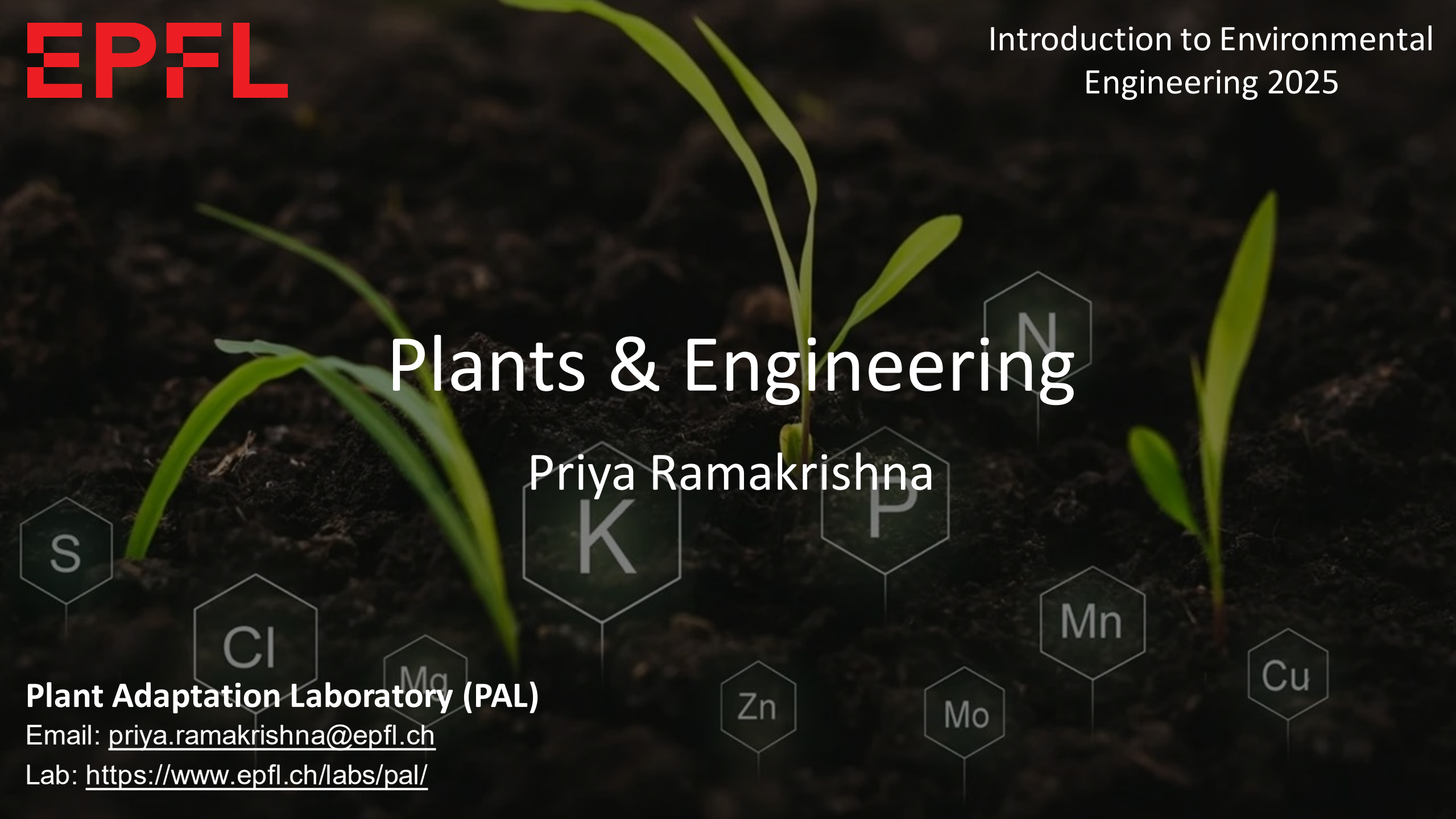


Introduction to Environmental Engineering 2025

Plants & Engineering

Priya Ramakrishna

Plant Adaptation Laboratory (PAL)

Email: priya.ramakrishna@epfl.ch

Lab: https://www.epfl.ch/labs/pal/

What do you see first in this image?

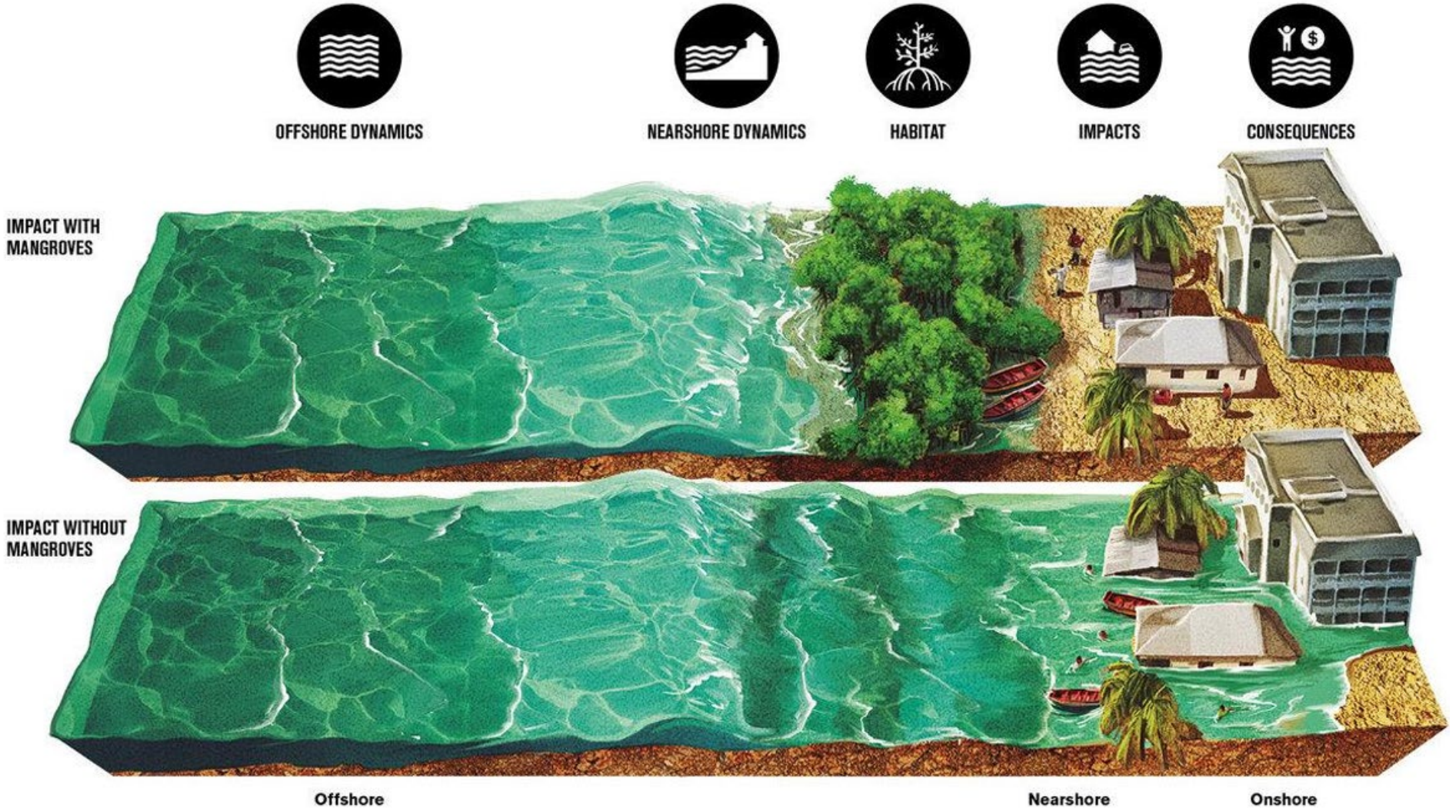
Overview

- Engineering with plants
- Stressors and their impact
- Engineering the plants
- Engineering for plants

Engineering with plants

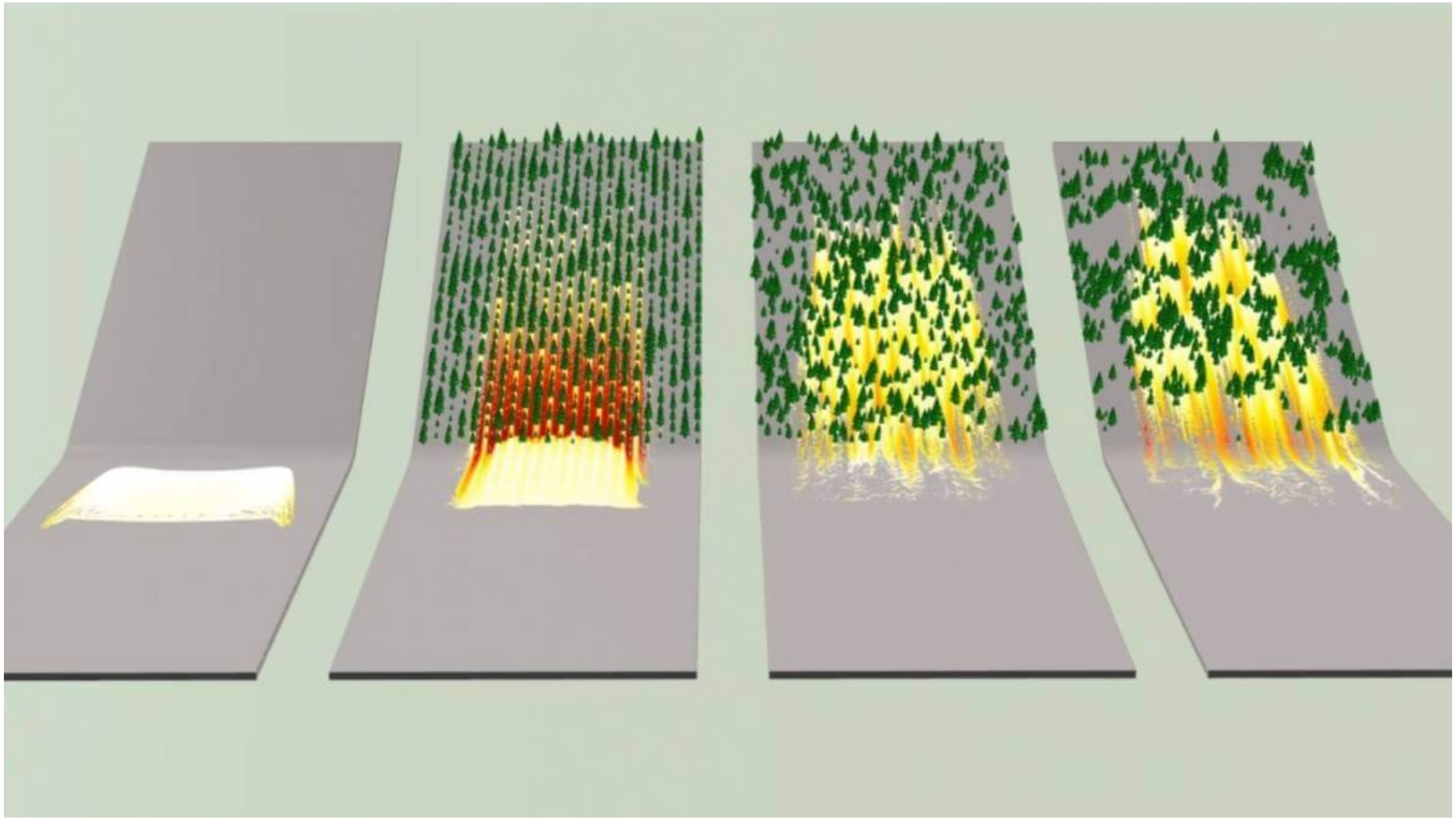
Plants as protection

Storm protection



Plants as protection

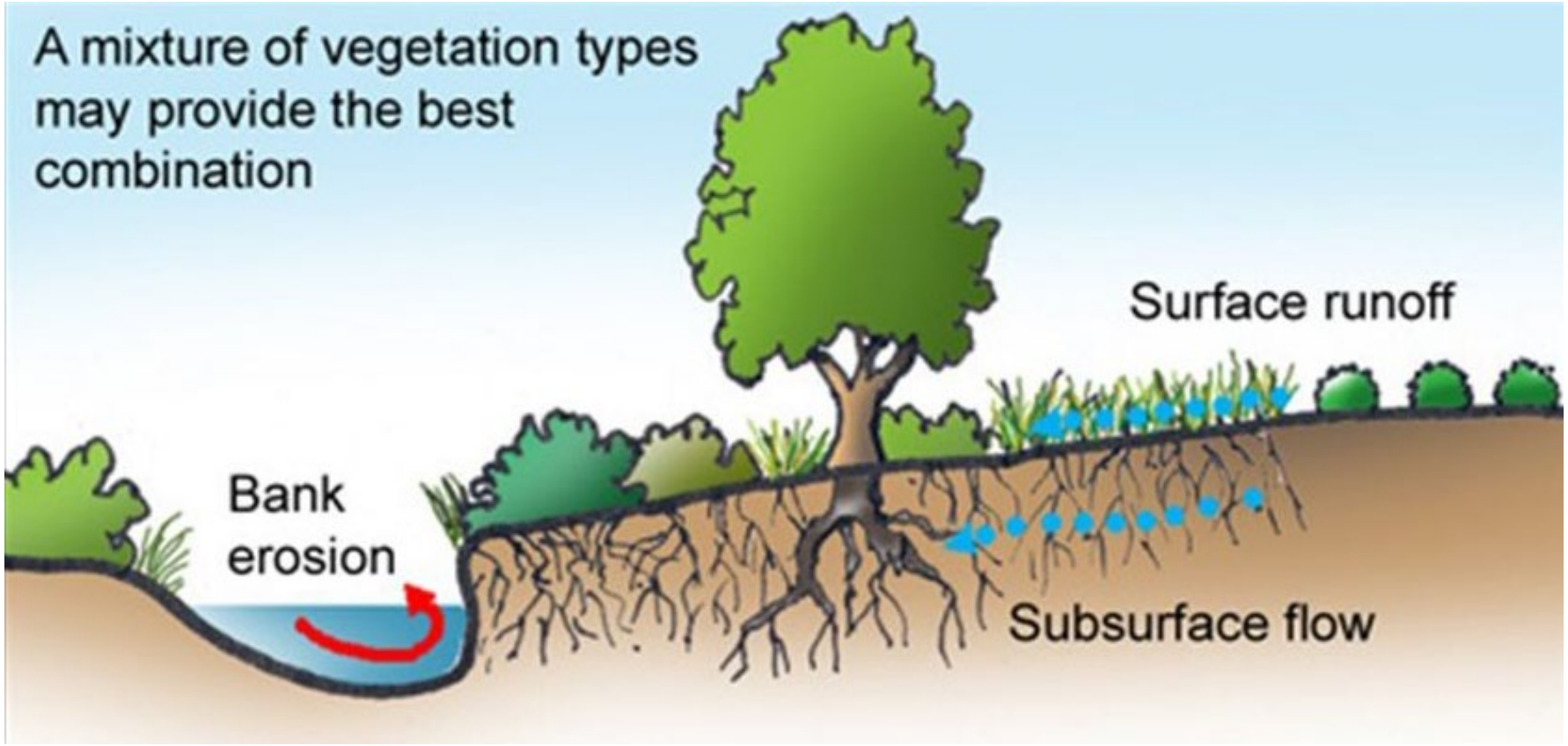
Avalanche protection



"Avalanche Modelling in Forested Slopes", Design Project, Francesc Molné, Clara Streule, Master Environmental Sciences and Engineering, EPFL, June, 2020.

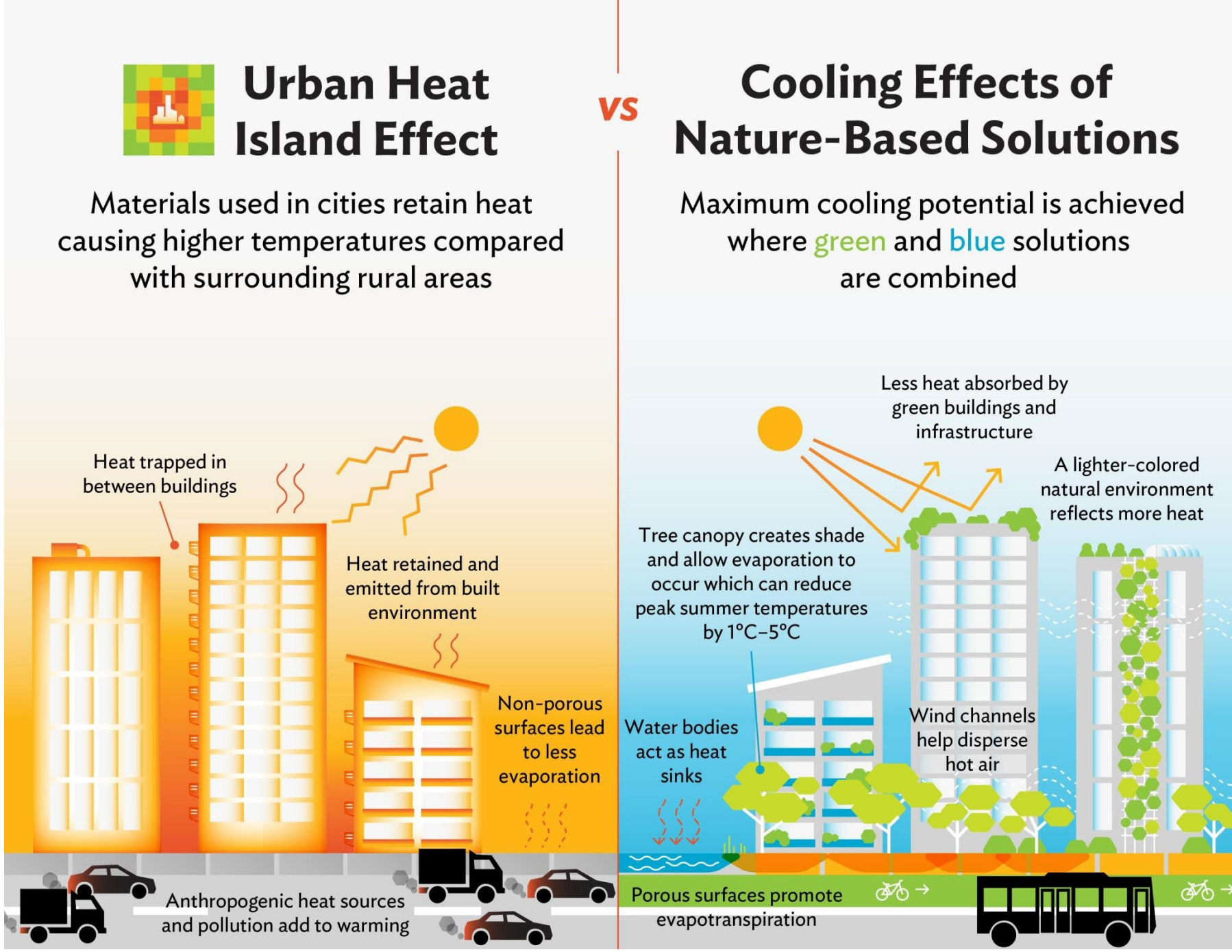
Plants as protection

Erosion protection



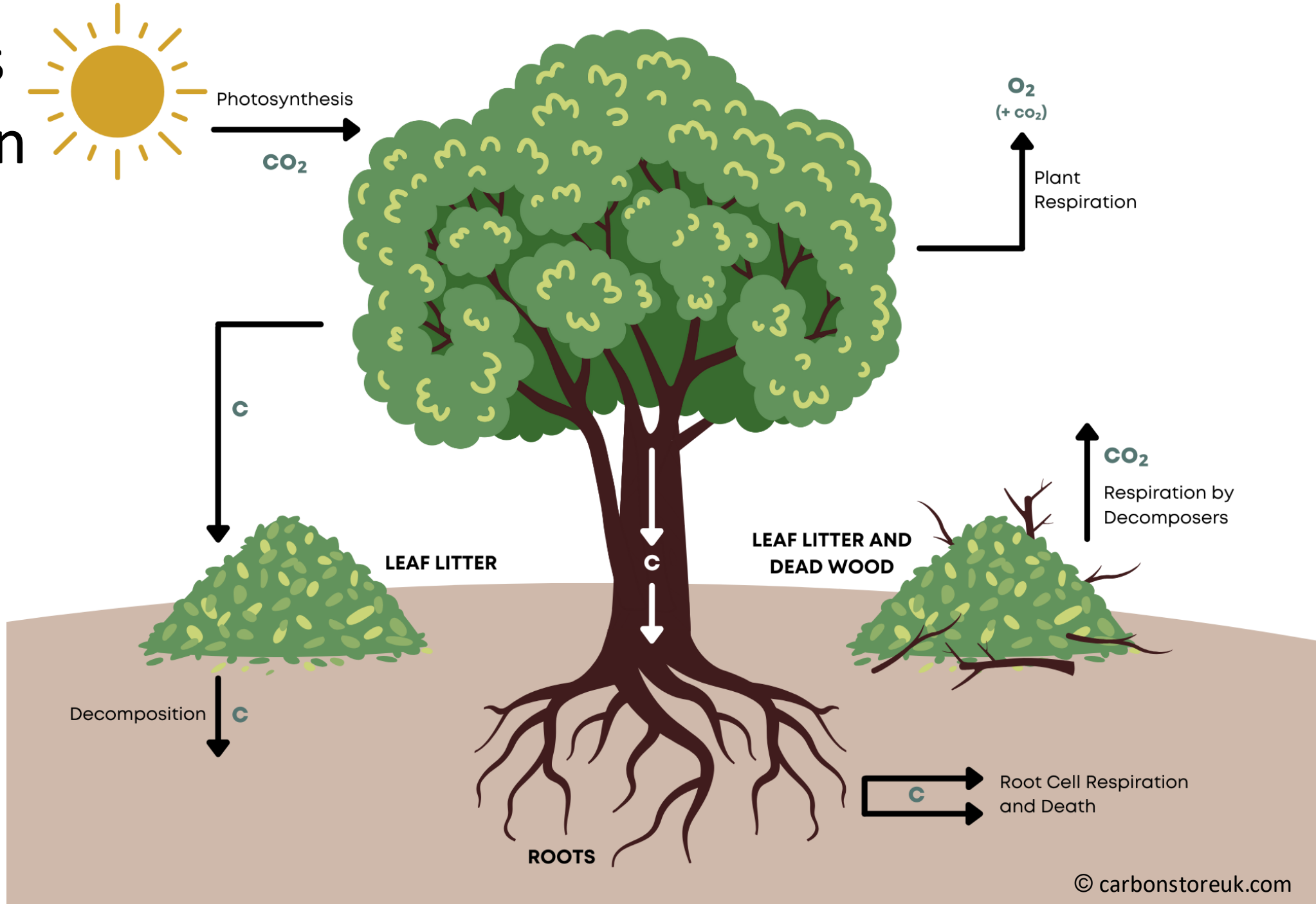
Plants as protection

Heat protection



Plants as protection

Climate change protection

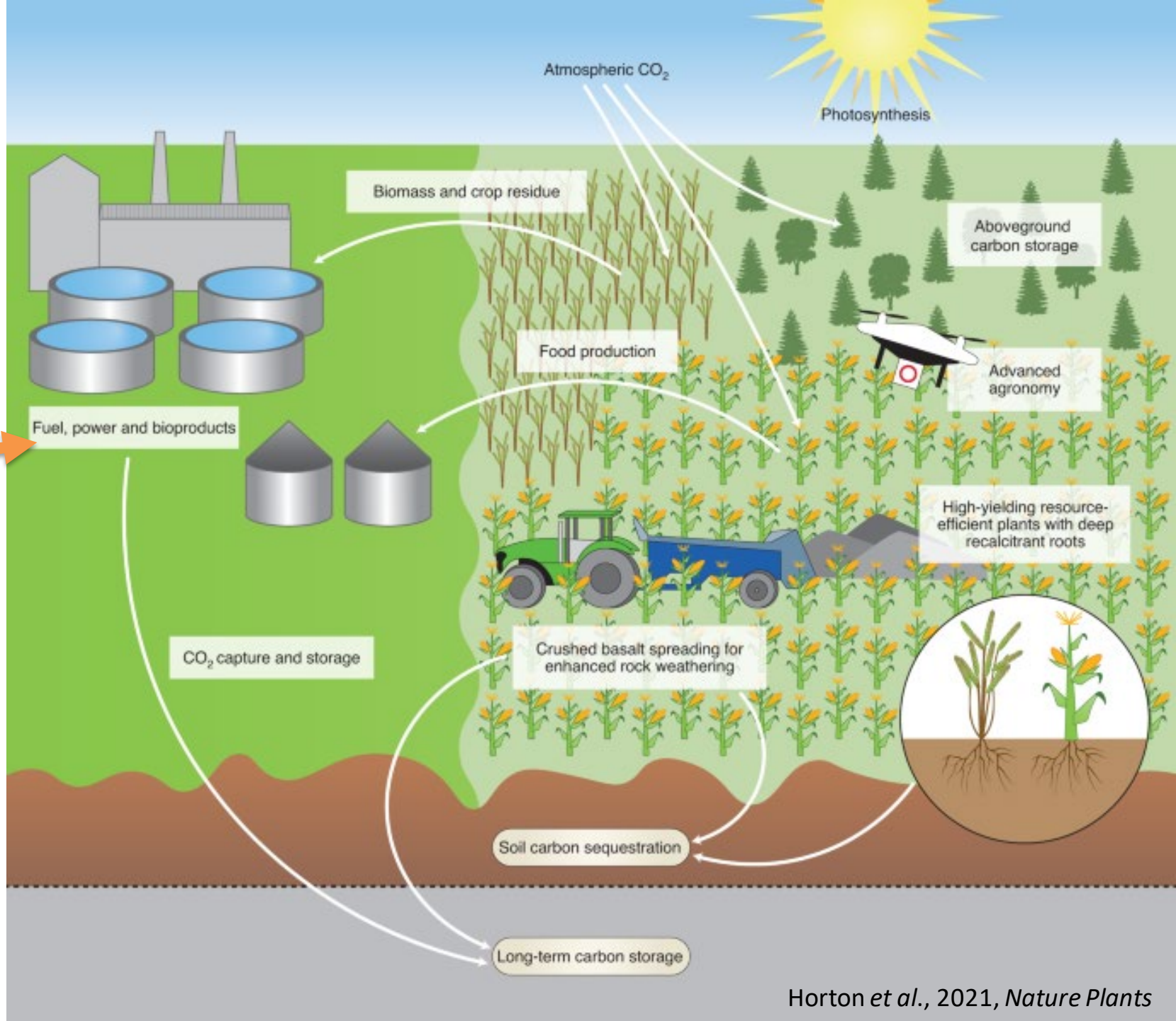


Plants as remedy and miners

Phytoremediation / phytomining

Plants as producers

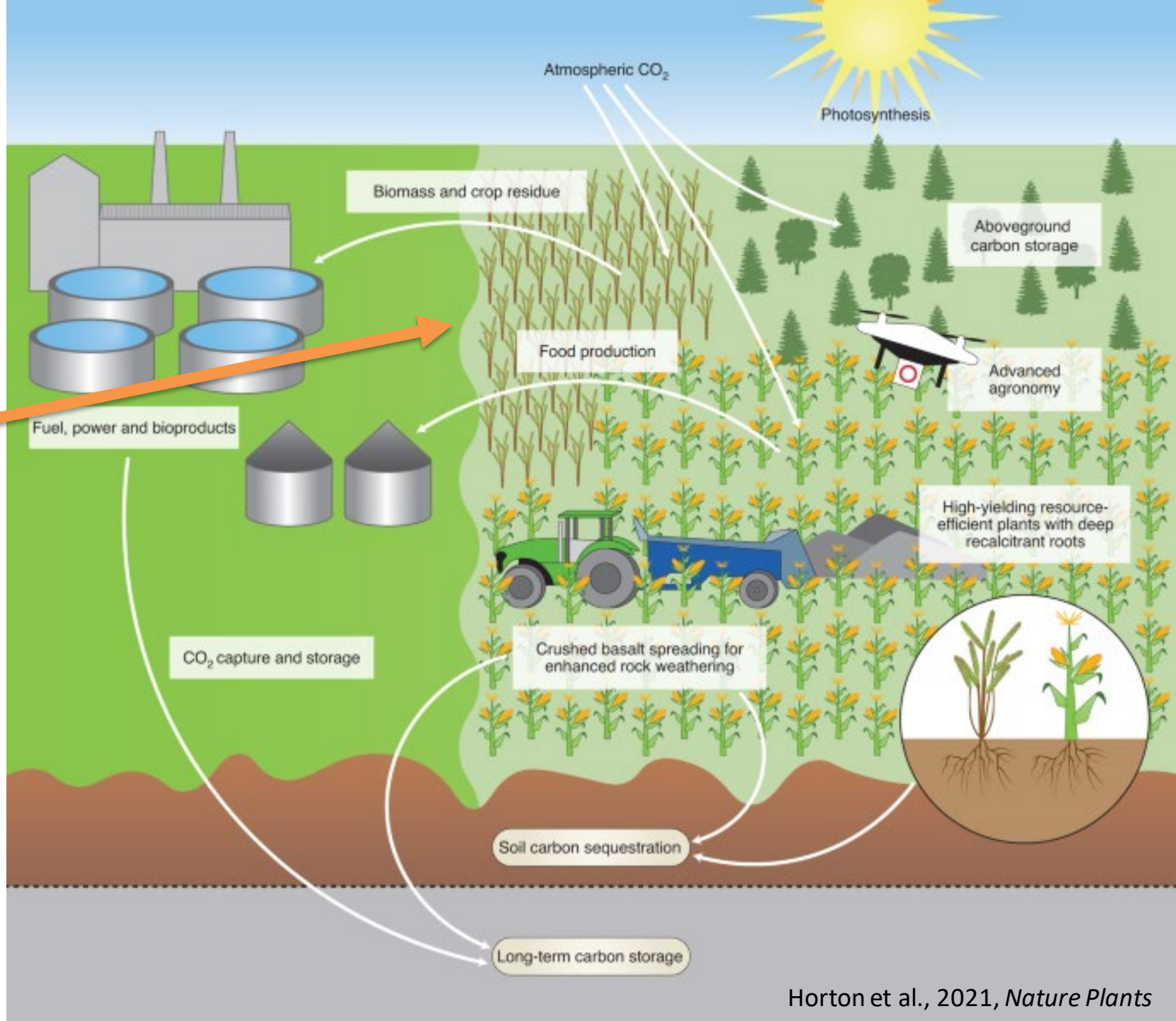
Biofuels



Horton *et al.*, 2021, *Nature Plants*

Plants as producers

Food



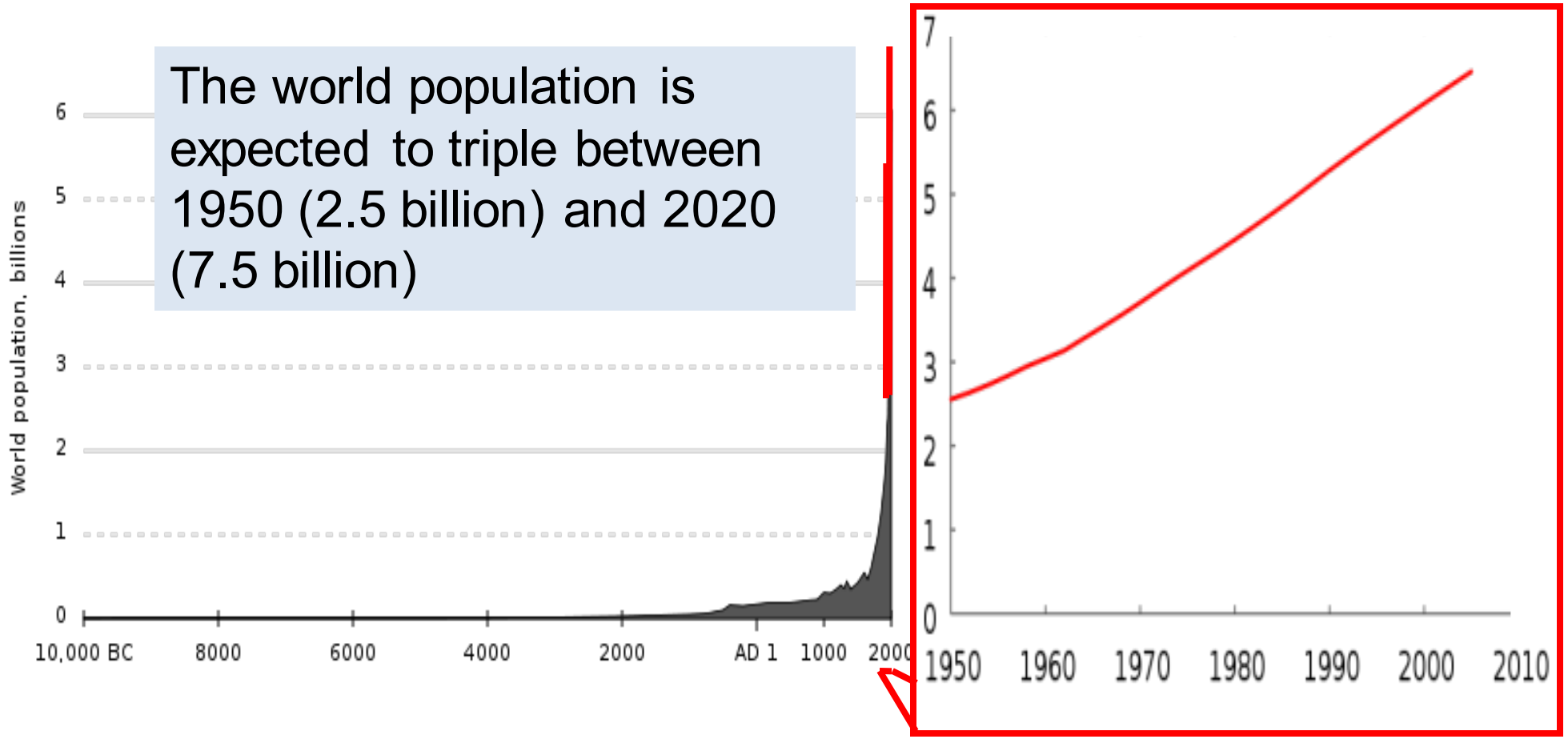
Horton et al., 2021, *Nature Plants*

Focus I

PLANTS & FOOD

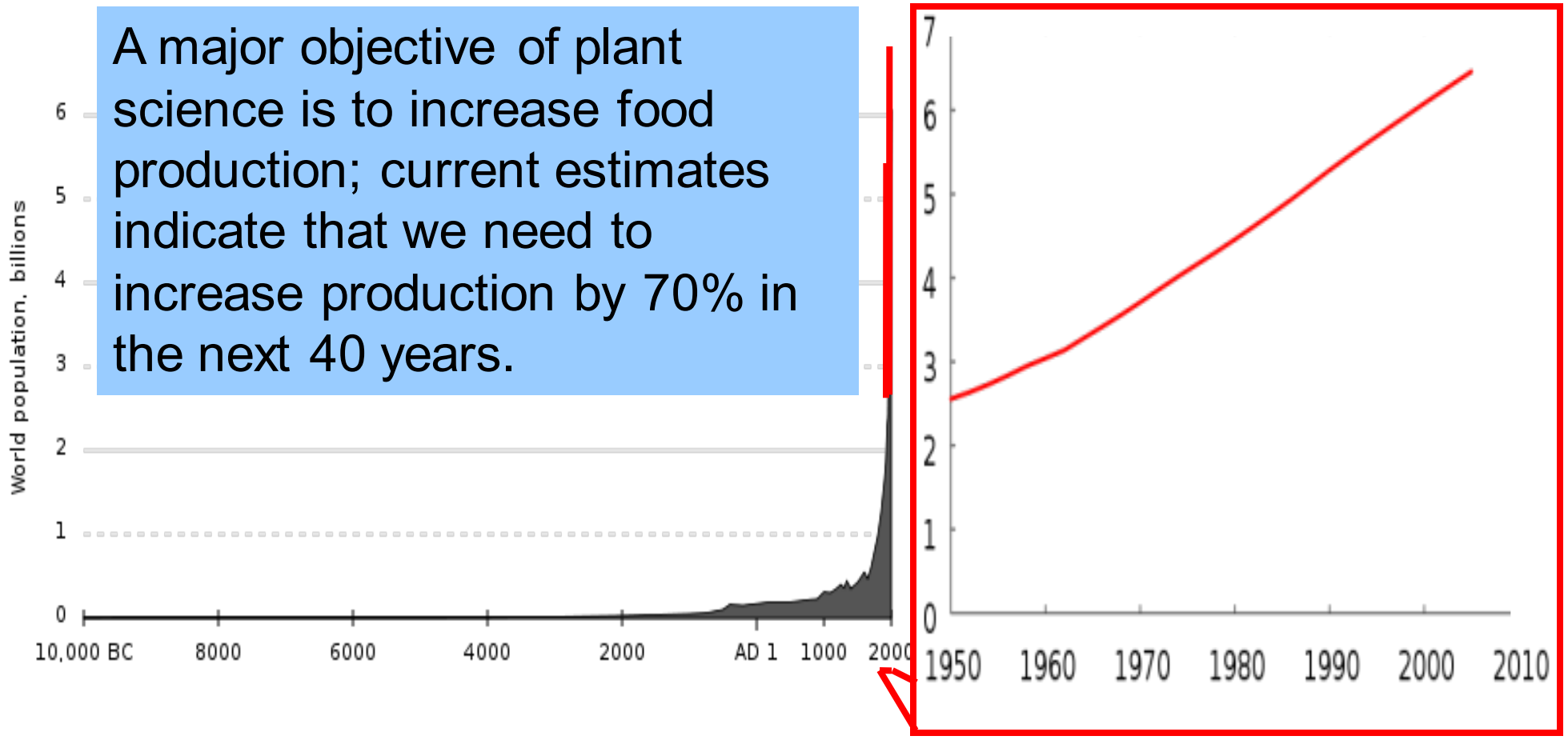
The world population grows and grows ...

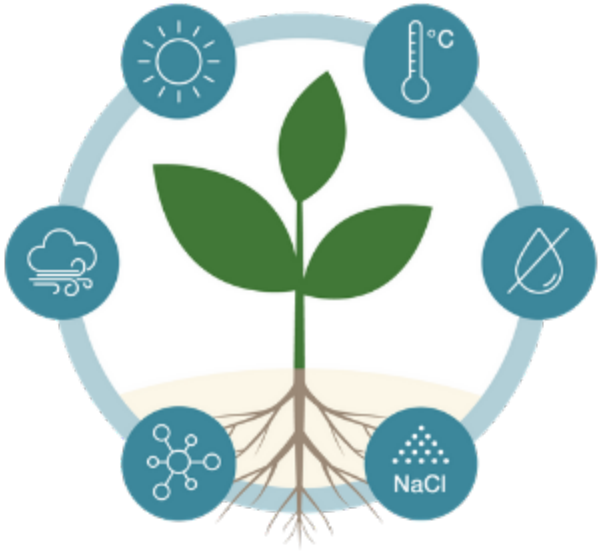
The world population is expected to triple between 1950 (2.5 billion) and 2020 (7.5 billion)



The world population grows and grows ...

A major objective of plant science is to increase food production; current estimates indicate that we need to increase production by 70% in the next 40 years.



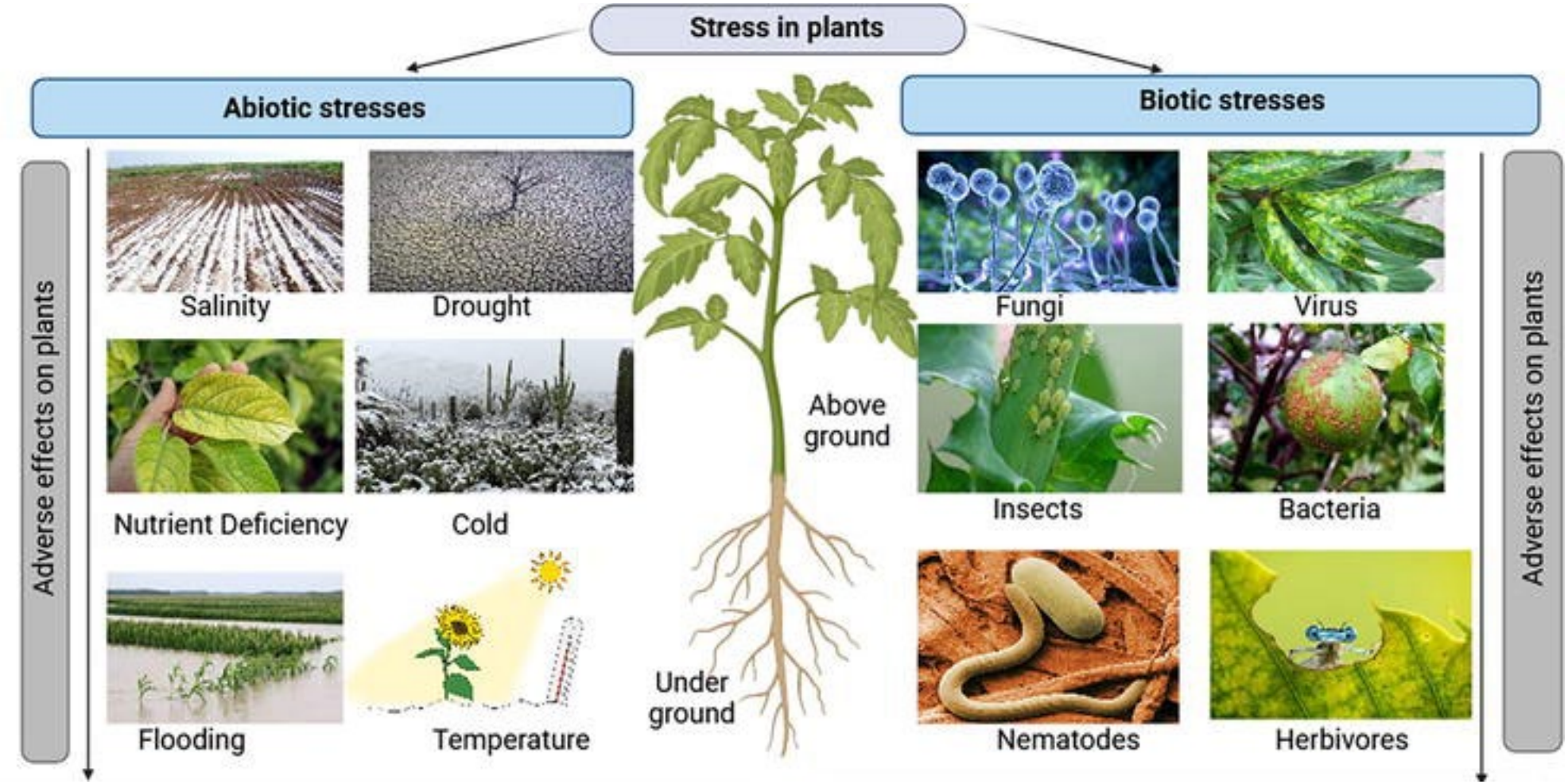


Stressors and their impact

Environmental stressors that impact ecosystems

Abiotic - non-living factors

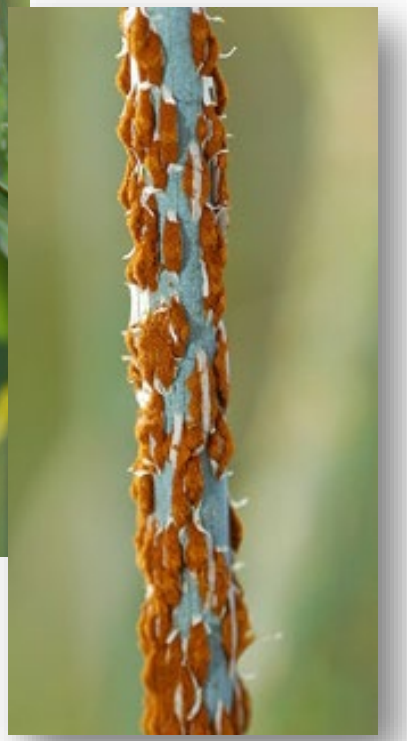
Biotic factors - living factors



Biotic factors - `living factors in the environment`

Biotic stress – negative effect on plants caused by living organisms such as insects, fungi, bacteria, viruses.

Phytophthora infestans



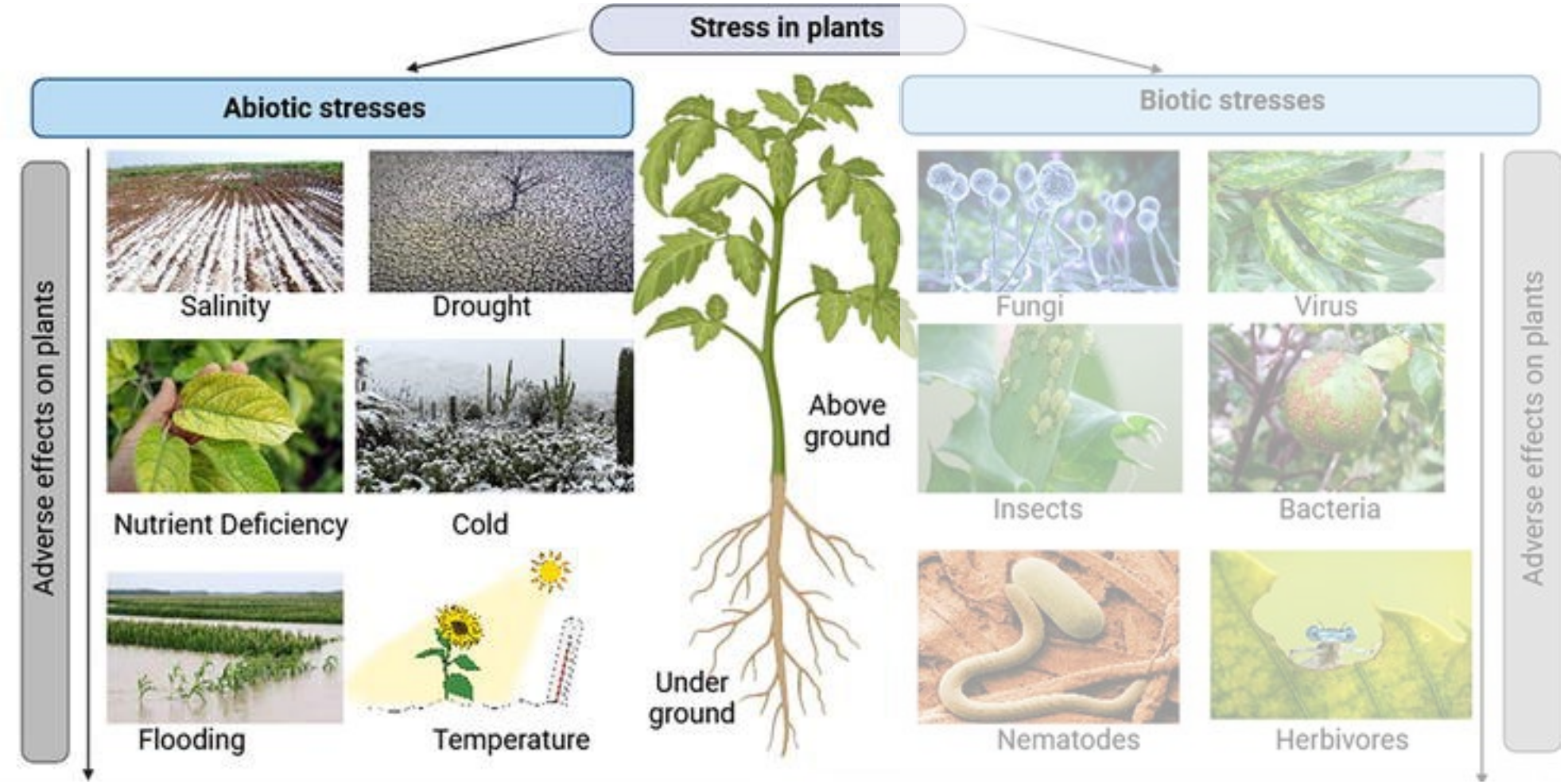
Puccinia graminis tritici

Photo credits: www.news.cornell.edu; www.fao.org, ARS USDA

Environmental stressors that impact ecosystems

Abiotic - non-living factors

Biotic factors - living factors



Plant growth is often limited by drought stress

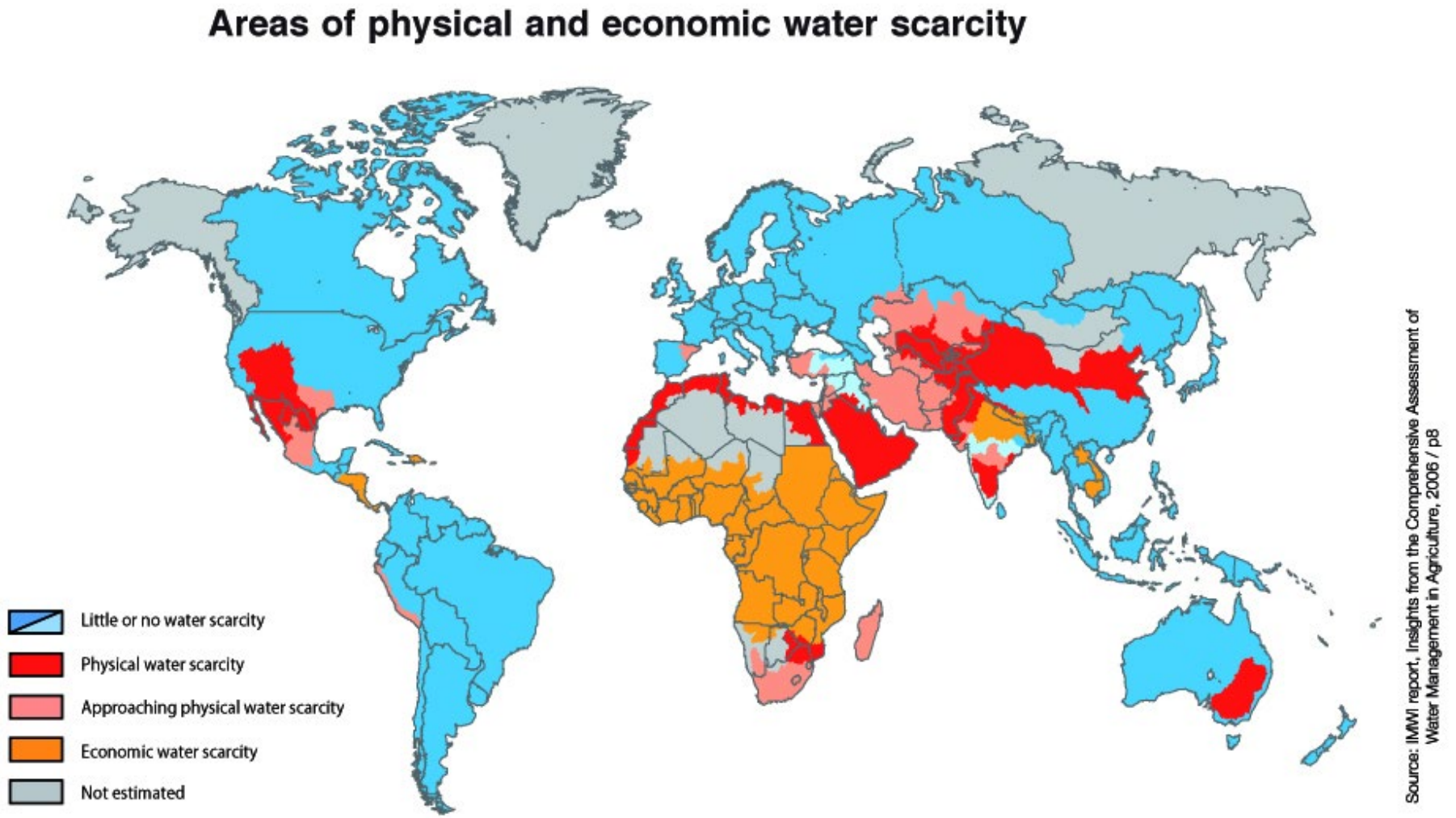
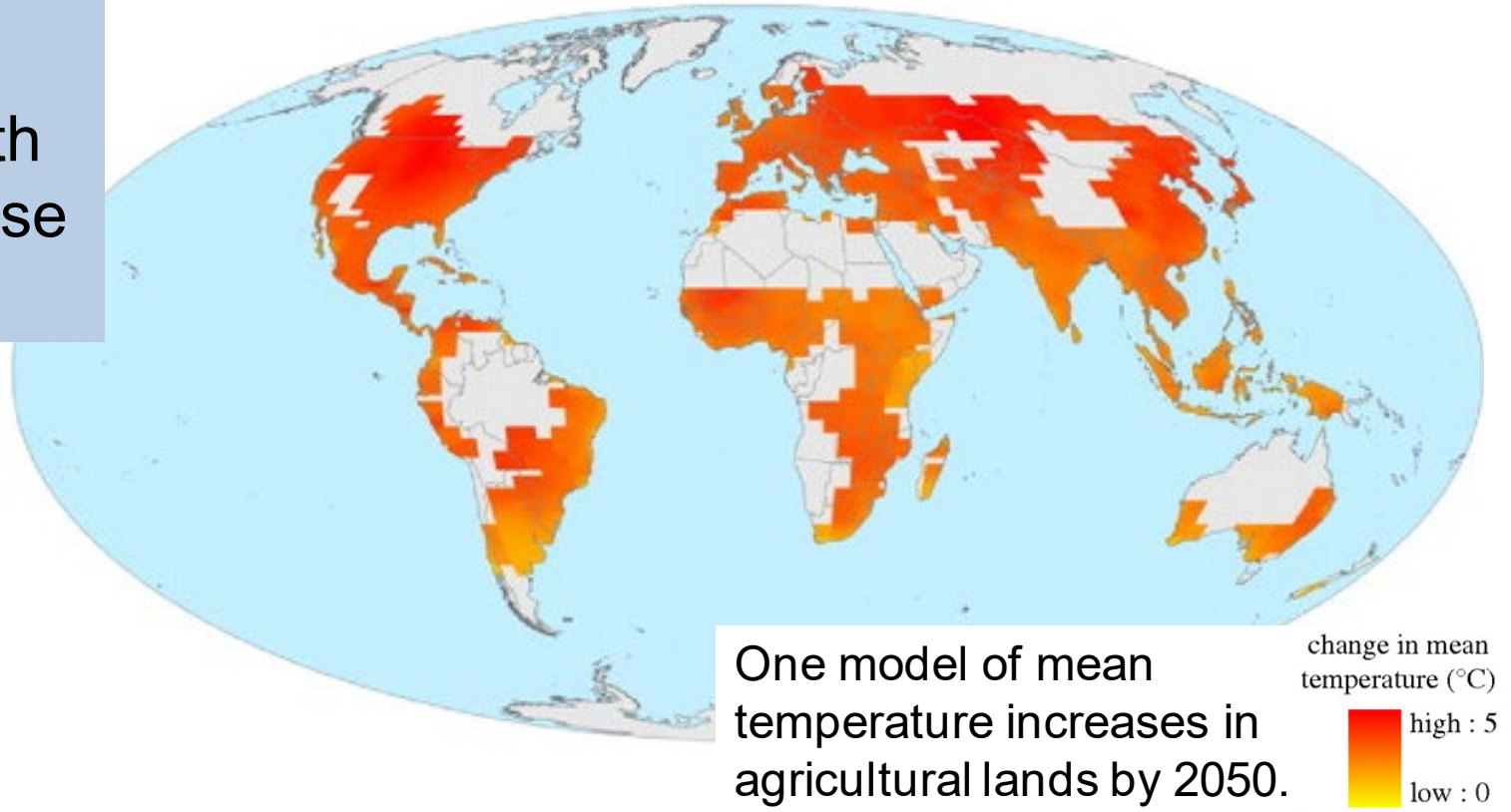


Image source: IWMI

Drought stress is compounded by increasing global temperatures

In warm regions, crop yields can drop ~3 – 5% with every 1°C increase in temperature.



One model of mean temperature increases in agricultural lands by 2050.

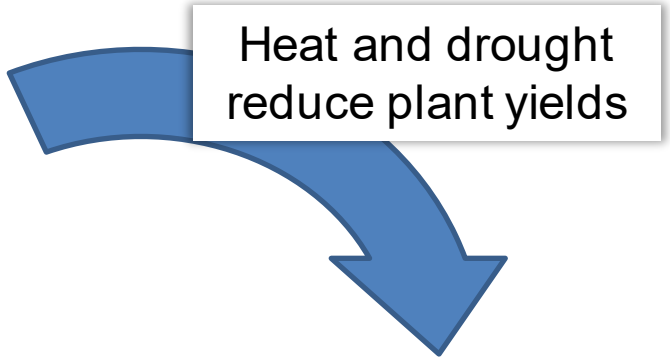
Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., and Wiltshire, A. Implications of climate change for agricultural productivity in the early twenty-first century. Phil. Trans. Royal Soc. B: 365: 2973-2989.m

Even mild drought stress reduces yields

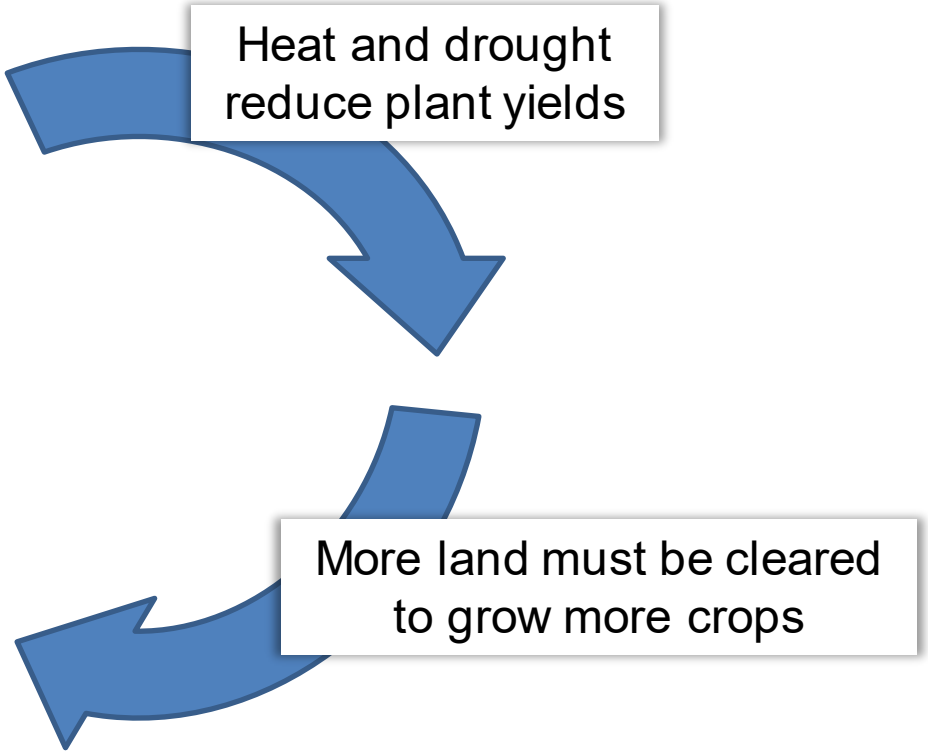
Mild drought stress reduces the rate of photosynthesis and growth, whereas extreme drought stress is lethal.

Photo: American Enterprise Institute

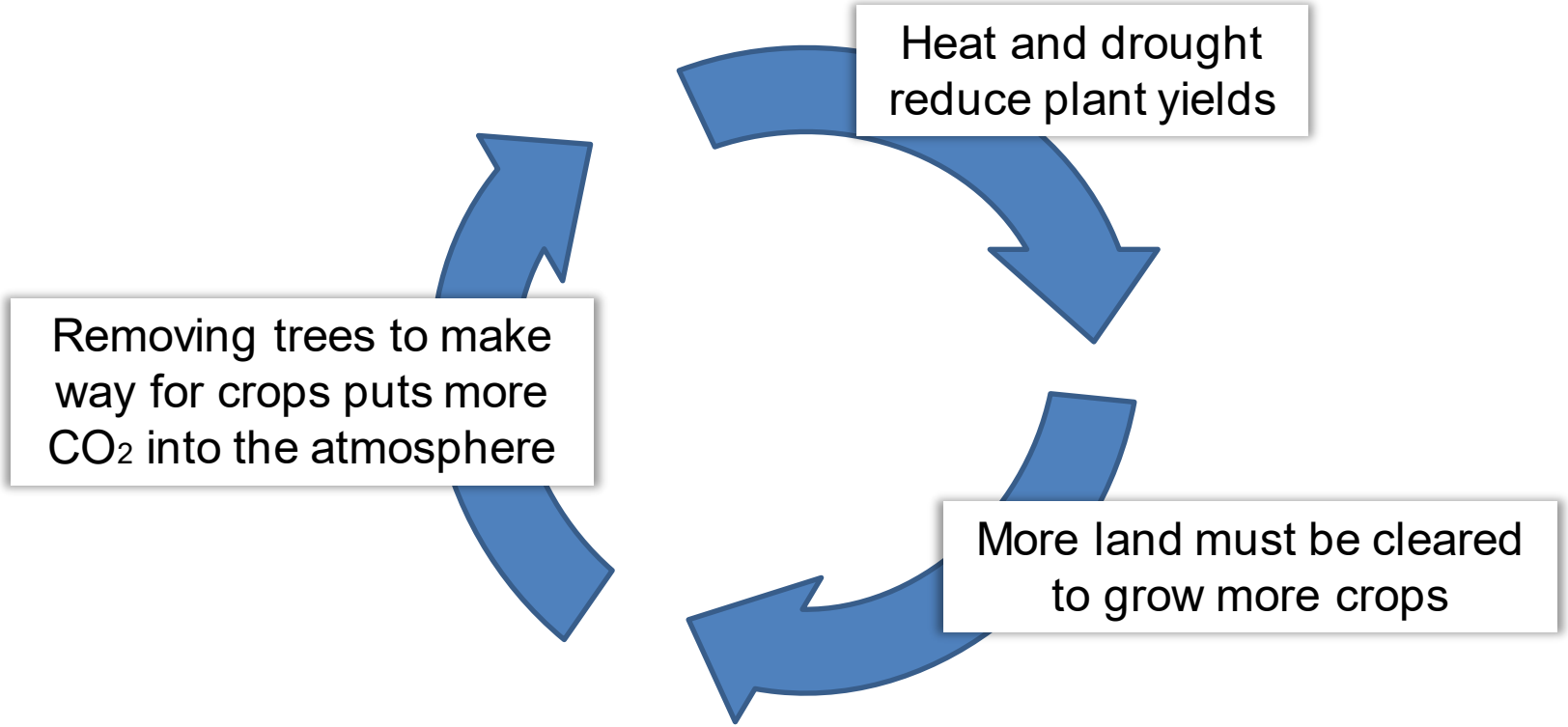
We need plants that grow well even under stressful conditions



We need plants that grow well even under stressful conditions



We need plants that grow well even under stressful conditions



"Soil surface sealing" by Julian Isasti, Argentina

Photo Contest on Salt-Affected Soils.

Focus II

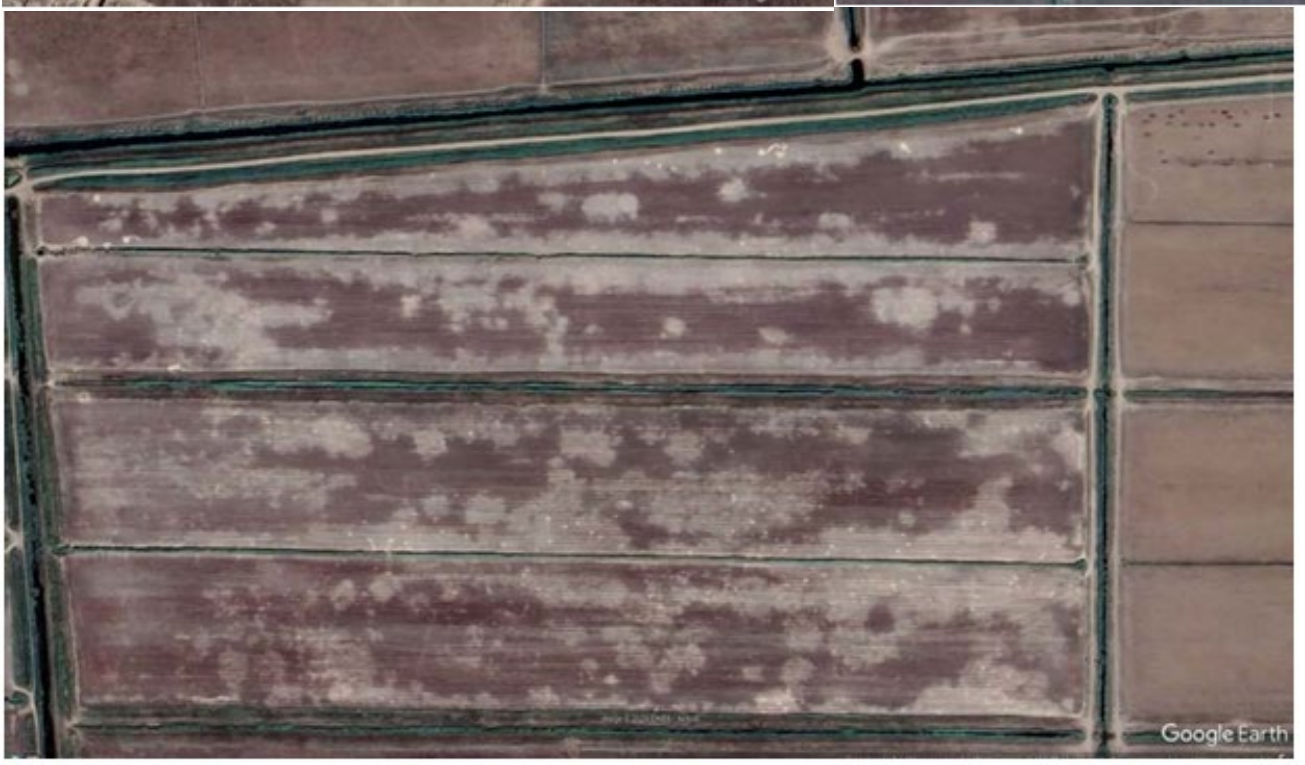
SALINITY AS A THREAT TO FOOD PRODUCTION

Salinity Stress - A Threat To Sustainable Global Food Production

Salinity affects millions of hectares of land

UN Photo Contest on Salt-Affected Soils.

Salinity from freshwater



Fringes of secondary salinized soils due to canal water seepage

Typical pattern of fringes with salt crusts or crop failures along canals

Salinity from fertilizers

- Crops need fertilizer – potassium, phosphate, nitrogen, and other nutrients
- Potassium and phosphate are non-renewable, mined resources
- Synthesis of nitrogen fertilizers requires huge amounts of energy

Photo credits: Mining Top News; Library of Congress, Prints & Photographs Division, FSA-OWI Collection, LC-USW361-374

Agricultural fertilizer use is a considerable source of environmental pollution

Fertilizer run-off causes dead zones, algal blooms that then decay, reducing oxygen levels in the water and making animal life impossible

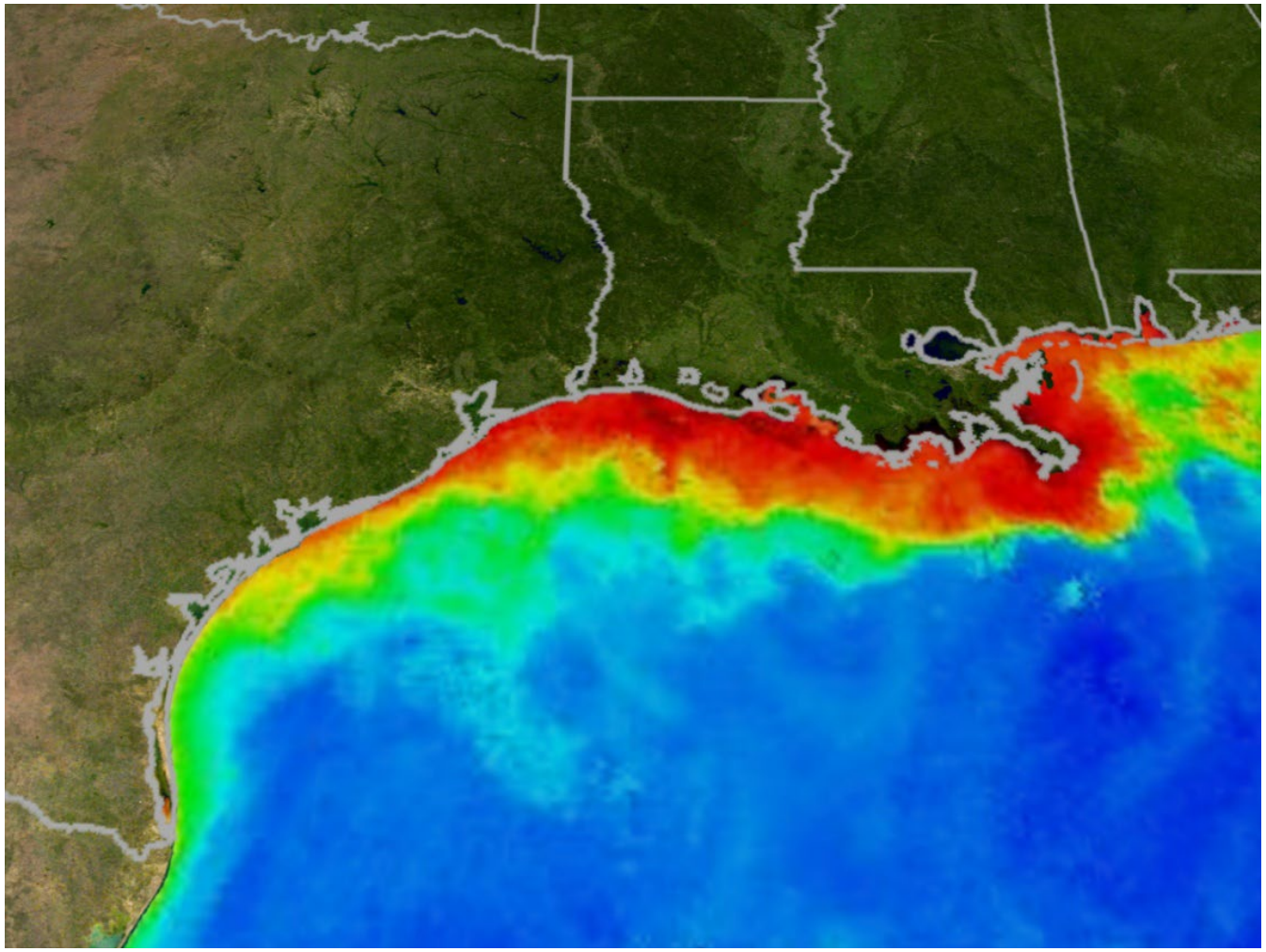
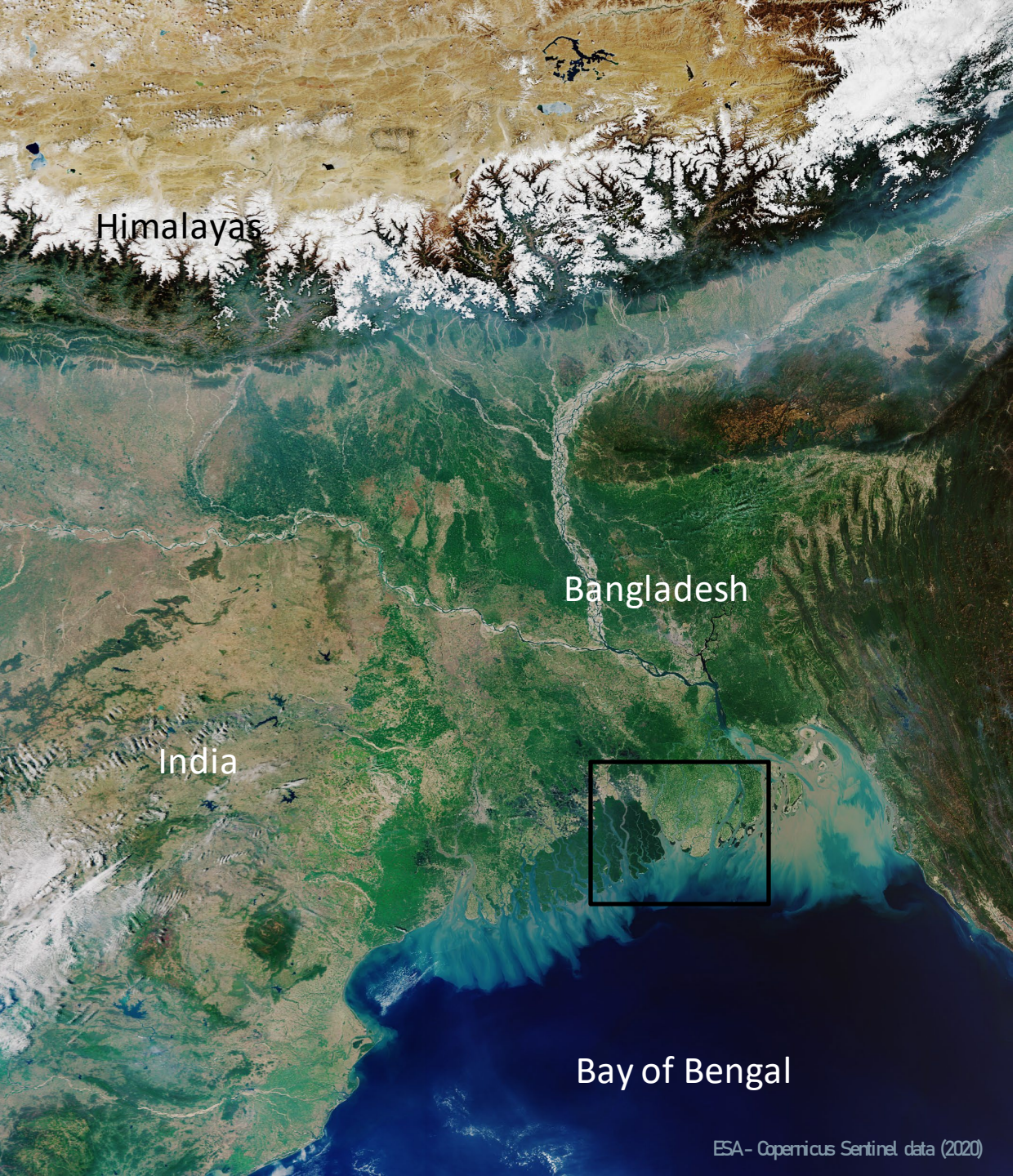
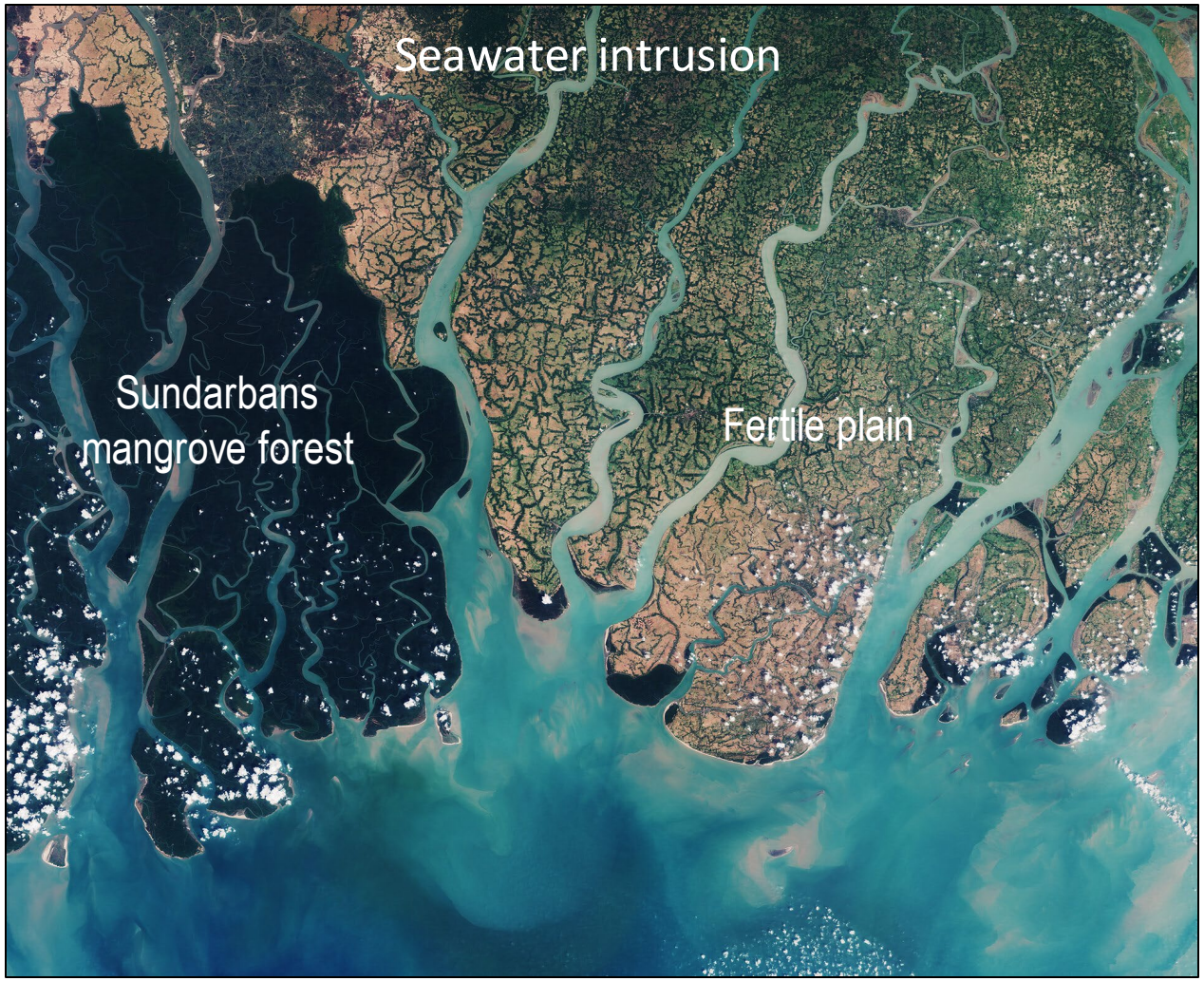


Photo courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio

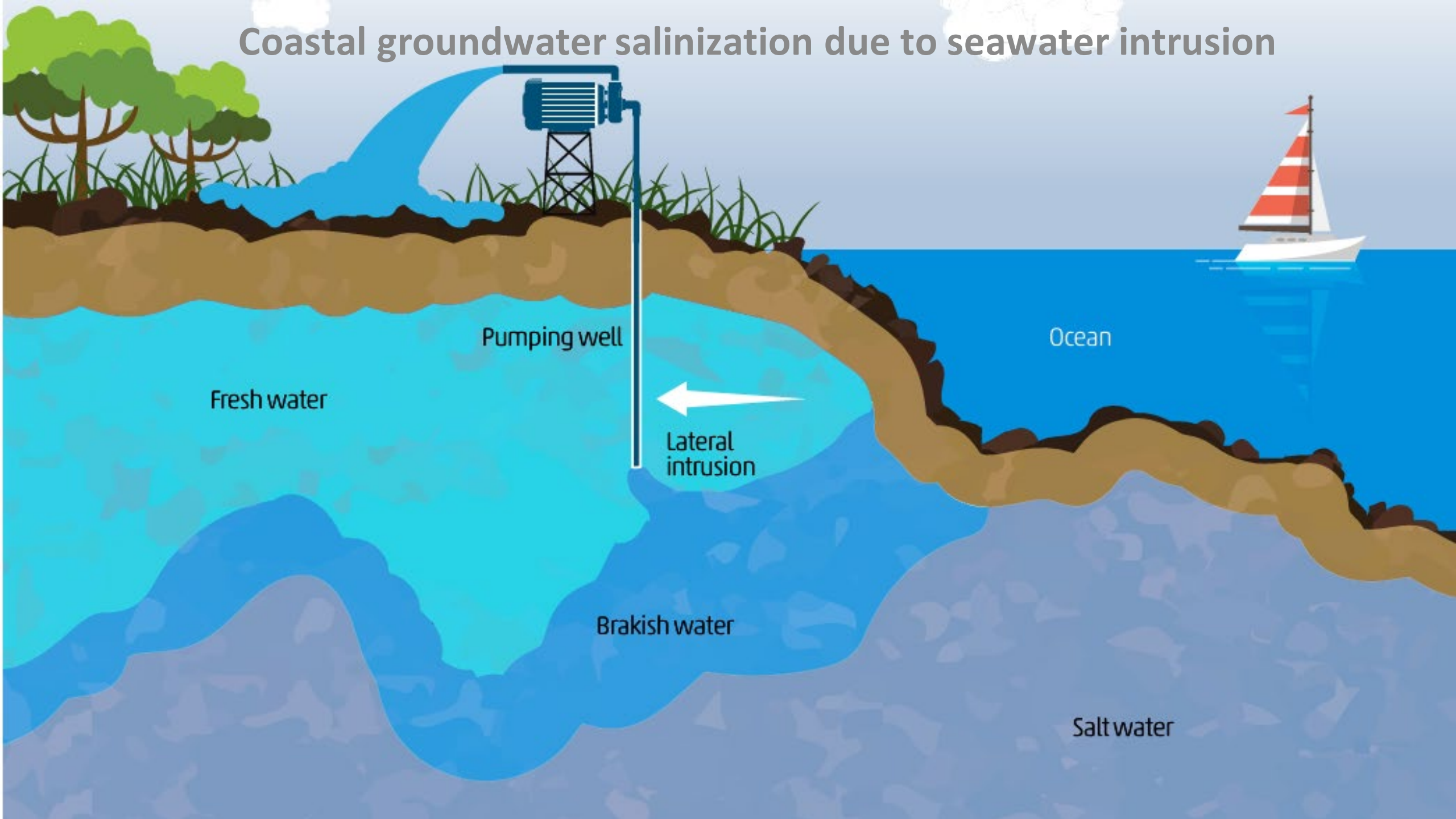
Salinity from seawater



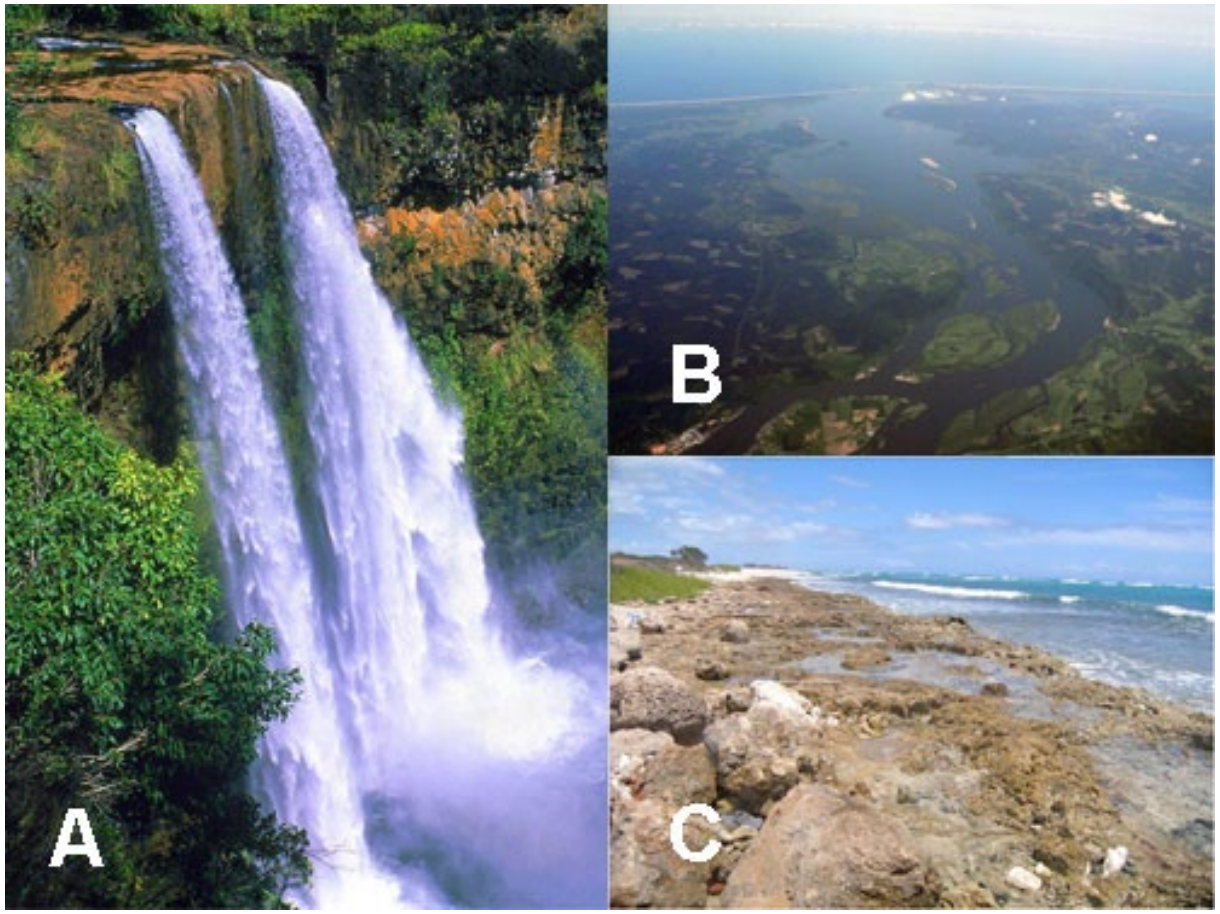


Contains modified Copernicus Sentinel data (2016), processed by ESA

Coastal groundwater salinization due to seawater intrusion



Salinity categories



Sea water: ~35 g/kg of sea water

Range: 33 - 38 ppt

A. Freshwater lakes, rivers, and streams:

Below 0.35 g/kg of water

B. Brackish water is a mixture of fresh water and seawater, below approximately 33 ppt

C. Hypersaline water, or brine, is very salty seawater, above approximately 38 ppt.
Example: in tidepools or salty lakes.

Dead Sea, has a salinity of 280 ppt, about eight times saltier than average seawater (35 ppt)!

Hydrometer

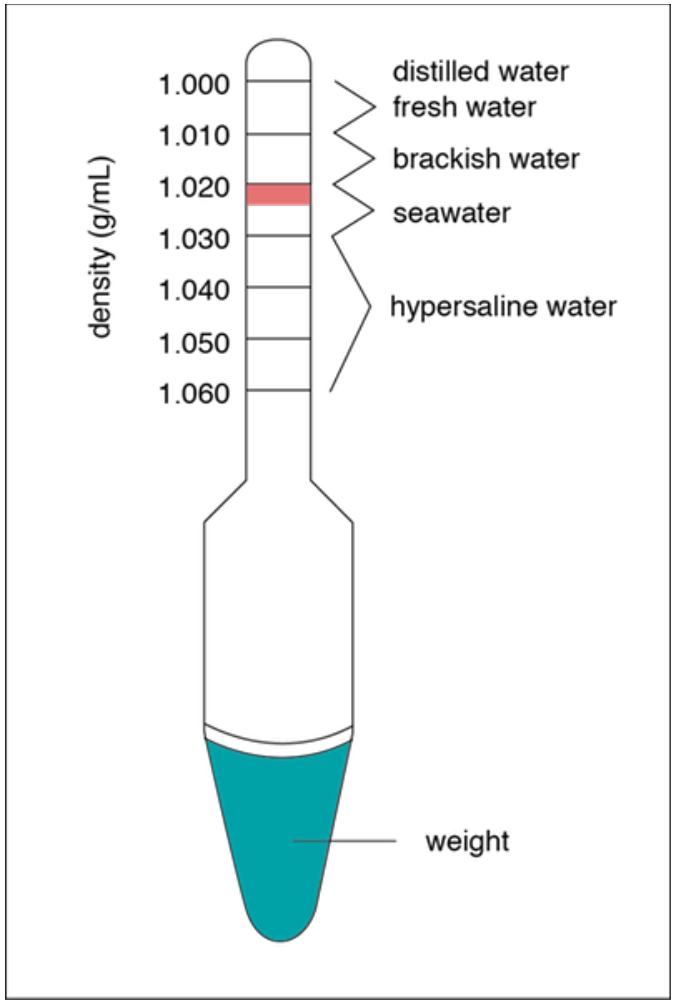


Image by Byron Inouye

A hydrometer used to determine water densities in g/mL.

The pink shaded region indicates the optimum density of saltwater aquaria at an average temperature of 20˚C to 25˚C.

Engineering the plants

Scientists can contribute to the alleviation of hunger

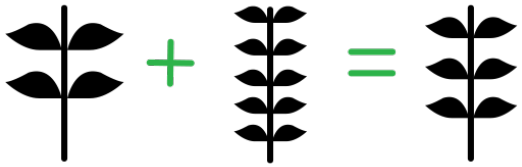
By developing plants that

- are drought or salt tolerant
- require less fertilizer or water
- are resistant to pathogens
- are more nutritious

National Geography, Green Revolution

Traditional Breeding

Desired traits are identified in separate individuals of the same species, which are then bred to combine those traits in a new hybrid variety.



Wheat History Wagon

1. A wild ancestor from the Middle East
2. Einkorn wheat, domesticated there 10,000 years ago
3. Durum wheat
4. Modern wheat, produced by crossing durum with goat grass
5. A green revolution variety with shorter stalks and larger seeds

Modern approaches

CRISPR-Cas9 – targeted editing

Gene Editing with CRISPR-Cas9

Using Native Characteristics to Improve Crops to Benefit People and the Planet

CRISPR-Cas9 Method

Clustered Regularly Interspaced Short Palindromic Repeats

- Cas9 (the most widely utilized system) is a special enzyme that can be guided by a short piece of RNA to find the target sequence of DNA and carry out the editing function

- Cas9 **edits, deletes or replaces** the targeted gene sequence to create specific results

Benefits for Crop Breeding

- Faster crop improvement
- Precise traits
- Inexpensive

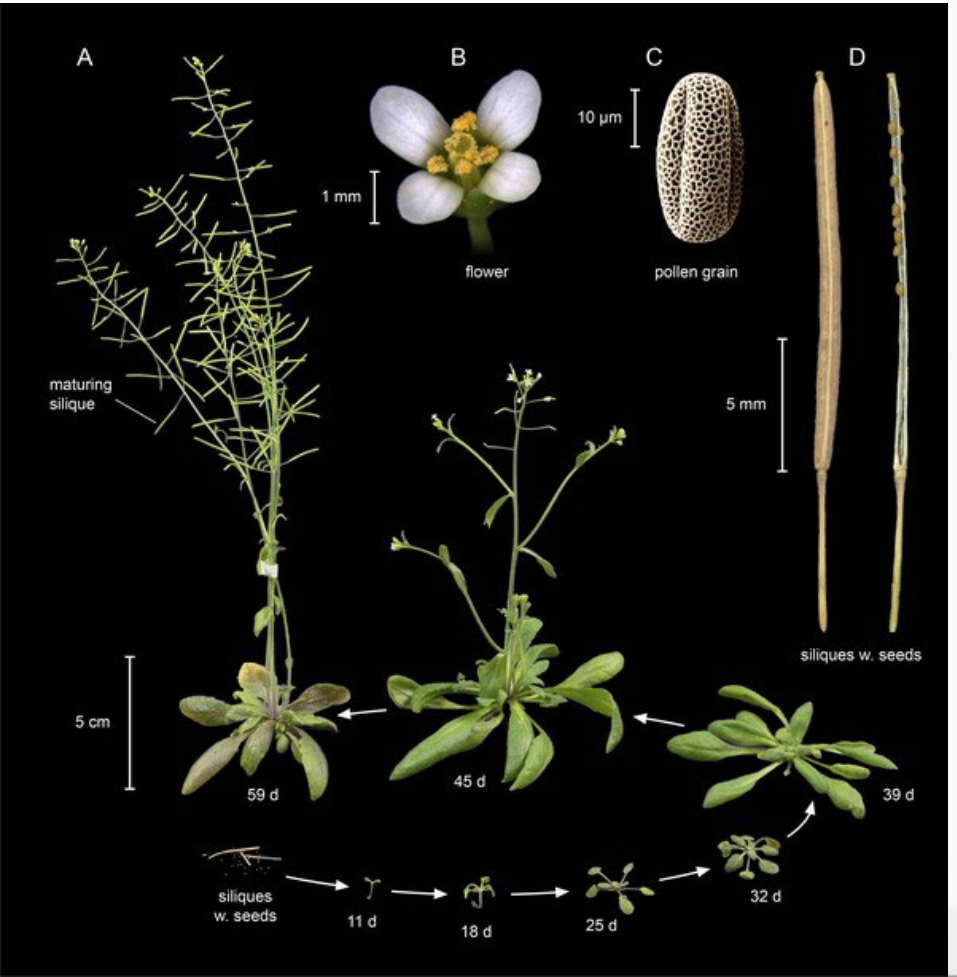
Benefits for Farmers and Consumers

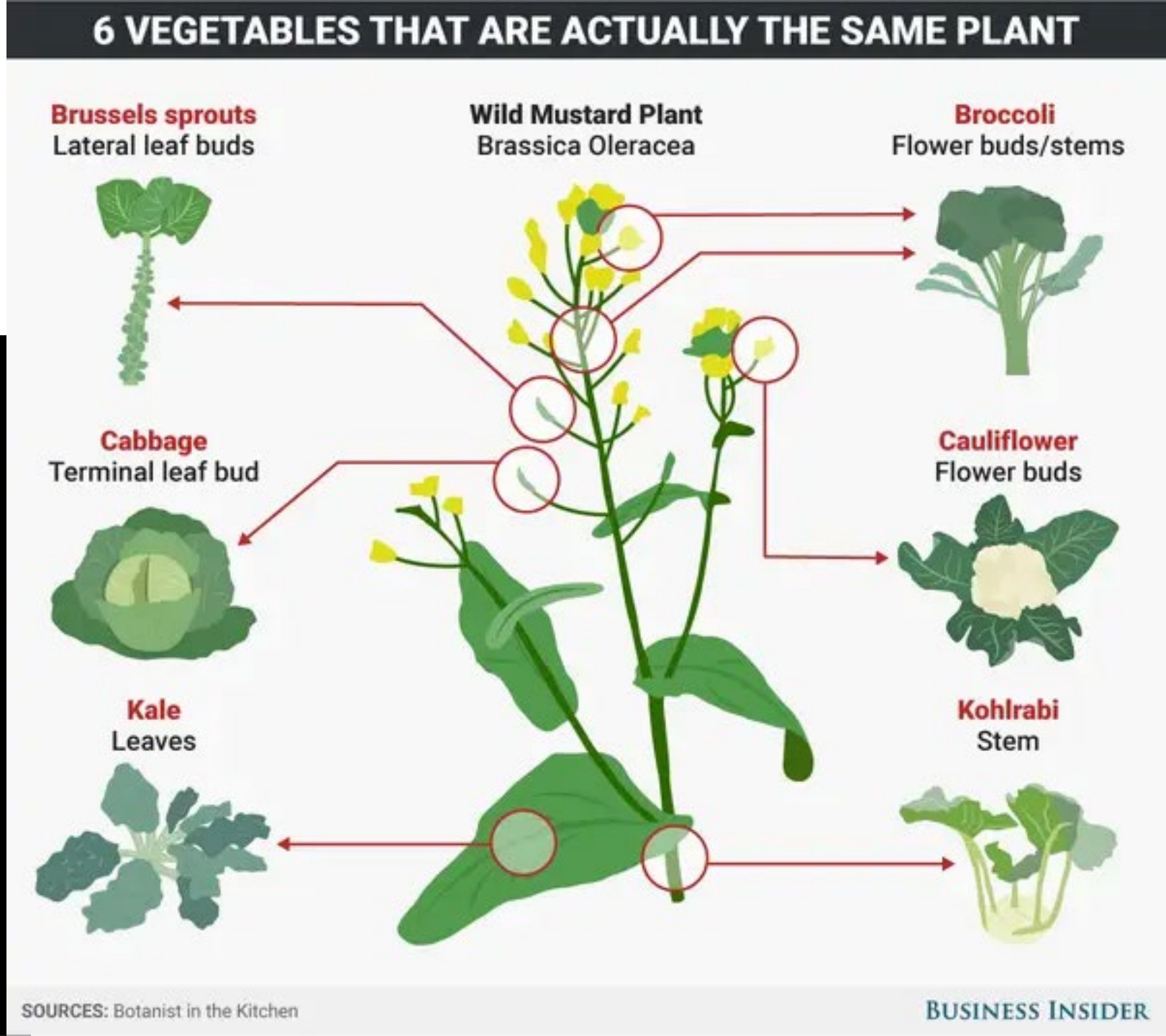
- Defense against pests
- Drought tolerance
- Larger harvests
- Better nutrition
- Longer shelf life

DONALD DANFORTH PLANT SCIENCE CENTER | danforthcenter.org

Arabidopsis thaliana

Model plant system



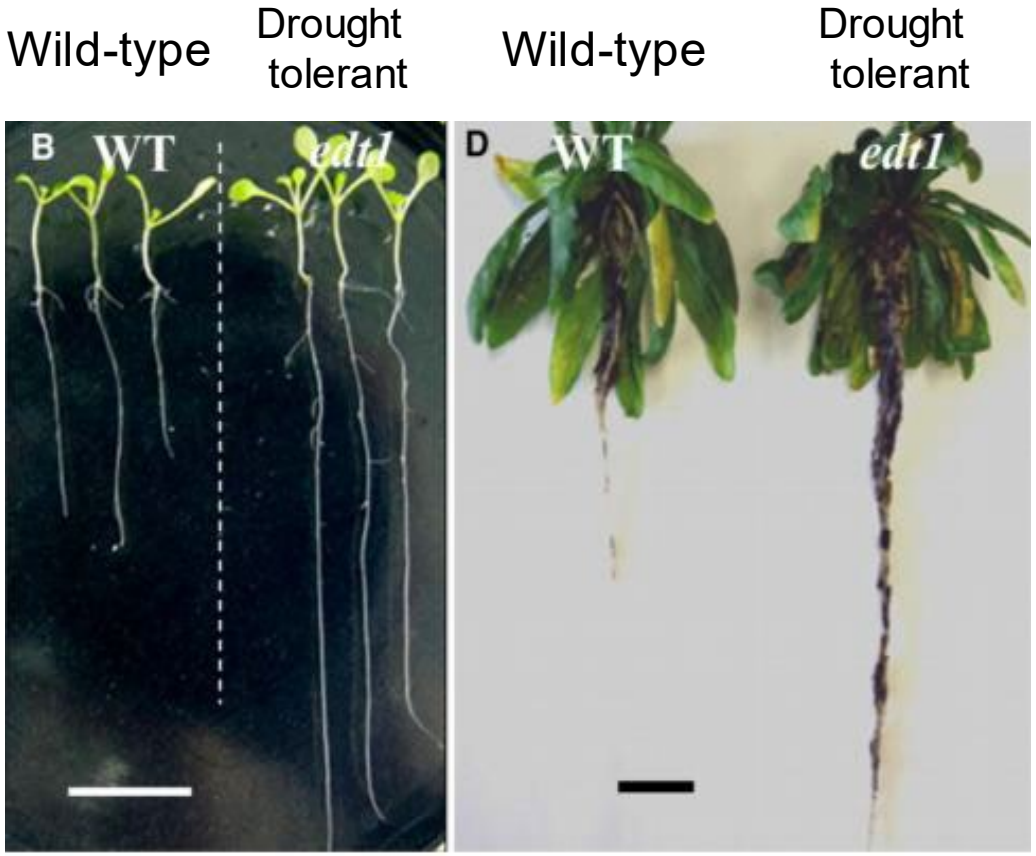


Monitoring stress in model systems in the lab

Aboveground system – shoots, leaves ...

Monitoring stress in model systems in the lab

Belowground system – soil, roots, …



A larger root system contributes to drought tolerance

Breeding plants for larger root systems can help them grow in drought-prone regions.

Yu, H., Chen, X., Hong, Y.-Y., Wang, Y., Xu, P., Ke, S.-D., Liu, H.-Y., Zhu, J.-K., Oliver, D.J., Xiang, C.-B. (2008) Activated expression of an *Arabidopsis* HD-START protein confers drought tolerance with improved root system and reduced stomatal density. Plant Cell 20:1134-1151.

Salinity stress in plants

Most of our crops are salt sensitive

Glycophytes – salt sensitive

Most fruits and veg...

Halophytes - naturally salt tolerant

Spartina alterniflora, a coastal salt marsh grass. Image: USDA

Marsh grasses can tolerate wet conditions that would typically drown terrestrial plants.

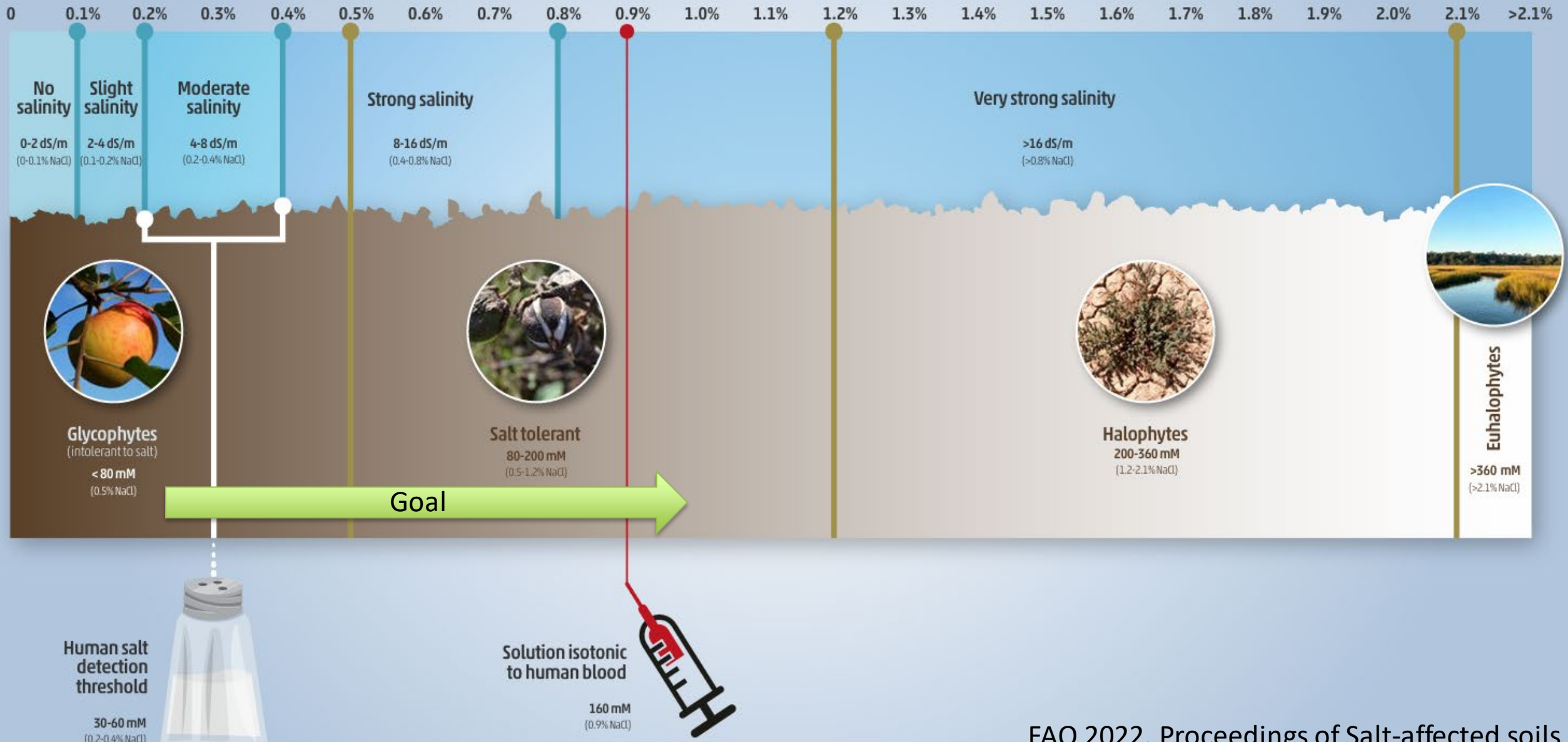
Many of these coastal species have also adapted to survive in salty seawater or brackish water.

A Dream of Plant Biologists and Farmers:

Breeding Salinity Tolerance Into Plants Without Significant Yield Penalty

Soil salinity levels

(solute concentration of soil solution):



FAO 2022, Proceedings of Salt-affected soils

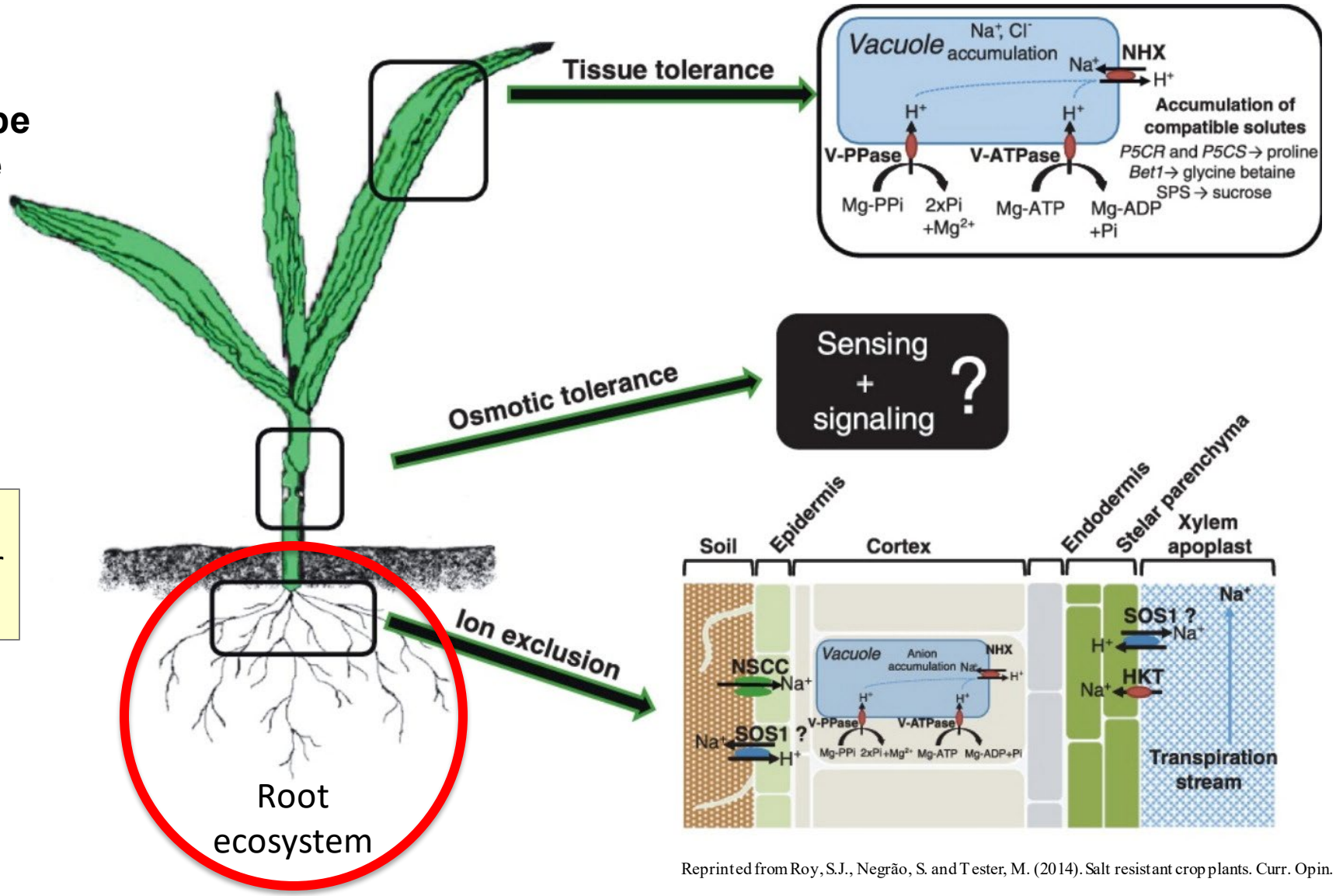
Focus III

HOW CAN WE CONFER SALINITY TOLERANCE TO OUR CROPS?

Breeding and engineering for salt tolerance

Salt tolerance can be attributed to three non-exclusive mechanisms

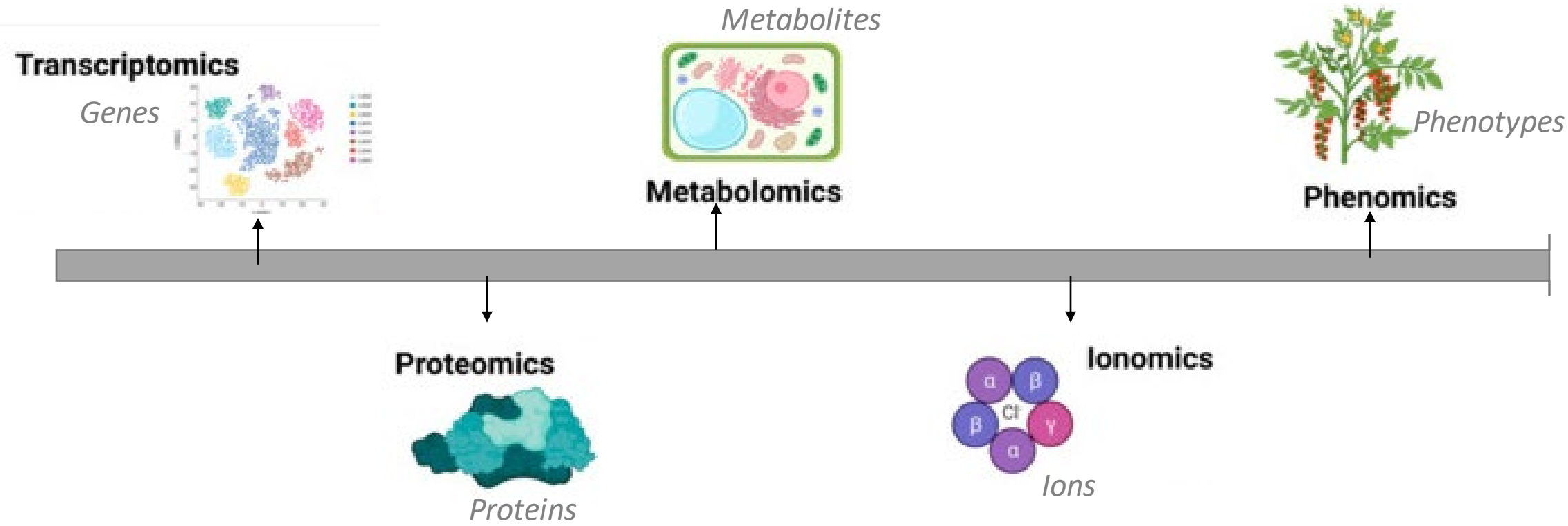
Salinity tolerance can be enhanced by breeding or engineering



Reprinted from Roy, S.J., Negrão, S. and Tester, M. (2014). Salt resistant crop plants. Curr. Opin. Biotech. 26: 115-124.

Combination of approaches

To capture plants responses to abiotic stress



Rhizotron – root laboratory

Phenomics

IN the native soil:

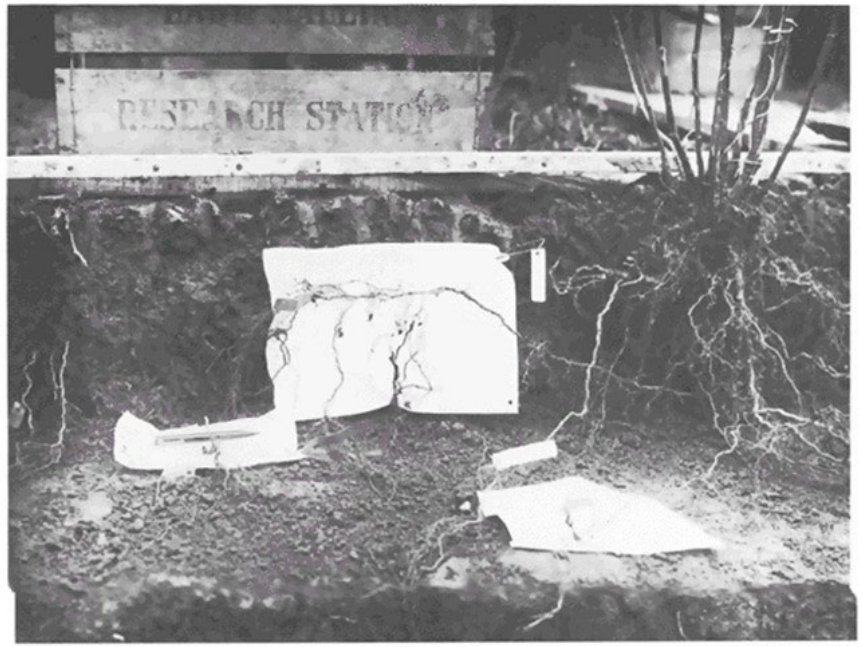
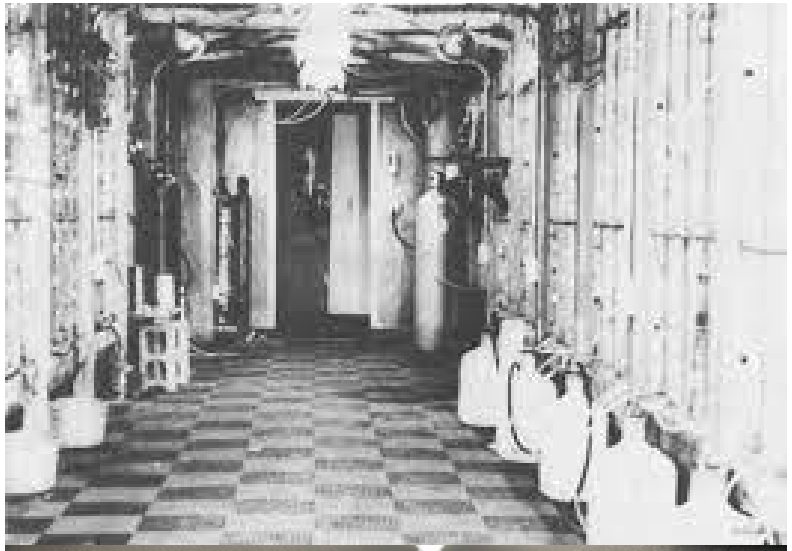


Fig. 3.2. View of a raspberry root system showing labelled and marked roots for better drawing in the course of a dry excavation (Christensen, 1947). With kind permission of the East Malling Research Station, England

Rhizotron, derived from the Greek verb "rhizóō / ῥιζόω" meaning "root" ("become stable")

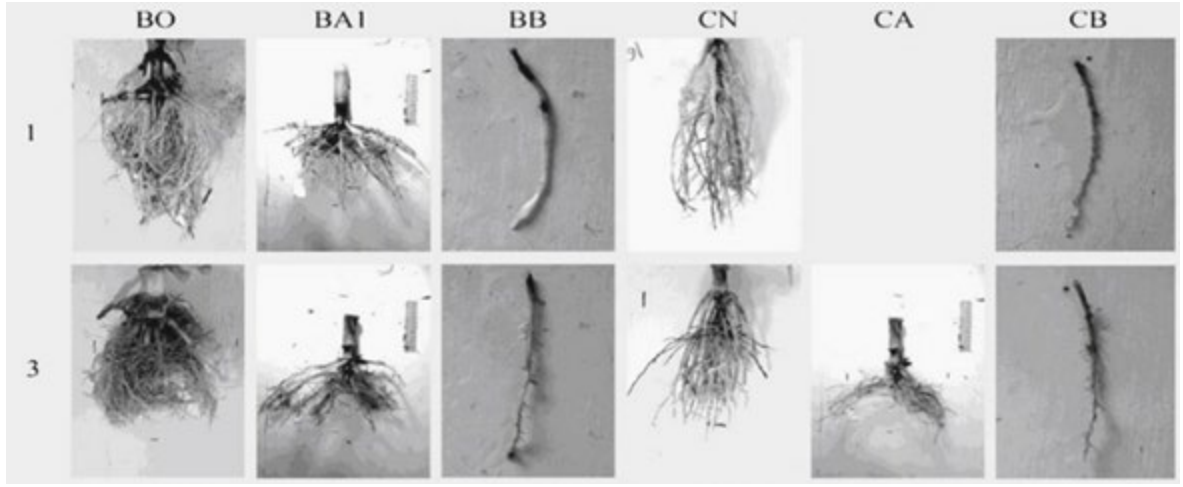
East Malling Research, UK.

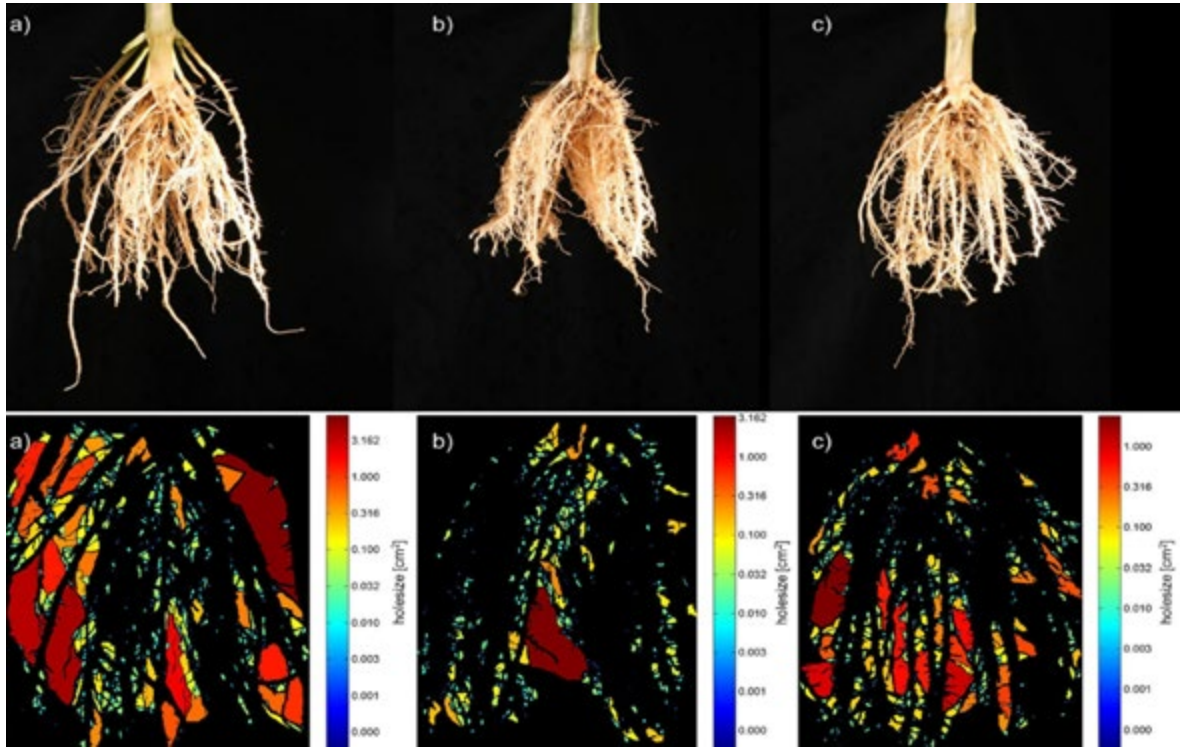
1960s, world's first underground root laboratory



An architectural device for subterranean observation

Shovelomics





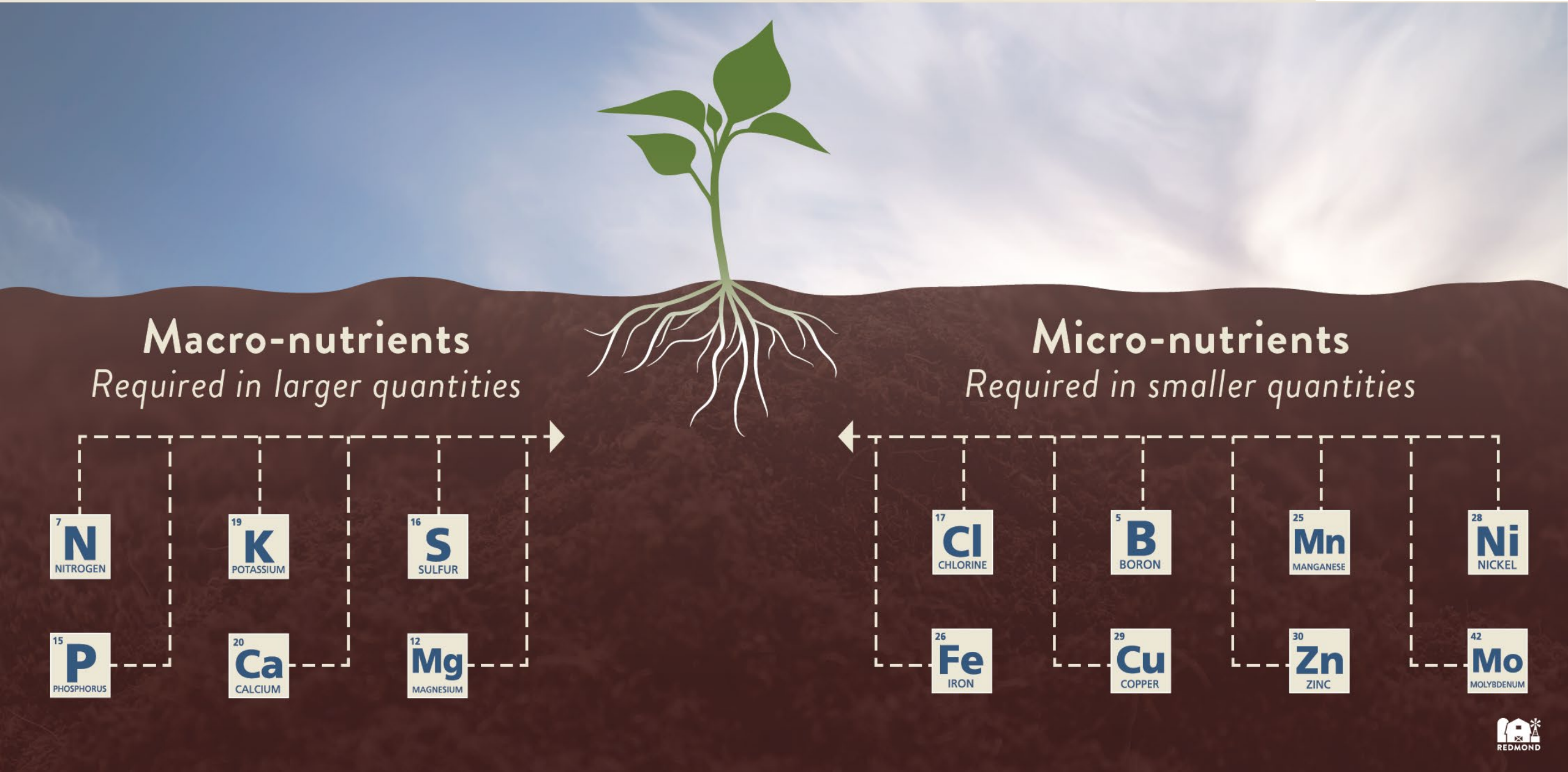
OUT of the native soil:

Plants are cultivated in the field, then the top part of the root system (crown) is excavated, washed and imaged.

Trachsel, S., Kaeppler, S.M., Brown, K.M., and Lynch, J.P. (2010). Shovelomics: high throughput phenotyping of maize (*Zea mays* L.) root architecture in the field. Plant Soil 341: 75–87; Colombi, T., et al. (2015). Next generation shovelomics: set up a tent and REST. Plant and Soil 388: 1-20.

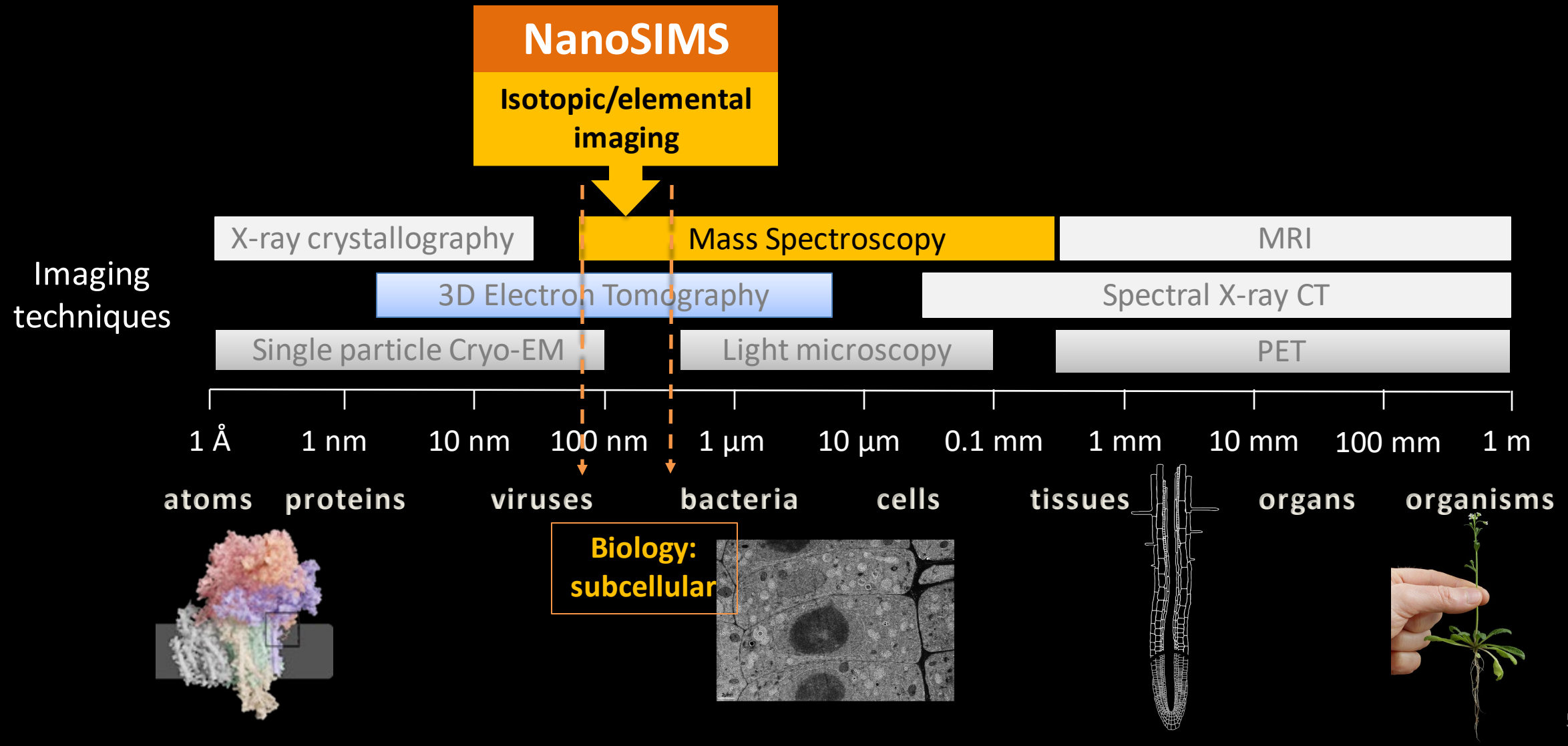
MACRO & MICRONUTRIENTS...BOTH ARE ESSENTIAL

Ionomics



Zooming into the plant!

See where the problem `*salt*` accumulates at the required resolution



What does salinity stress look like within the plant tissue?

https://actu.epfl.ch/news/how-cryogenic-microscopy-could-help-strengthen-foo/

How cryogenic microscopy could help strengthen food security

A joint EPFL and University of Lausanne research team reports on a novel observation of a plant protection mechanism in response to salt stress. The study opens new avenues of research to strengthen food security.

15.01.25

LINKS

- Laboratory for Biological Geochemistry (LGB)
- "EPFL scientists unlock new horizons for cryogenic microscopy", EPFL News, 07/06/2023

According to the United Nations, soil salinization affects between 20% and 40% of arable land globally, with human activity and climate change – especially rising sea levels – largely responsible for this process. While the human body needs sodium to function, this is not the case for most plants. In fact, excess salt around plants' roots gradually blocks their access to water, stunting their growth, poisoning them and hastening their death. Ten million hectares of farmland are destroyed by soil salinization every year, posing a threat to global food security.

TAGS

Andera Meibom | climate change | environment | food security | health | Laboratory for Biological Geochemistry (LGB) | microscopy | Research | School of Architecture, Civil and Environmental Engineering - ENAC

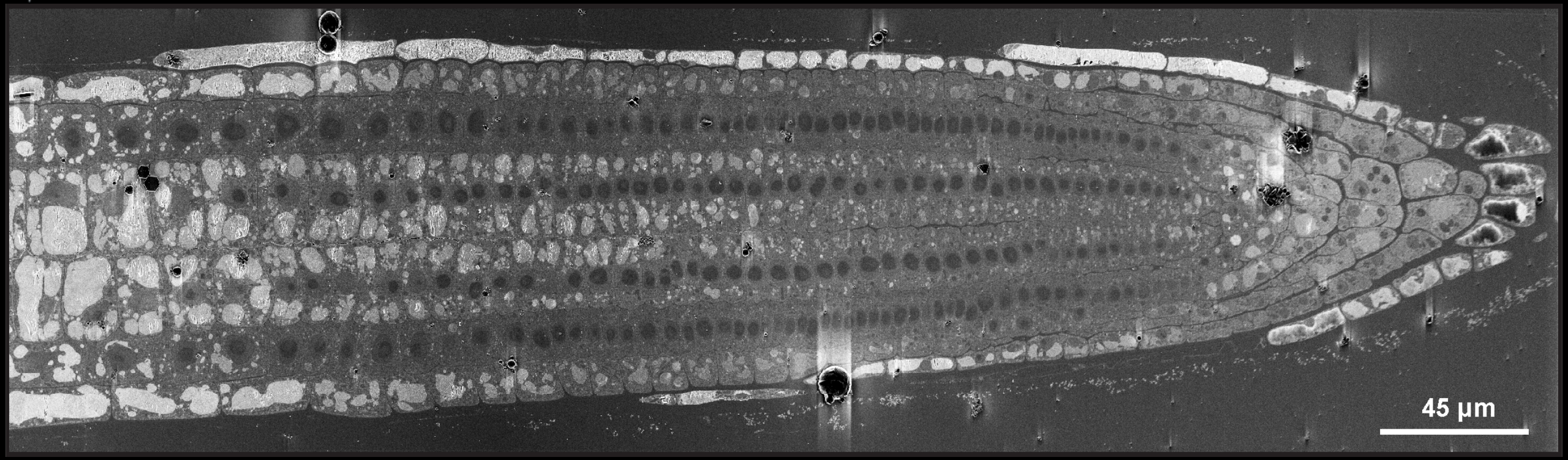
RELATED ARTICLES

20.04.2023
Centralized database helps scientists better understand coral reefs

26.06.2024
Scientists reveal why some people with

ent-cycling/

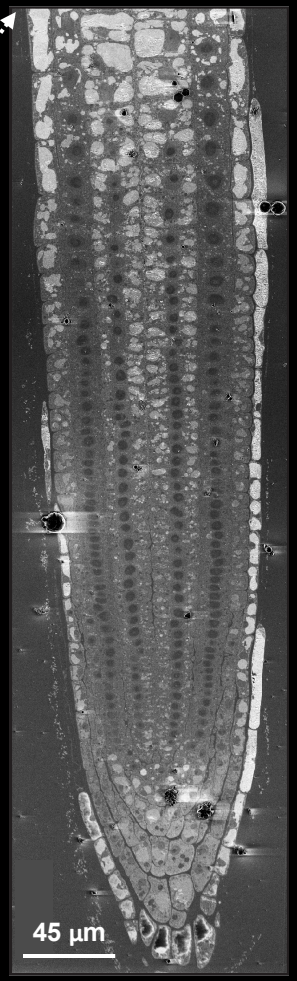
Arabidopsis root tip – ultrastructure preservation!



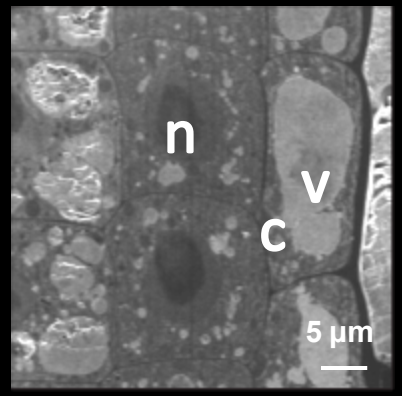
Start to build a roadmap into cellular salinity stress responses…

First images of elemental distribution in plant root meristems!

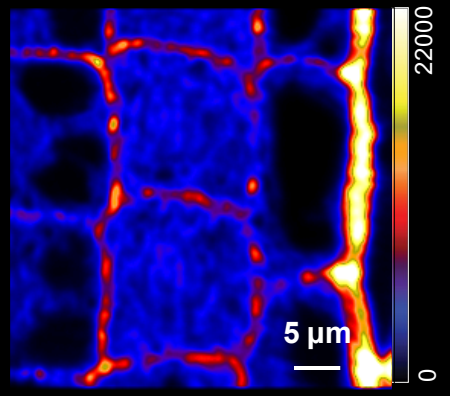
Root meristem



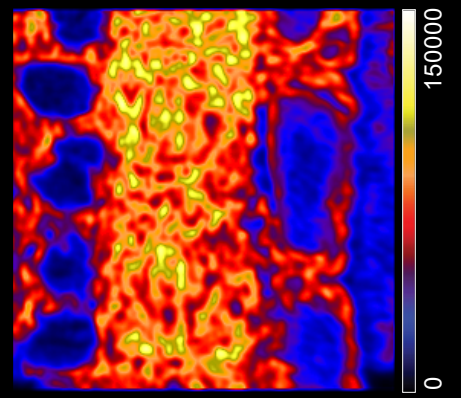
Blockface CryoSEM



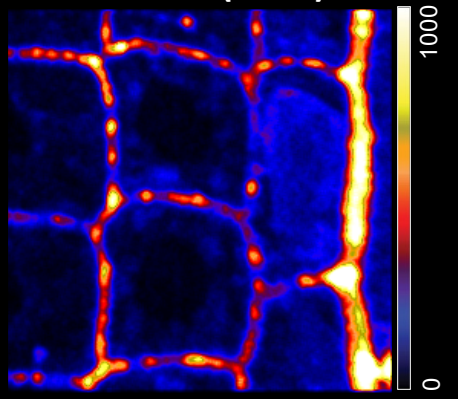
Sodium ($^{23}Na^+$) c/s



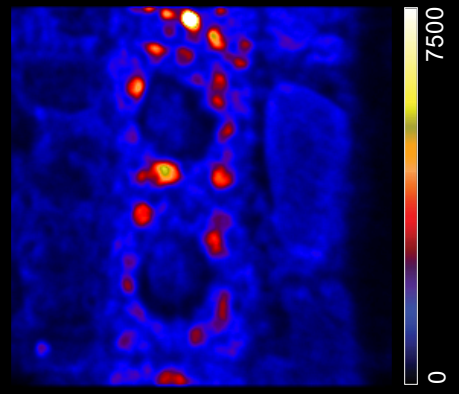
Potassium ($^{39}K^+$)



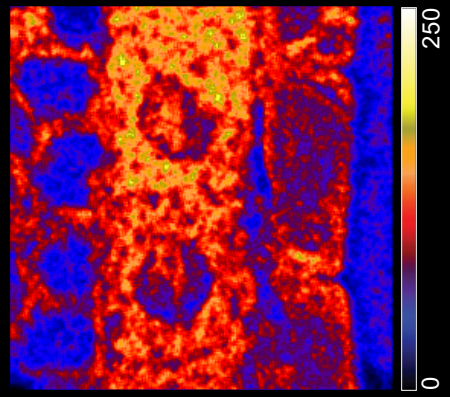
Calcium ($^{40}Ca^+$)



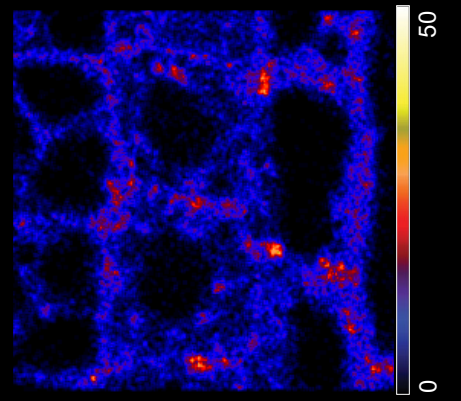
Magnesium ($^{24}Mg^+$)



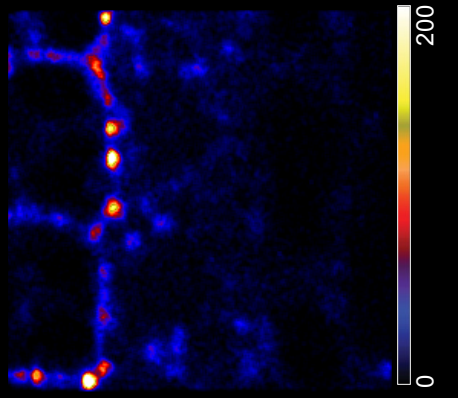
Sulfur ($^{32}S^+$)



Manganese ($^{55}Mn^+$)



Iron ($^{56}Fe^+$)



Scale bar, 5 µm

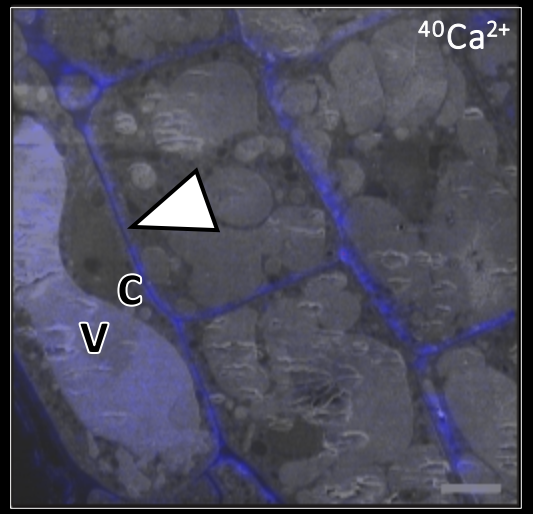
v – vacuole; c – cytosol; n - nucleus

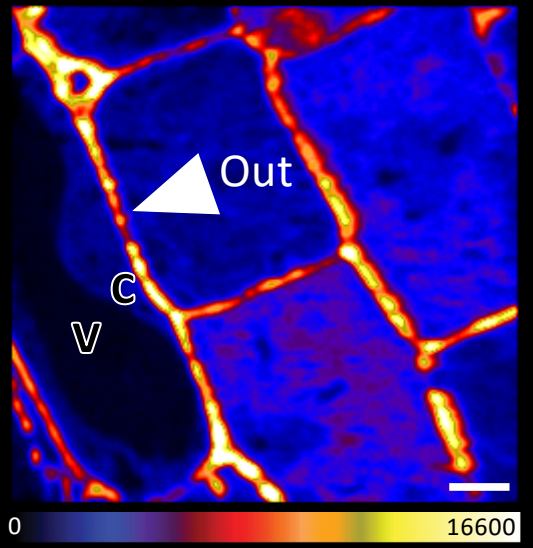
Ramakrishna *et al.*, 2025, *Nature*

Salt redistribution within cellular landscape

CryoSEM | **Sodium ($^{23}Na^{+}$)**

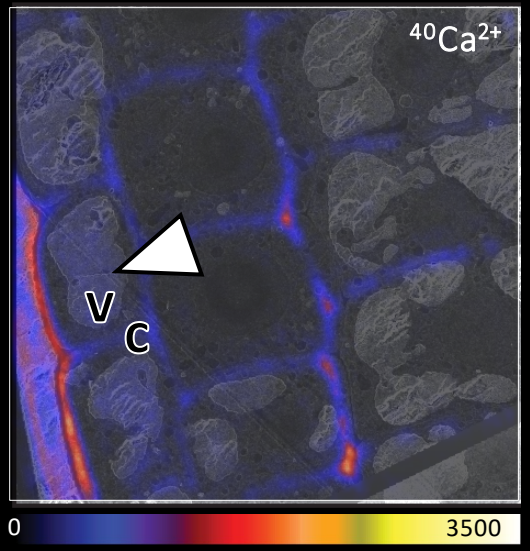
Mild salt-stress



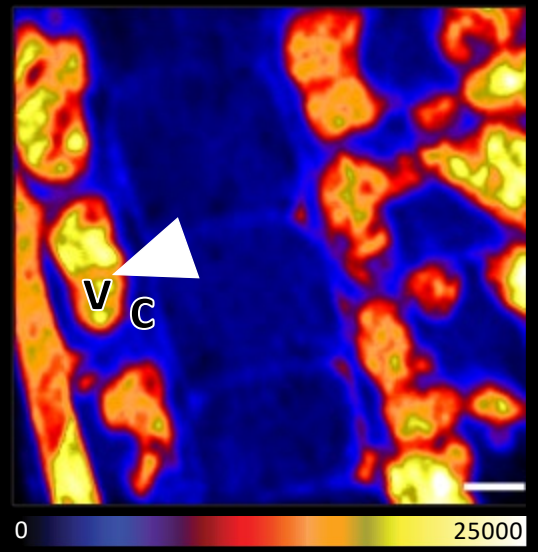


Out of cell

Moderate salt-stress



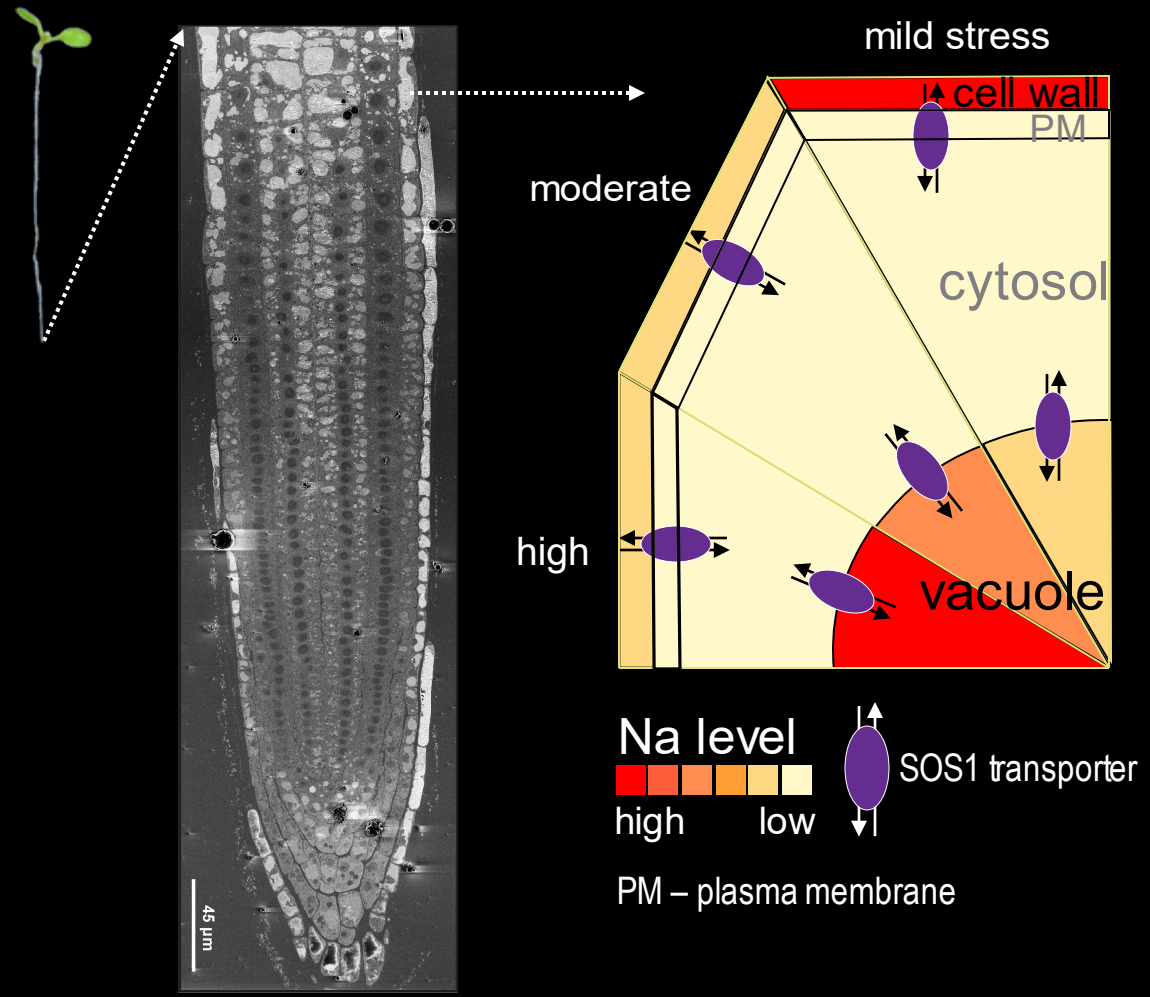
V – vacuole; C – cytosol



Scale bar, 5 µm

Into vacuoles

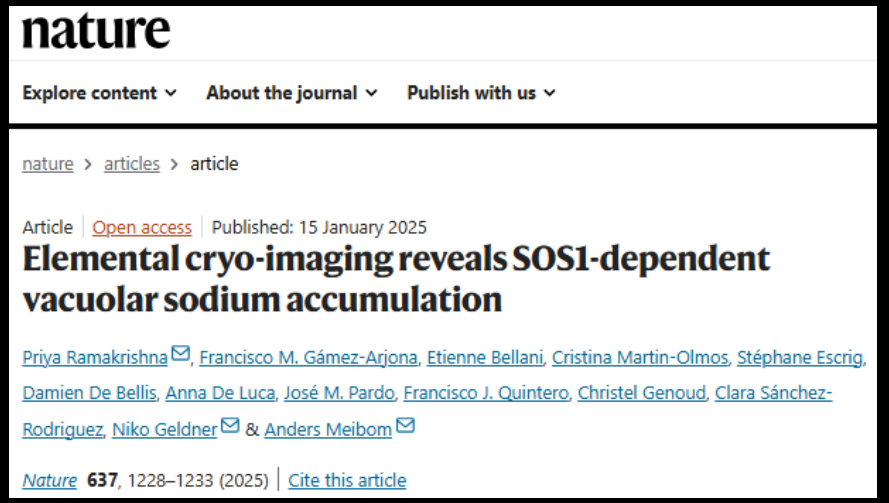
Model for how plant roots cope with salinity stress



Salt concentration driven switch in sodium accumulation strategy in cells

Low stress – exclude Na^+ from cell

High stress – load Na^+ into vacuoles



nature

Explore content | About the journal | Publish with us

nature › articles › article

Article | Open access | Published: 15 January 2025

Elemental cryo-imaging reveals SOS1-dependent vacuolar sodium accumulation

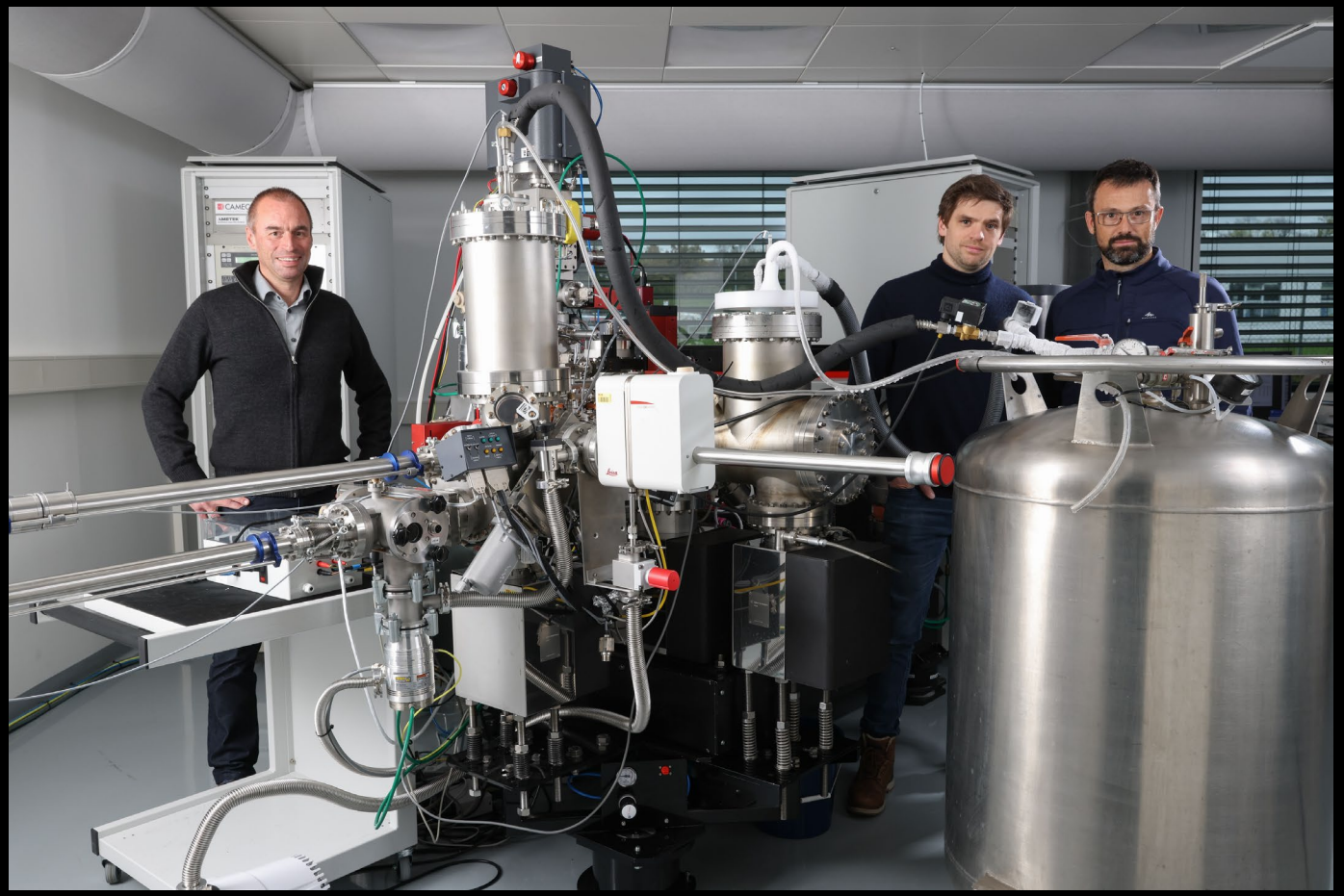
Priya Ramakrishna, Francisco M. Gámez-Arjona, Etienne Bellani, Cristina Martin-Olmos, Stéphane Escrig, Damien De Bellis, Anna De Luca, José M. Pardo, Francisco J. Quintero, Christel Genoud, Clara Sánchez-Rodriguez, Niko Geldner & Anders Meibom

Nature **637**, 1228–1233 (2025) | Cite this article

https://www.nature.com/articles/s41586-024-08403-y

Engineering for plants

CryoNanoSIMS



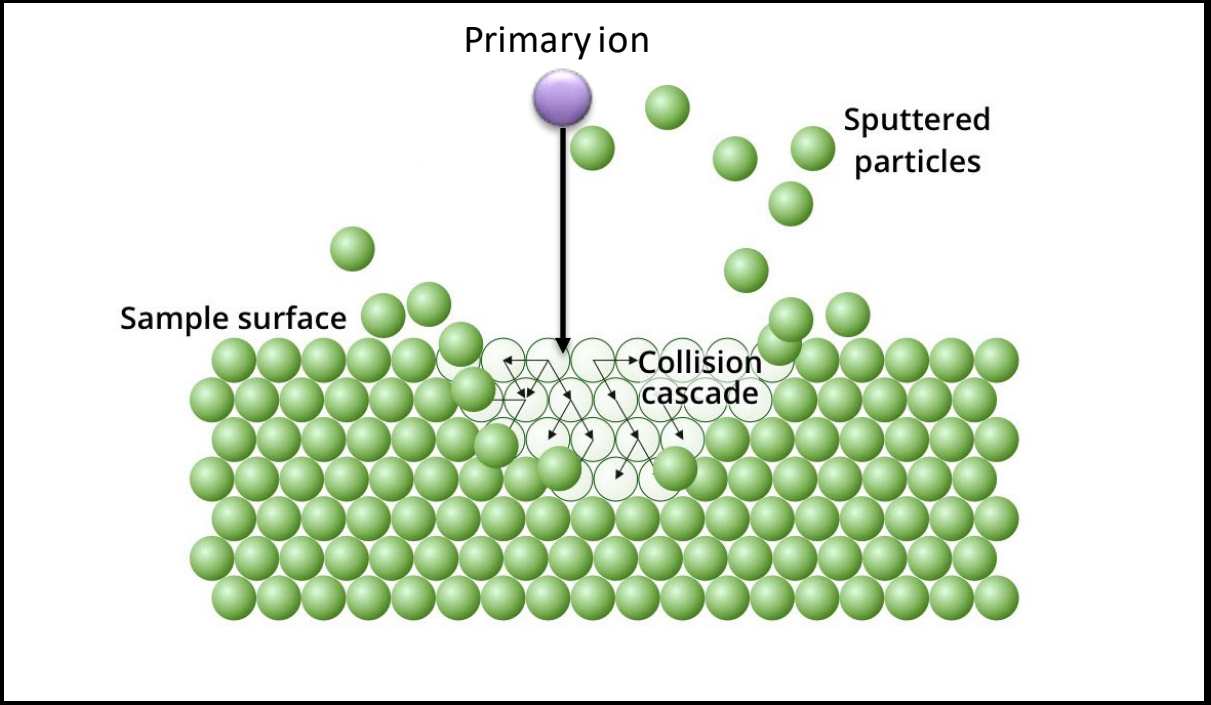
Unique instrument -> operates under **cryo**

EPFL Center for Advanced Surface Analysis

UNIL | Université de Lausanne

Nanoscale secondary ion mass spectrometry (NanoSIMS)

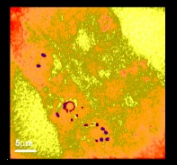
Build a chemical map of the elemental/isotope distribution inside the sample



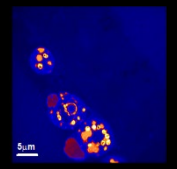
Modified from Myscope.training

Nanoscale secondary ion mass spectrometry (NanoSIMS)

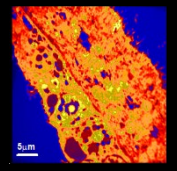
$^{12}C^-$



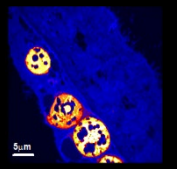
$^{13}C^-$



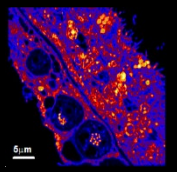
$^{14}N^{12}C^-$



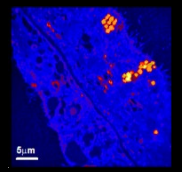
$^{15}N^{12}C^-$

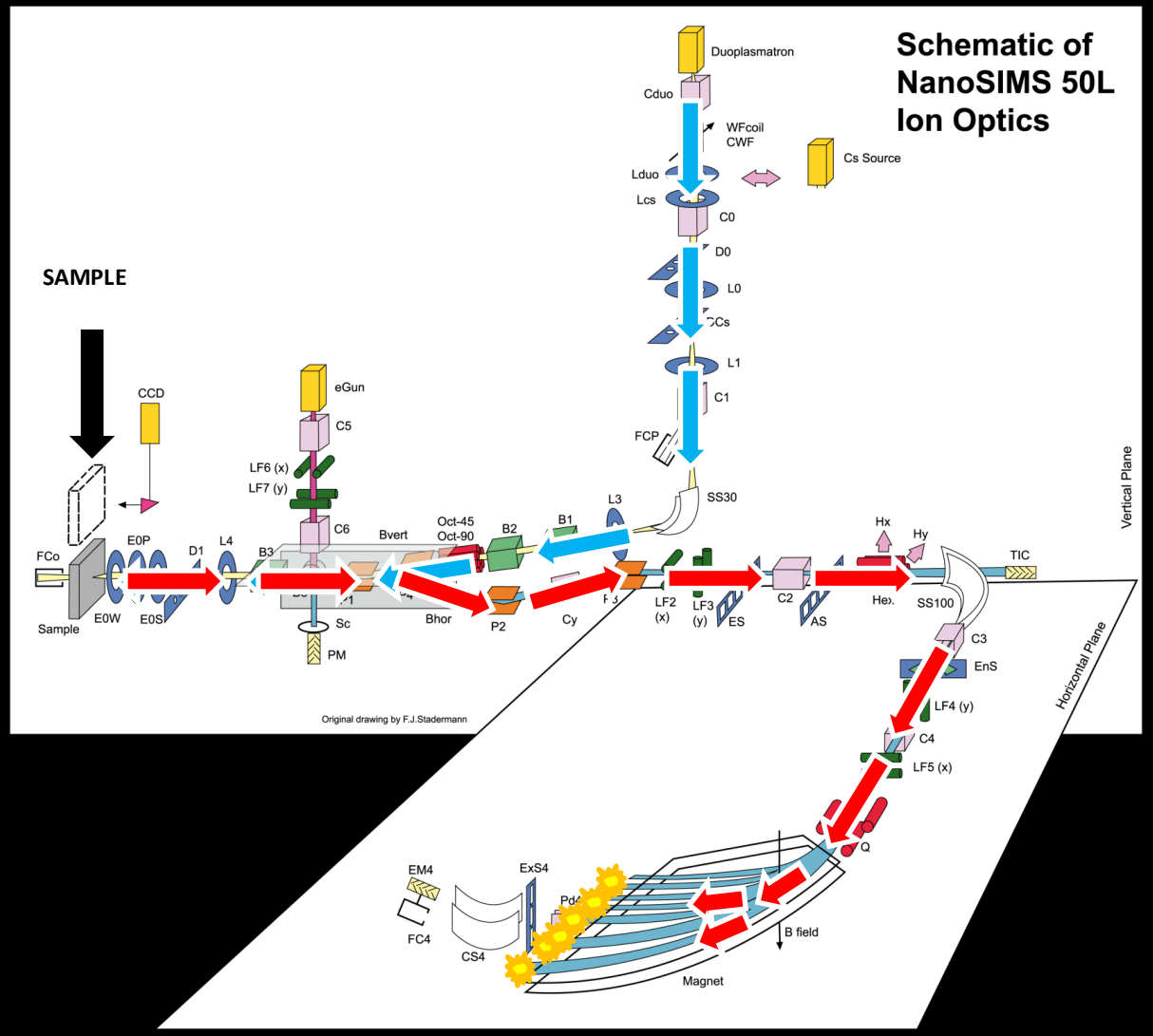


$^{31}P^-$



$^{32}S^-$





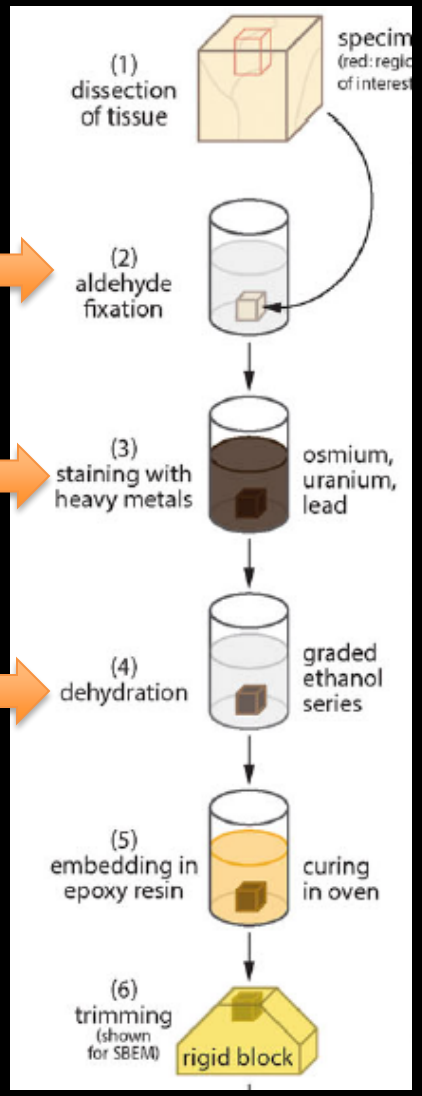
NanoSIMS so far for biology: imaging of chemically fixed samples

Classic Electron Microscopy sample preparation

Fixation

Heavy metal staining

Dehydration



Cross links proteins

Stains membranes, mitochondria, ER..

Loss of water soluble components - solutes, free ions...

Bound components of cell

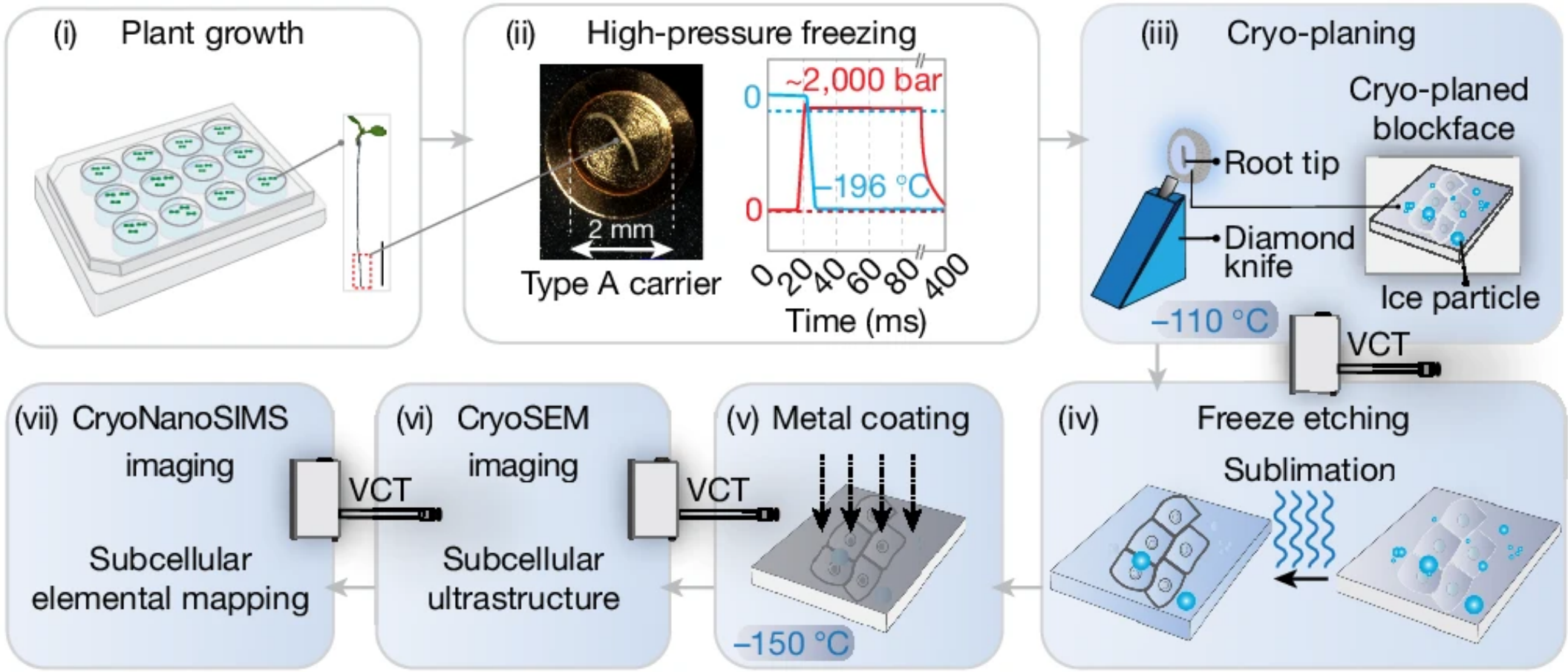
DNA	Proteins
Membranes (lipids)	Cell wall (polysaccharides)

What about the water soluble components?
The physiologically relevant ions, the salts?

Lewis, Genoud *et al*, *Curr. Op. in Struct. Biol*. 2019

Cryogenic workflow for correlative cryoSEM-CryoNanoSIMS

Vitrification of biological tissue in its most pristine state!



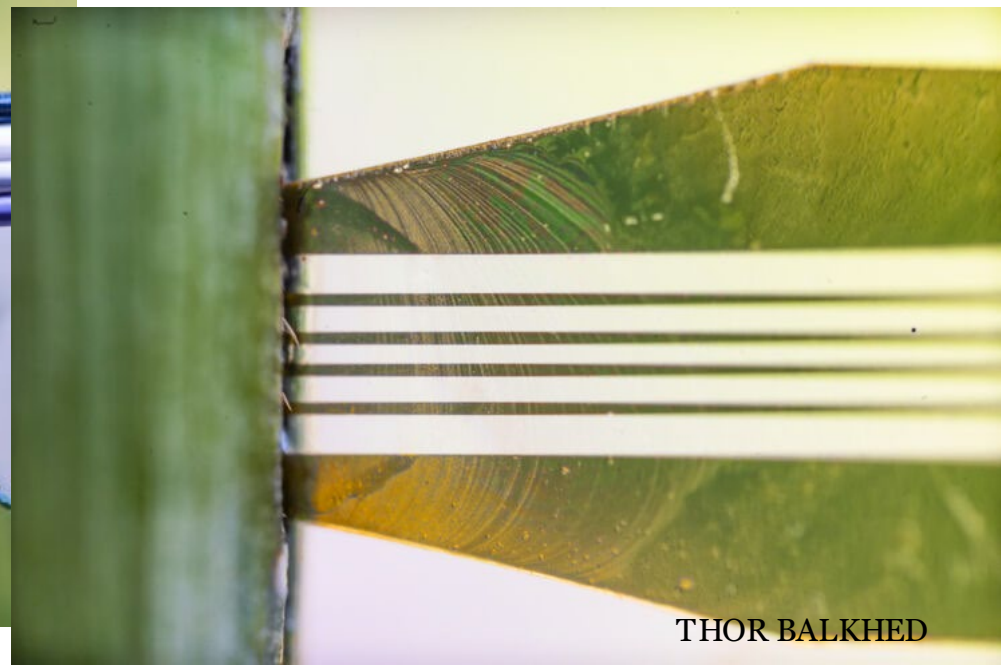
VCT – Vaccum Cryo Transfer shuttle
Blue – analysis under **cryo**-conditions

Meibom *et al.*, 2023, *BMC Biology*

Biosensors

Hybrid aspen, *Populus tremula*.

Based on organic electrochemical transistors.



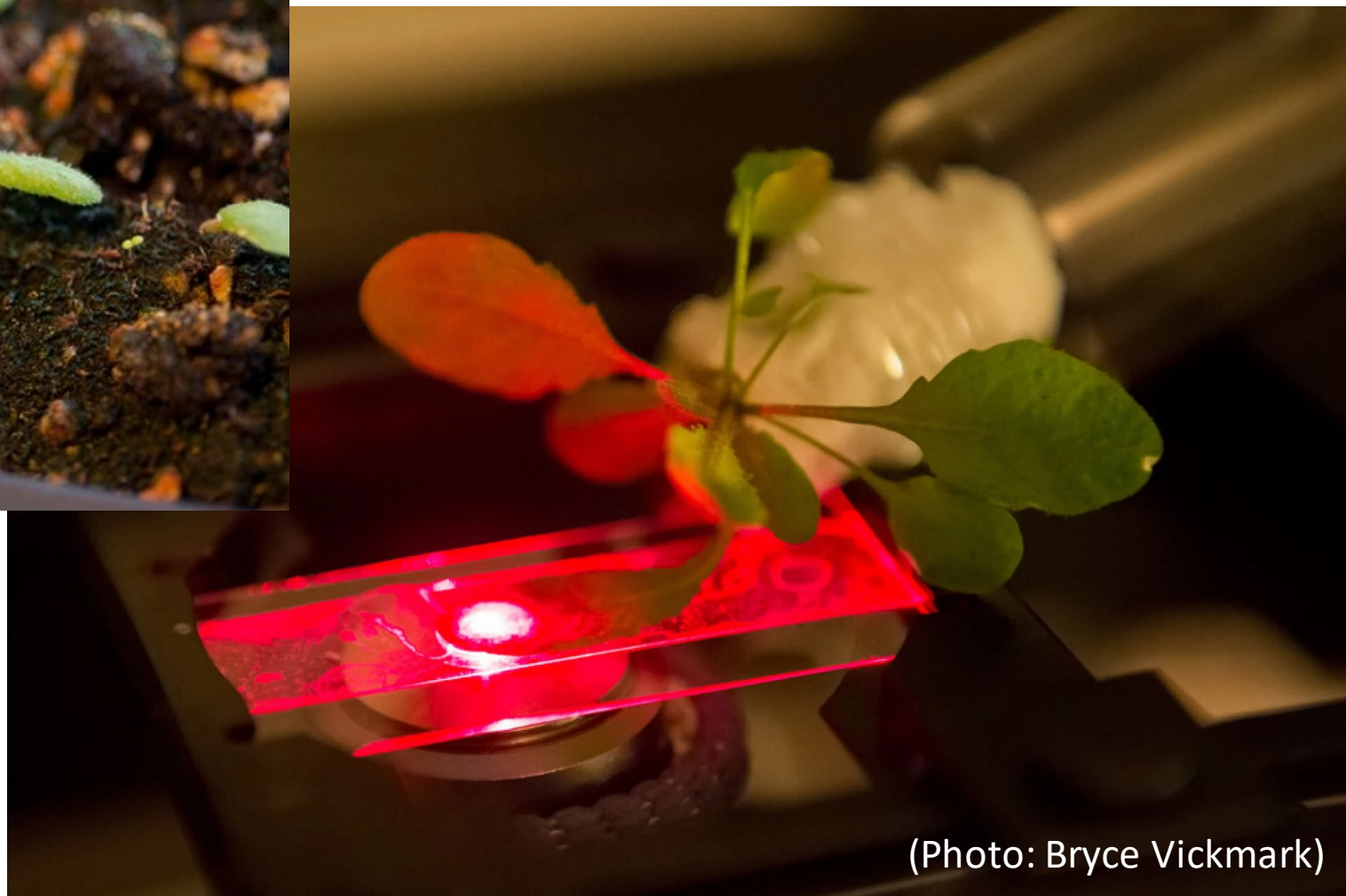
Sugar levels without damaging the plant

Ion flow sensors

Detects and records the tiny electrical signals plants generate

By infusing the leaves of an *Arabidopsis thaliana* plant with nanoparticles, researchers have boosted the plant's energy production.

(Photo: Bryce Vickmark)



(Photo: Bryce Vickmark)

Near-infrared microscope - output of carbon nanotube sensors embedded in the plant

Future farms?


THANK YOU!