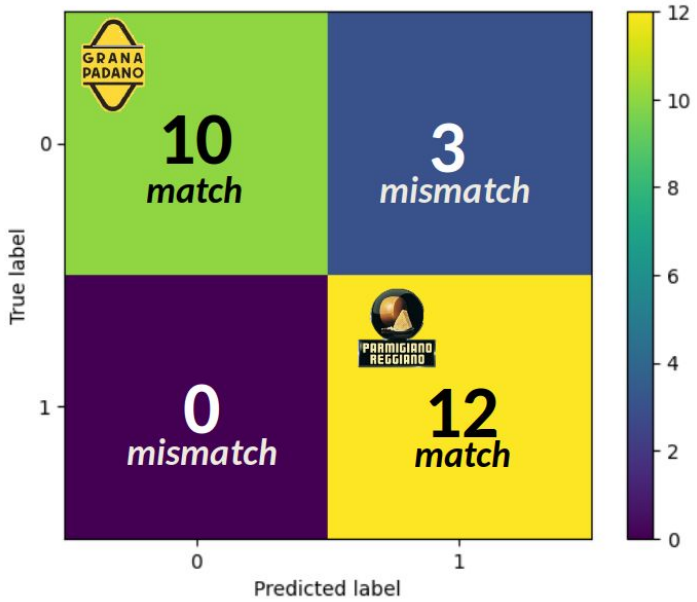
Computer Vision

Automatic reading, processing, analysing and "understanding" of digital images by computers:

- **image recognition (classification)**

Largely based on **CNN**



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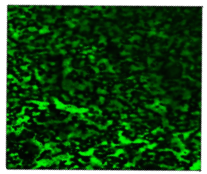
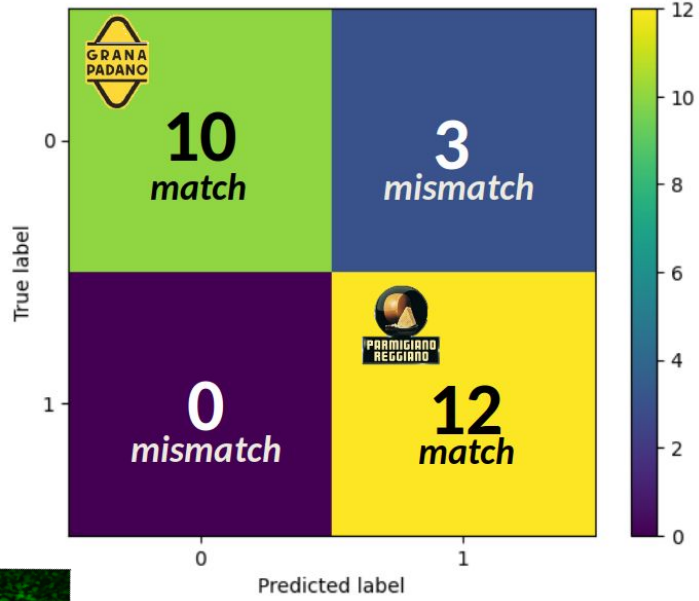


- confocal microscopy images of GP and PR
- N = 130 images (69 GP + 61 PR)
- CNN model (85,089 parameters, 200 epochs)
- 25 validation images (13 GP + 12 PR)
- validation accuracy = 0.84 (but highly variable!)



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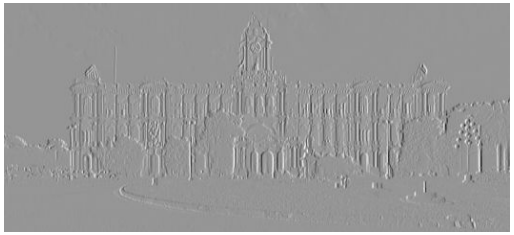
CNN: ~~Cable News Network~~

*

=



CNN: Convolutional Neural Networks

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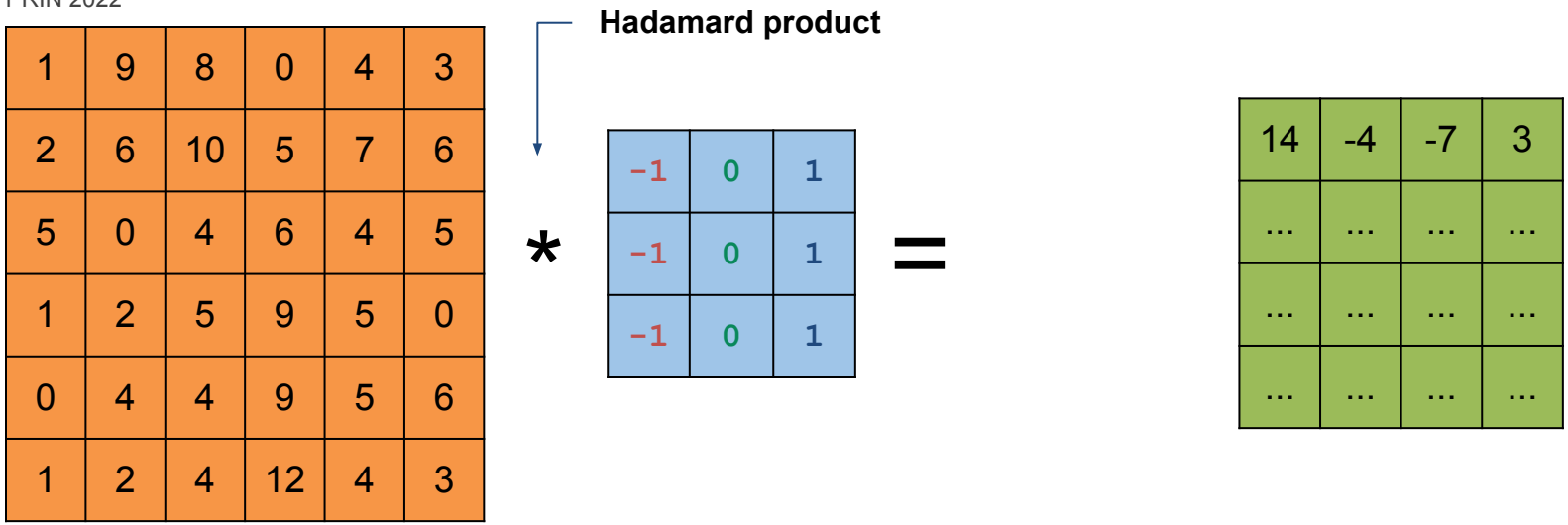
CNN: how the computer sees an image



1 x -1 + 2 x -1 + 5 x -1 + 9 x 0 + 6 x 0 + 0 x 0 + 8 x 1 + 10 x 1 + 4 x 1 = 14

9 x -1 + 6 x -1 + 0 x -1 + 8 x 0 + 10 x 0 + 4 x 0 + 0 x 1 + 5 x 1 + 6 x 1 = -4

...

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CNN: how the computer sees an image

1	9	8	0	4	3
2	6	10	5	7	6
5	0	4	6	4	5
1	2	5	9	5	0
0	4	4	9	5	6
1	2	4	12	4	3

Hadamard product

*

-1	0	1
-1	0	1
-1	0	1

=

14	-4	-7	3
…	…	…	…
…	…	…	…
…	…	…	…

The numbers in the filter are the CNN parameters!

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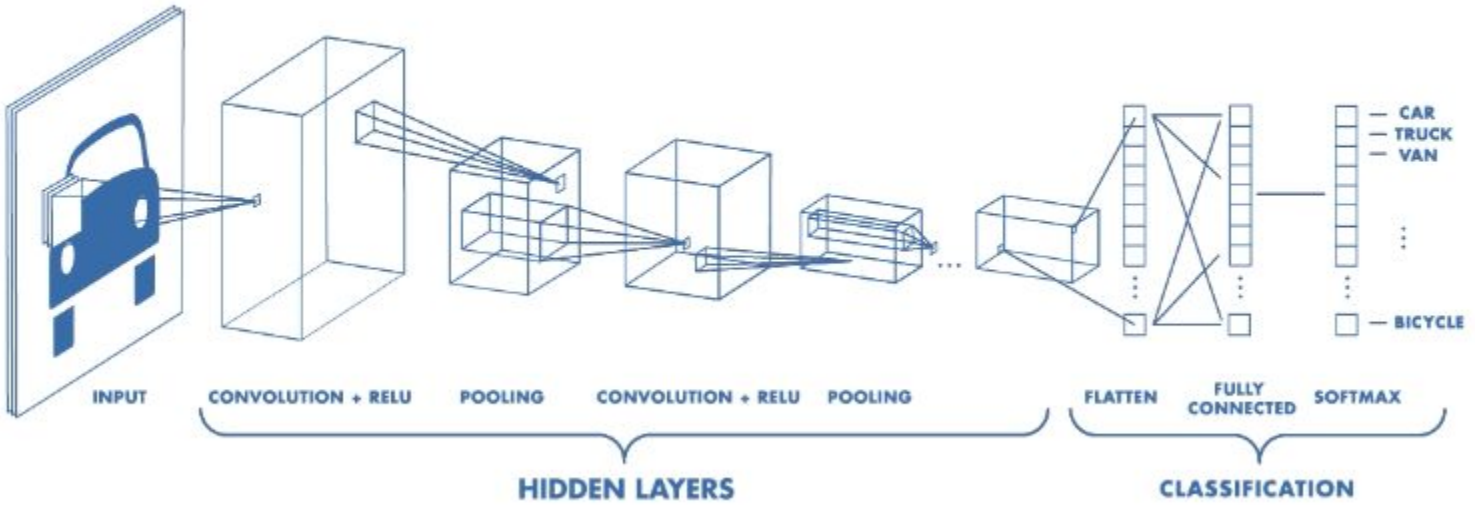
CNN: image recognition



Source: https://www.mathworks.com/videos/introduction-to-deep-learning-what-are-convolutional-neural-networks--1489512765771.html

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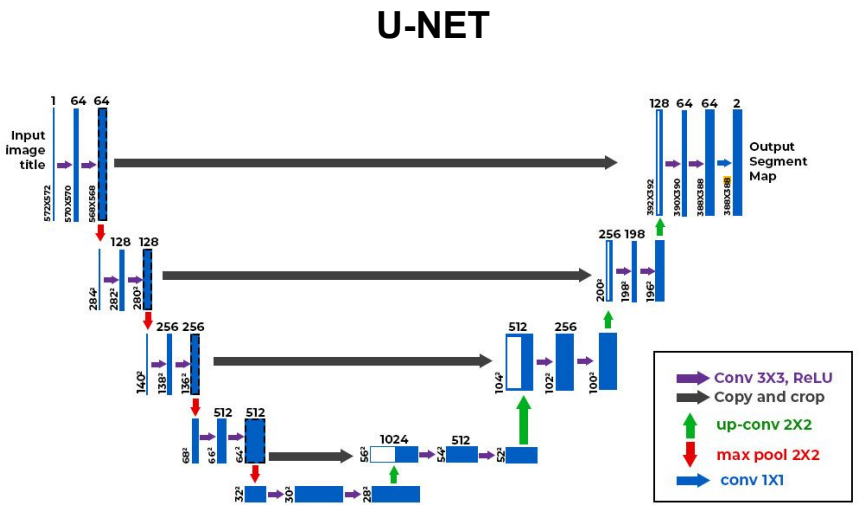
CNN: image segmentation

https://indiaai.gov.in/article/image-segmentation-the-deep-learning-approach



https://www.geeksforgeeks.org/u-net-architecture-explained/

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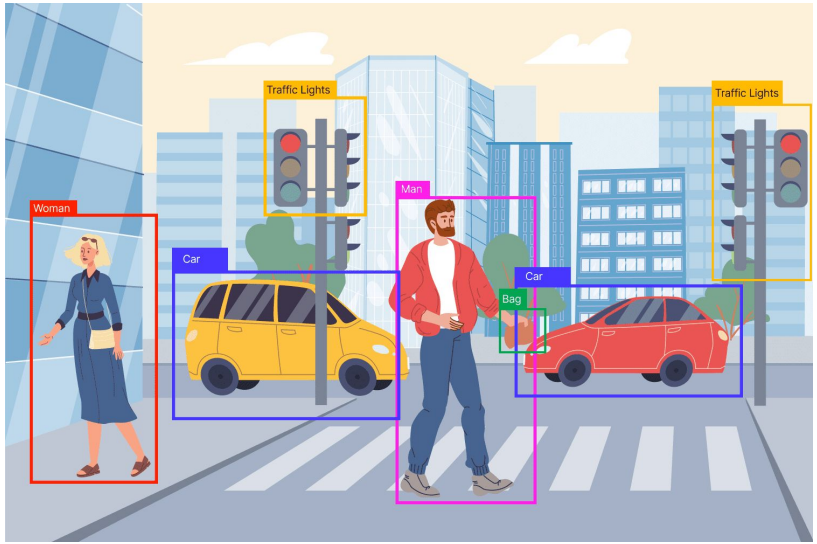
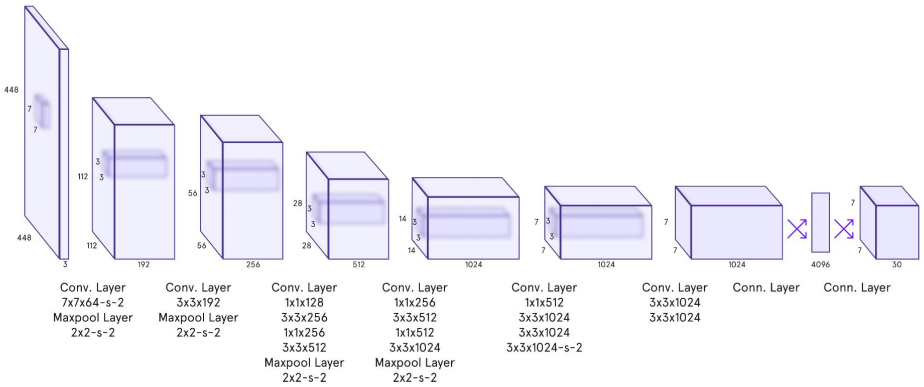
CNN: object detection



https://deeplobe.ai/exploring-object-detection-applications-and-benefits/

YOLO: you only look once



The Architecture. Our detection network has 24 convolutional layers followed by 2 fully connected layers. Alternating 1x1 convolutional layers reduce the features space from preceding layers. We pretrain the convolutional layers on the ImageNet classification task at half the resolution (224x224 input image) and then double the resolution for detection.

https://pareto.ai/blog/yolo-object-detection

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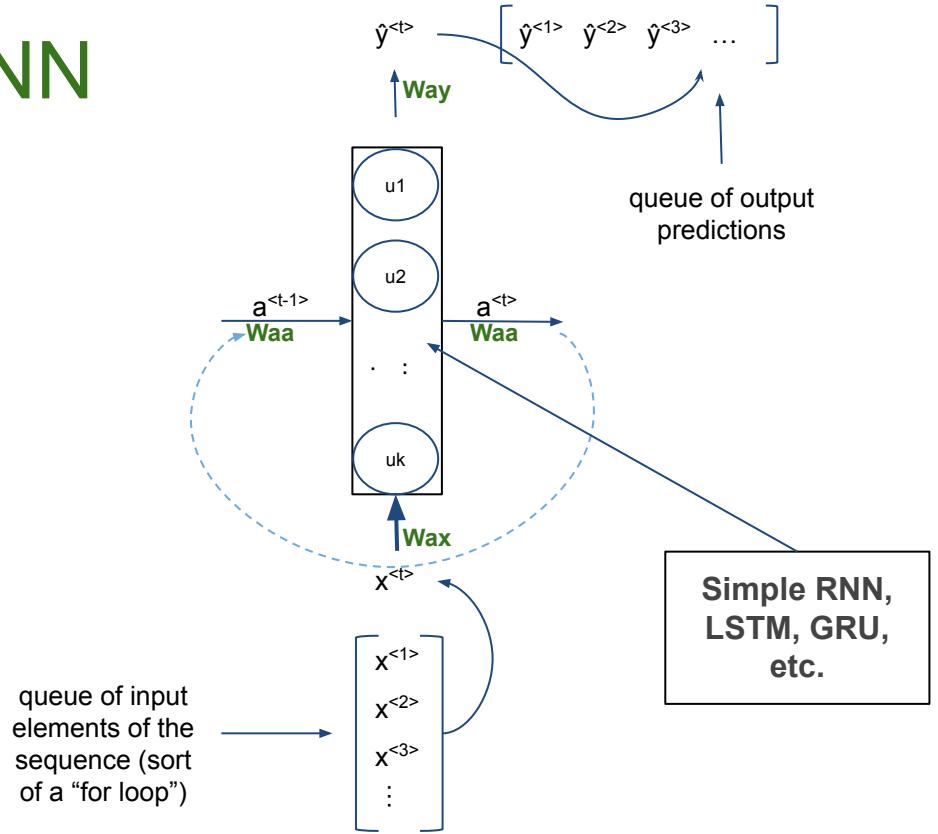
Sequence data: RNN

audio sequence	[speech recognition]
type of music (integer/string)	[music generation]
text sequence	[text classification]
DNA sequence	[pattern recognition]
text sequence in Italian	[text translation]



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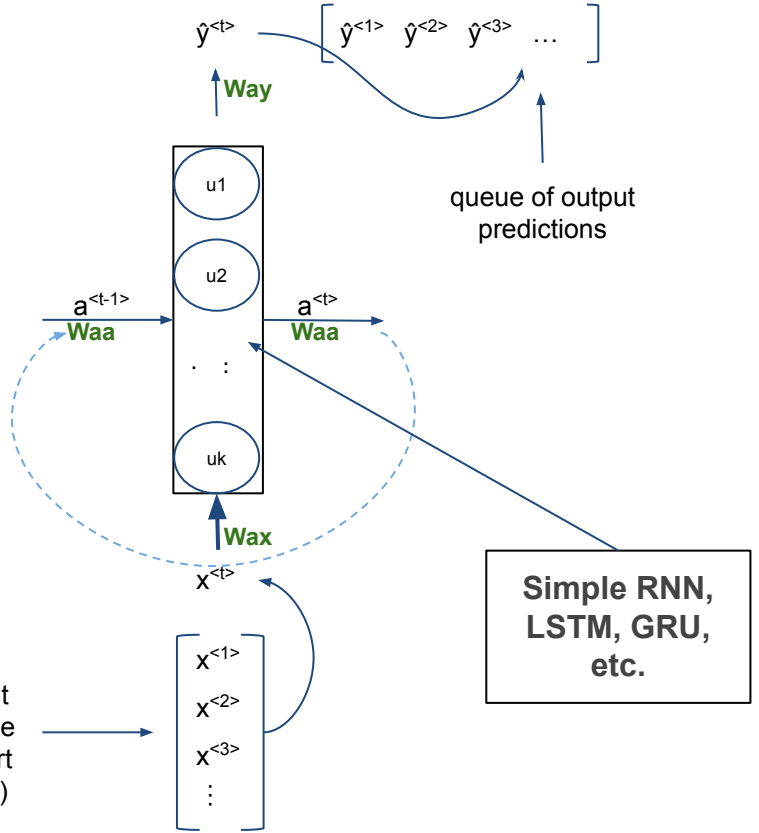
Sequence data: RNN

LLMs

audio sequence	[speech recognition]
type of music (integer/string)	[music generation]
text sequence	**[text classification]**
DNA sequence	[pattern recognition]
text sequence in Italian	**[text translation]**



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Self-attention

Attention Is All You Need

Ashish Vaswani* Google Brain avaswani@google.com

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12/06/2017

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Transformers

- **(self)attention**: ability of the model to automatically, dynamically and independently **highlight** and **use** the **salient parts of the input data**
- attention is the engine of **transformer models**
- RNN, LSTM, GRU etc.: sequential calculations, no parallelization possible (severe computational limit)
- transformers capture long-range dependencies in the data and at the same time are amenable to parallelization
- transformers are a new network architecture that **dispenses with recurrence and convolutions entirely** (no CNN, no RNN)
- transformers are successfully <u>applied also to image data</u> (computer vision)

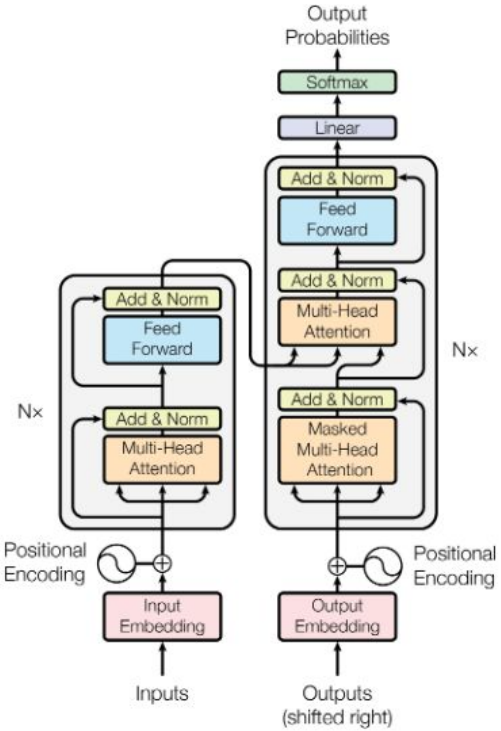

Figure 1: The Transformer - model architecture.

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Transformers?

Were RNNs All We Needed?

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04/10/2024

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Part 2:

The Polyploidbreeding project

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Polyploidbreeding

PRIN 2022

"Expanding the toolbox for cereal breeding: high-throughput genomics, 2D-3D phenomics and artificial intelligence for breeding with increasing genome complexity, from **barley** to **durum** and **bread wheat**"

- PRIN (EU/ITA funds) **research project**
- 09/2024 - 09/2025
- **~ € 240k**
- project website: https://polyploidbreeding.ibba.cnr.it/
- barley (**diploid**), durum wheat (**tetraploid**), bread wheat (**hexaploid**)

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Polyploid Breeding
PRIN 2022

Polyploidbreeding - the team

1. **CNR** (National Research Council) (www.cnr.it): project coordinator
   a. Filippo Biscarini (coordinator)
   b. Giulia Moscatelli (post-doctoral researcher)
2. **University of Bologna** (www.unibo.it):
   a. Elisabetta Frascaroli
   b. Marco Maccaferri, Matteo Bozzoli + new trainee (to be appointed)
3. **CREA** (Council for Research in Agriculture) (www.crea.gov.it):
   a. Nelson Nazzicari
   b. Agostino Fricano
4. **SIS** (Società Italiana Sementi): breeding company (www.sisonweb.com/):
   a. Eder Groli, Paolo De Franceschi
5. **Forschungszentrum Jülich** (www.fz-juelich.de):
   a. Fabio Fiorani, Kerstin Nagel

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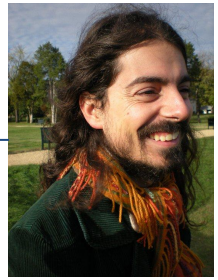
(vegetation indices)



(drone2report)

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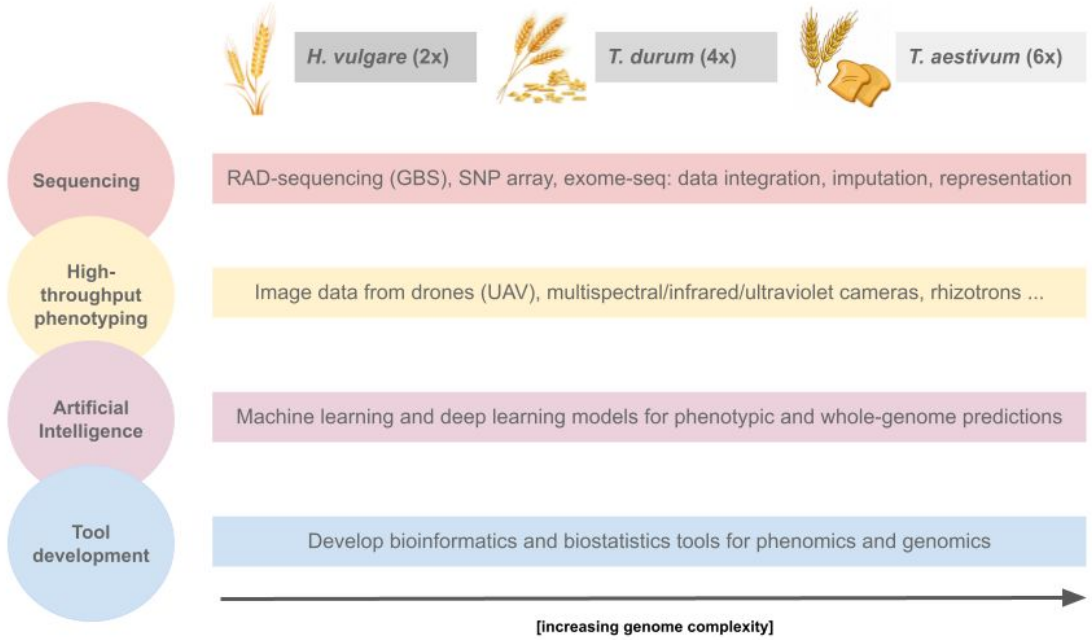
Polyploidbreeding - overview



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The experiments

Crop	Number of individuals	Traits	Genotypic data	Connected project	Notes
Barley (*H. vulgare*)	403	DtH,PH,TKW, AL	Exome sequencing (~300K SNPs)	WHEALBI, FP7, 2019	multiple seasons and sites
Bread wheat (*T. aestivum*)	483	DtH,PH,TKW, AL, PL + other categorical traits (cold tolerance, biotic stress resistance)	Exome sequencing (~100K SNPs)	WHEALBI, FP7, 2019	
Barley (*H. vulgare*)	~200	DtH, GY + phenological adaptation, yield stability, and resilience	50k SNP array	BARISTA. SusCrop-ERA-NET, 2022	multiple seasons and sites
Barley (*H. vulgare*)	~1000 (diverse landraces)	DtH	GbS (~100K SNPs)	GENDIBAR, EU-PRIMA, 2022	multiple seasons and sites
Durum (*T. durum*)	250 (cultivar, landraces, emmer)	DtH,PH,TKW + other categorical spike fertility grain characterzation	Exome sequencing (~800K SNPs)	UNIBO (background material)	multiple years
Durum (*T. durum*)	250 (cultivar, world)	HTP vegetation indexs DtH,PH, + osmotic adj, drought index	illumina (~90K SNPs array)	InnoVar, EU-H2020, 2024	multiple years
Durum (*T. durum*)	250	DtH,PH,TKW + GY and components NDVI, SPAD	illumina (~90K SNPs array)	InnoVar, EU-H2020, 2024	multiple sites
Durum (*T. durum*)	300	HTP vegetation indexs, DtH,PH,TKW, GY and components, NDVI, SPAD, disease rust fusarium	illumina (~90K SNPs array)	InnoVar, EU-H2020, 2024	
Durum (T. durum)	300 (landraces)	phenological adaptation, yield stability, resilience and resistance to diseases	illumina (~90K SNPs array)	CerealMed, EU-PRIMA, 2022	multiple sites
Durum (T. durum)	300 (cultivars)	phenological adaptation, yield stability, resilience and resistance to diseases	illumina (~90K SNPs array)	CerealMed, EU-PRIMA, 2022	multiple sites

1. <u>drone phenotyping experiment</u> (led by CNR, CREA): completed
   a. 10 flights, 3 cameras, 3 crop species:
      i. barley (Fiorenzuola, CREA): ~260 varieties
      ii. durum and bread wheat (S. Lazzaro - Bologna, SIS): ~247 (durum) and 230 (bread) varieties

2. <u>rhizotron experiment</u> (led by Jülich): 15 jan - 15 feb 2025
   a. durum wheat, ~60 varieties

3. <u>sequencing/genotyping experiment</u> (led by UNIBO): in progress
   a. durum and bread wheat:
      i. ~300 varieties (150/150): genotyping (25k SNP array)
      ii. sequencing (high-coverage): ~50-100 varieties →**polyploidy**

new data + **historical data**

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Polyploidbreeding - drone phenotyping

Campo	Sensore	Altezza volo (m)	GSD (cm/pixel)	Overlap	Sidelap
1	RGB	12	0.33	80%	80%
1	Termico	12	1.57	68%*	90%
1	Multispettrale	12	0.83	80%	80%
2	RGB	12	0.33	80%	80%
2	Termico	12	1.57	68%*	90%
2	Multispettrale	12	0.83	80%	80%

- Location
- Camera
- Height
- Ground Sampling Distance (~resolution)

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Polyploid Breeding

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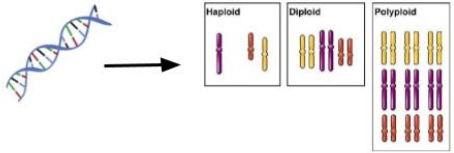
Polyploidbreeding - drone phenotyping

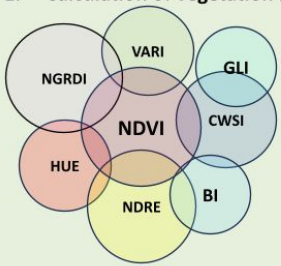
UAV (unmanned aerial vehicle: drone)-high-throughput phenotyping:

Multi-camera image acquisition:

Genomic information



1. Calculation of vegetation indices



2. Phenotypic predictions

DNN models to predict: i) future growth; ii) high-resolution phenotypes from lower-resolution data

3. Genomic predictions

Use genomic data to predict image phenotypes (besides traditional phenotypes)

Genomic selection

Develop bioinformatics and biostatistics tools for phenomics and genomics

predictions of target phenotypes

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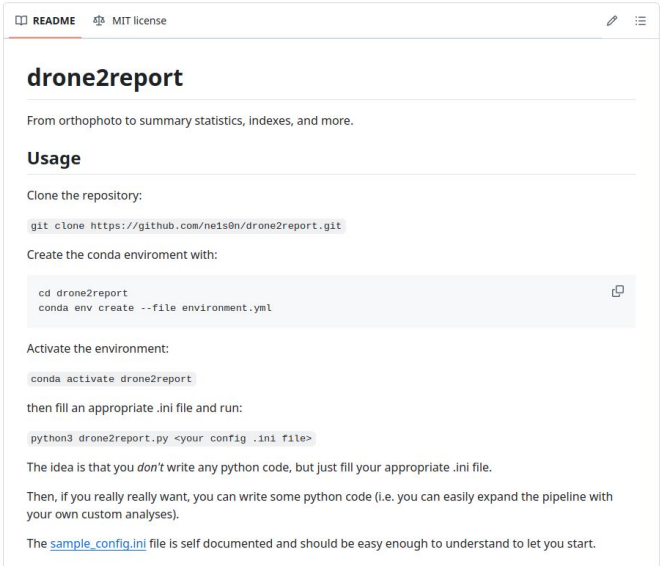
Tool development: drone2report

https://github.com/ne1s0n/drone2report

Python-based software to read drone-captured images (RGB, multispectral, thermal) and calculate vegetation indices



README MIT license

drone2report

From orthophoto to summary statistics, indexes, and more.

Usage

Clone the repository:

```
git clone https://github.com/ne1s0n/drone2report.git
```

Create the conda enviroment with:

```
cd drone2report
conda env create --file environment.yml
```

Activate the environment:

```
conda activate drone2report
```

then fill an appropriate .ini file and run:

```
python3 drone2report.py <your config .ini file>
```

The idea is that you *don't* write any python code, but just fill your appropriate .ini file.

Then, if you really really want, you can write some python code (i.e. you can easily expand the pipeline with your own custom analyses).

The sample_config.ini file is self documented and should be easy enough to understand to let you start.

Credits

This is a joint effort between:

crea Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria

NPEC

The development has also been sponsored by the Polyploidbreeding project (PRIN 2022, Settore LS2)

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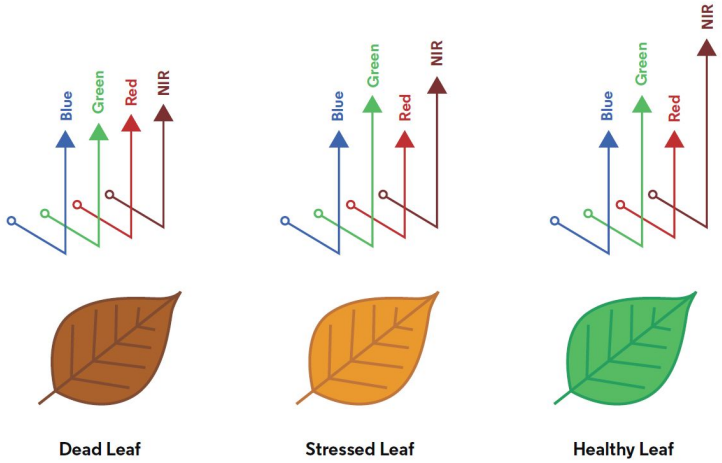
Vegetation Indices

Vegetation Indices are **metrics / summary stats** obtained from spectral images of any kind, that are intended to capture some properties of the crops

https://www.indexdatabase.de/db/i.php : > 500 different vegetation indices

- RGB → VARI
- Multispectral → NDVI
- Thermal →TSI
- DEM →height, volume



https://support.insights.granular.ag/hc/en-us/articles/360034834012-How-does-the-Vegetation-Index-work

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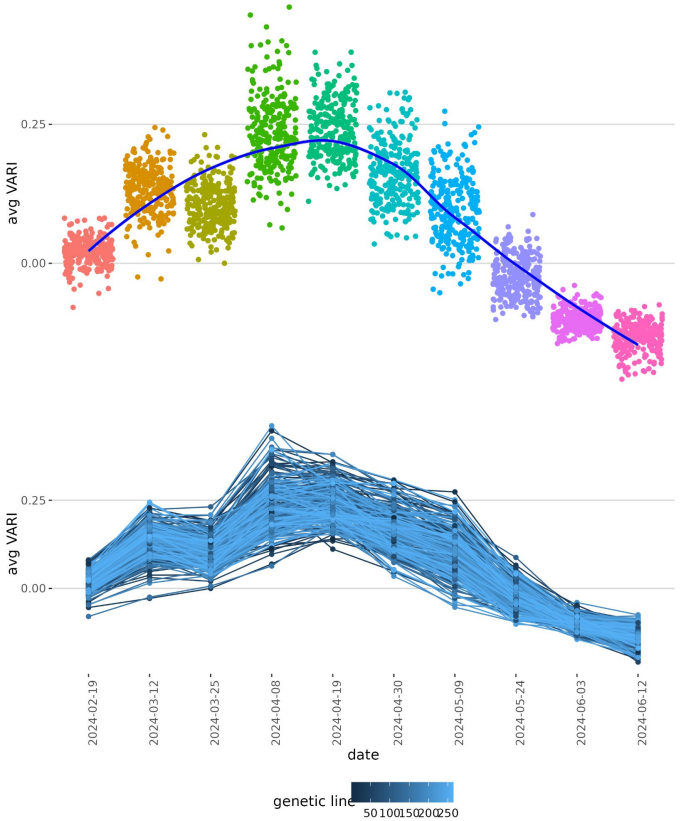
VARI

VARI: Visible Atmospherically Resistant Index

- **RGB** camera (M3E): 400~700nm.
- VARI emphasizes vegetation in the visible portion of the spectrum, while mitigating illumination differences (reflectance, scattering) and atmospheric effects

VARI can be used to detect changes in biomass accumulation and responds to the amount of chlorophyll in the leaves

$$\mathrm{VARI} = \frac{(\mathrm{green} - \mathrm{red})}{(\mathrm{green} + \mathrm{red} - \mathrm{blue})}$$



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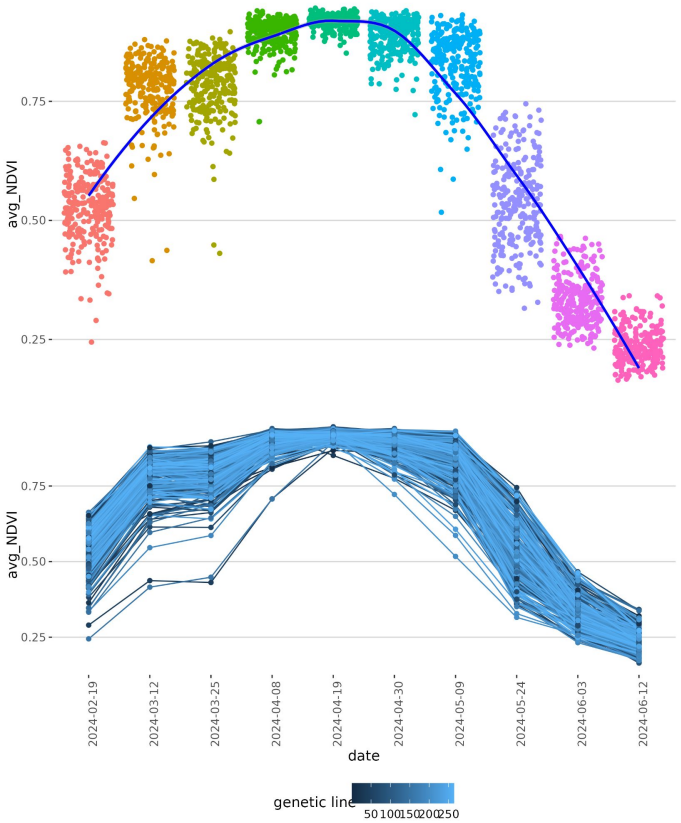
NDVI

NDVI: Normalized Difference Vegetation Index

- **multispectral** camera (MICA): measure the plant canopy reflectance in both the visible (VIS) and the near-infrared (NIR) spectra
- normalized difference between NIR (correlated to leaf structure) and red (correlated to chlorophyll content)
- visible and NIR vegetation reflectance intensities are, respectively, negatively and positively correlated to leaf N content and biomass
- greater leaf area and green plant biomass translate into higher NDVI values

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})}$$



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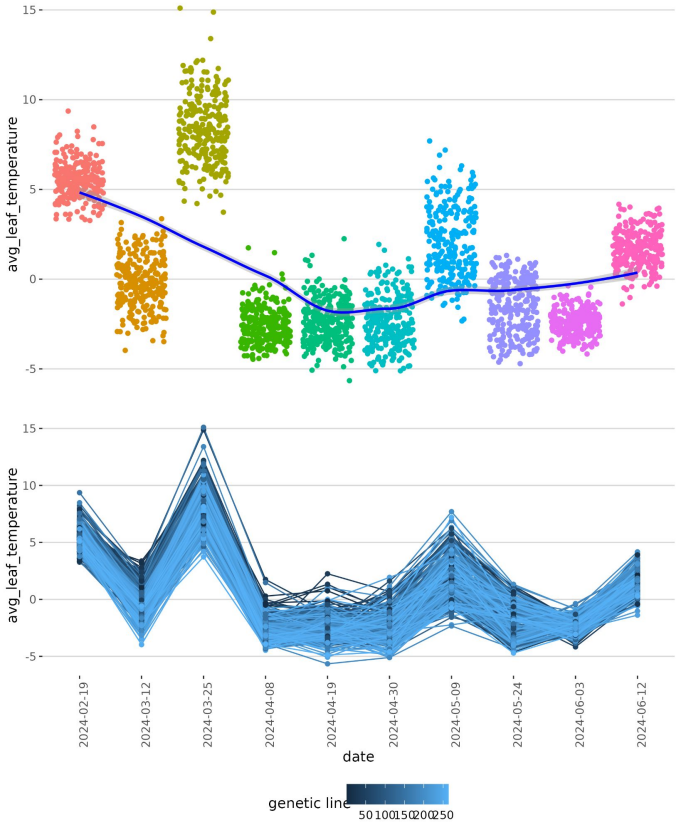
TSI

TSI: Thermal Stress Index

- **Thermal camera** (M3T)
- canopy to air temperature difference: canopy temperature considered as a proxy for monitoring crop water status

$$TSI = (T_{foliage} - T_{air})$$

DATE and HOUR	T_{air}
19/02/2024 h 13.00	14,8 °C
12/03/2024 h 12.00	16,7 °C
25/03/2024 h 12.30	15,5 °C
08/04/2024 h 13.00	23,5 °C
19/04/2024 h 12.00	17 °C
30/04/2024 h 12.45	23,7 °C
09/05/2024 h 12.30	22,5 °C
24/05/2024 h 14.30	20,7 °C
03/06/2024 h 11.30	21 °C
12/06/2024 h 11.30	24 °C



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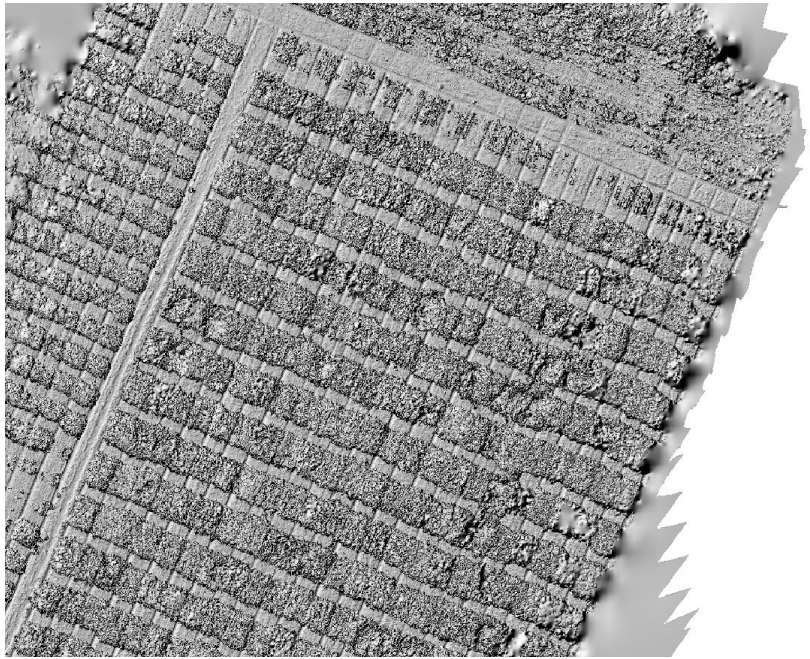
Digital Elevation Model



- .dem file
- hillshade view
- (same barley field)

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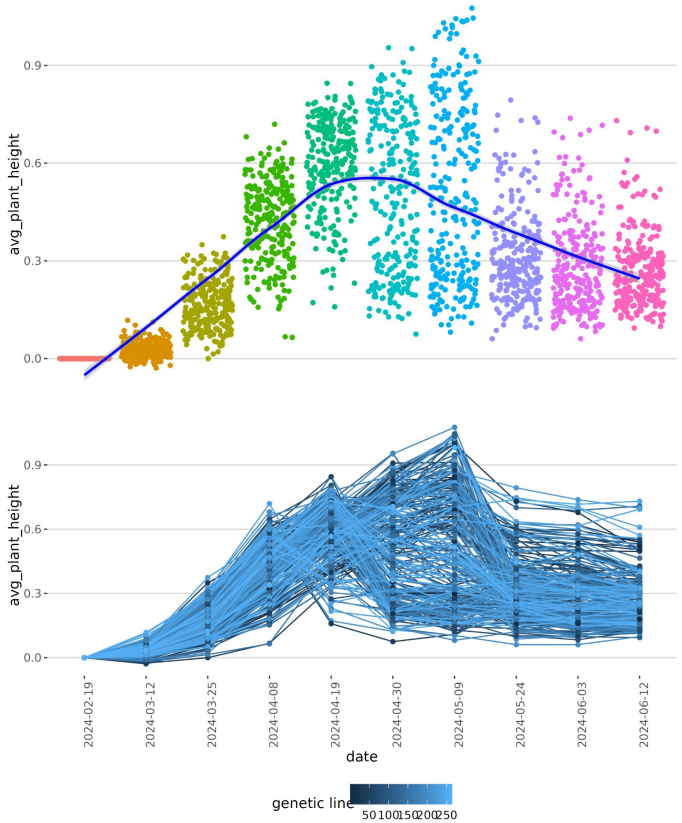
DEM → plant height

- First flight taken as reference
- meters



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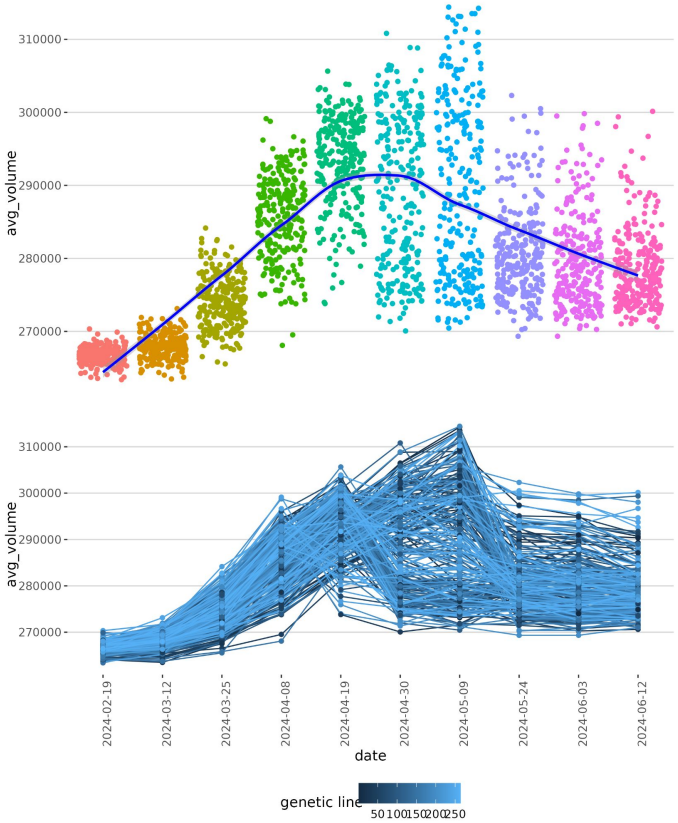
DEM → volume

- First flight taken as reference
- By summing up all plant heights we can get the volume
- Volume is a good proxy for crop biomass
- Still refinements are needed: i) check normalization; ii) thresholding; iii) other?



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Part 3:

The AGRI-VISION COST-Action proposal

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AGRI-VISION

“Computer vision applications for sustainable, productive and efficient food & agriculture sectors”

- COST Action proposal **[submitted]**: interdisciplinary research network
- food & agriculture (livestock, plants, aquaculture, insects, food science), computer science, statistics, law
- € 575k (total), 4 years

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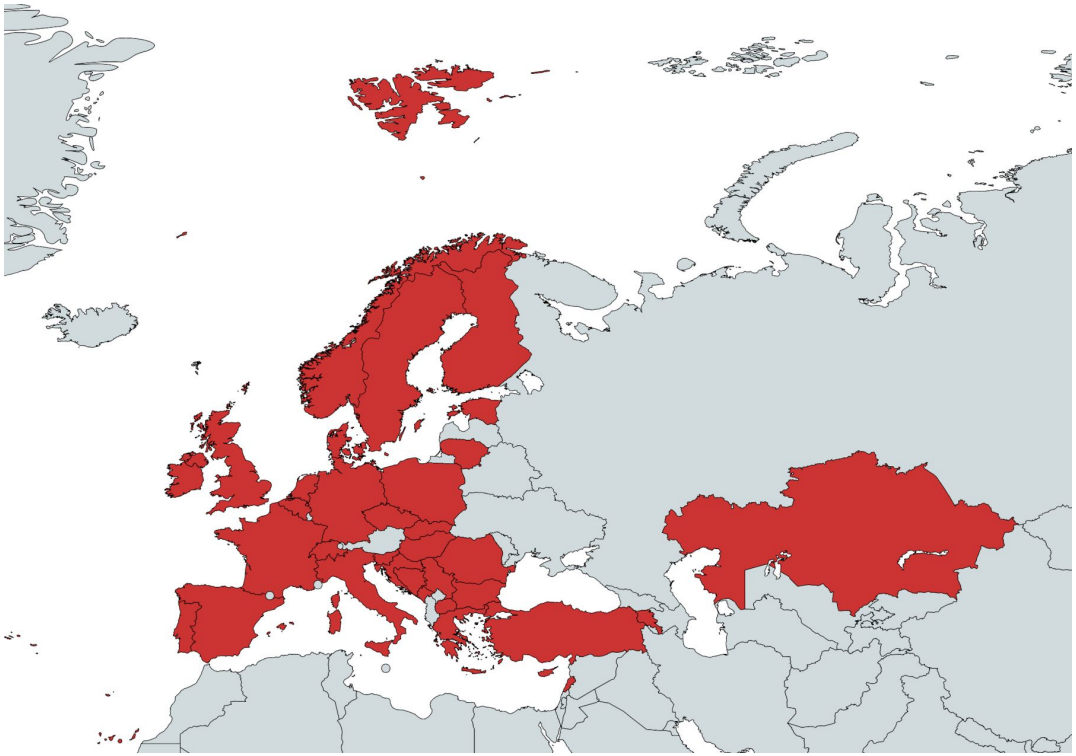
AGRI-VISION - network

- 80 partners
- 35 countries and international organizations
- 60% ITCs
- academia, government, SME
- coordinator: CNR



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AGRI-VISION - project

WG1: Technology, data and infrastructure for Computer Vision

- survey on devices, hardware and data requirements for computer vision: current landscape and future developments
- training school(s) on big data processing, scalable infrastructure and ML methods for computer vision for food & agriculture (jointly with WG2)
- guidelines and recommendations on the needed infrastructure for computer vision in food and agriculture at the European scale, including scaling up from national to EU level

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AGRI-VISION - project

WG2: Methods and models for Computer Vision

- report on state-of-the-art and cutting-edge ML methods and models for computer vision to be used in food & agriculture
- guidelines on standardised practices for the application of computer vision to food & agriculture, including use of software tools, model implementation and data annotation
- tutorials on the practical use of computer vision tools and models, that will cover the most common scenarios and challenges

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AGRI-VISION - project

WG3: Case-studies from food & agriculture

- report on current and future (foreseen, desired) computer vision applications in various areas of food & agriculture: livestock, insect, plant farming and breeding, aquaculture, food processing
- videos of expert talks on the impact of computer vision on sustainable agriculture and food production in different areas

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AGRI-VISION - project

WG4: Societal impact, policies and the future frontier

- critical review of computer vision applications in food & agriculture in relation with the 2024 EU AI Act
- workshop on the drafting of data sharing agreements, intellectual property and licensing issues, and the compliance with GDPR
- report on the future directions of computer vision developments and the relationship with similar technologies
- collection of available surveys on the benefits and potential risks of AI applications in food and agriculture as perceived by relevant stakeholders

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AGRI-VISION - project

WG5: Dissemination, training and public engagement

- white paper on current and future computer vision developments in food and agriculture (jointly with all other WGs)

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Tak!

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