Sustainably Doubling Agricultural Output by 2050: Where are the Nanotechnology Niches?

Gregory V. Lowry

Walter J. Blenko, Sr. Professor of Civil & Environmental Engineering

Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

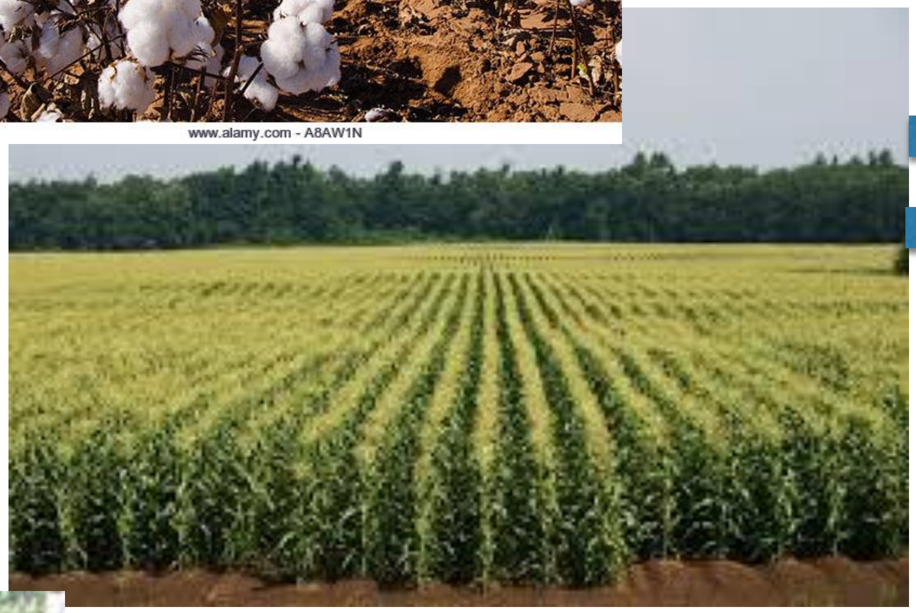
Center for the Environmental Implications of NanoTechnology (CEINT)

Sustainable Nanotechnology Organization
November 6, 2017




What is Agriculture?

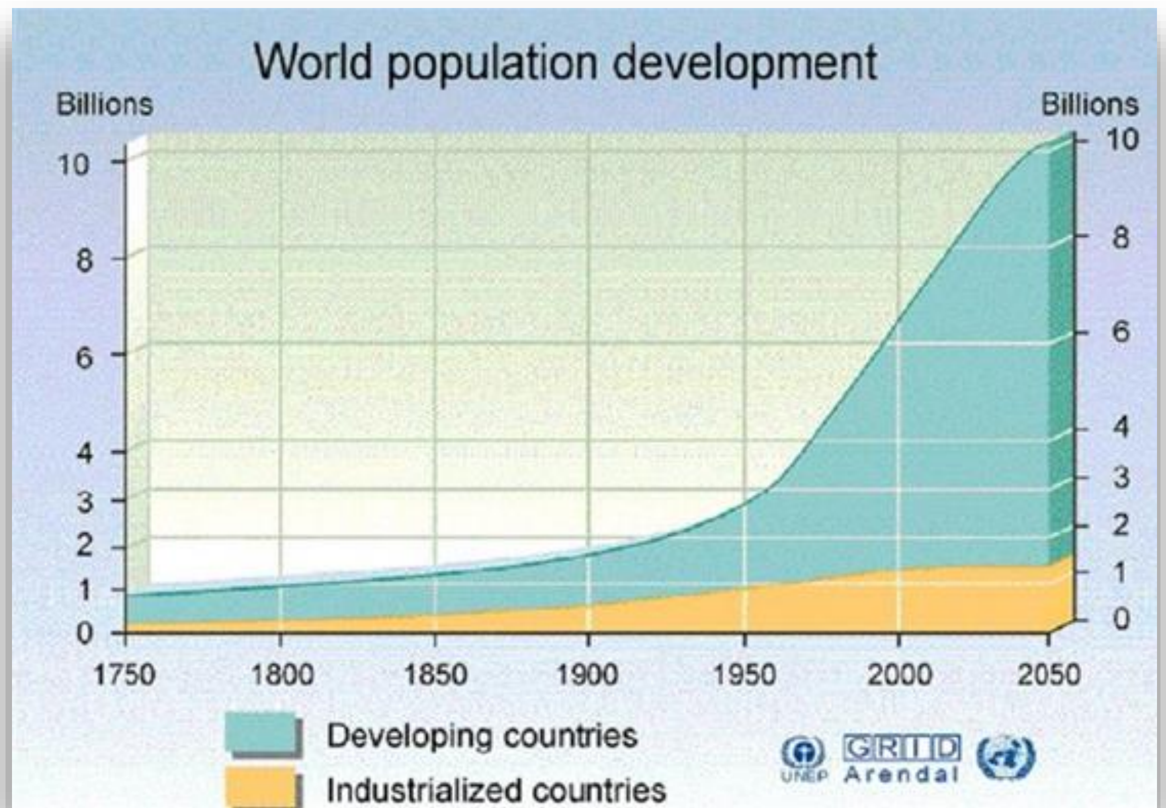
- Food
- Fiber
- Fuel



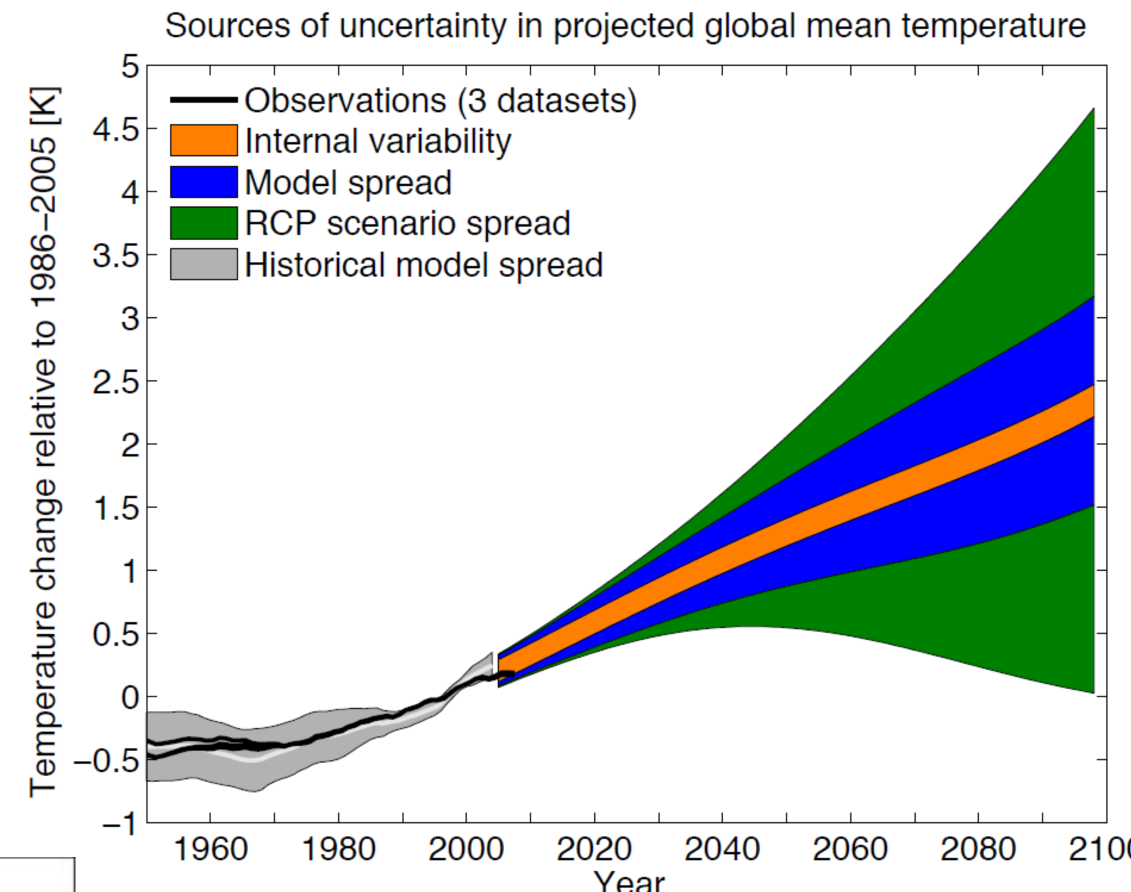
Carnegie Mellon

What will Earth look like in 2050?

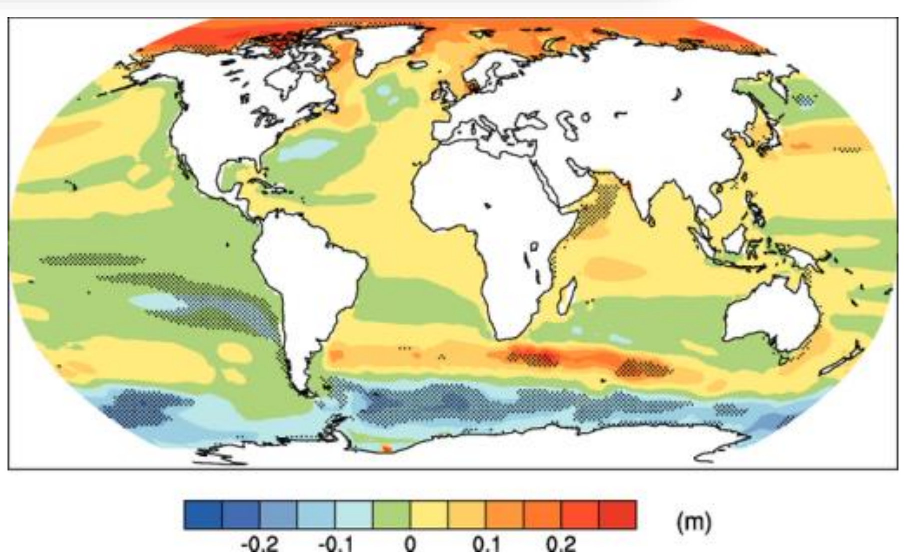
50% more people



Hotter



Kirtman, et al. 2013: Near-term Climate Change: Projections and Predictability. In: Climate Change 2013: The Physical Science Basis. IPCC

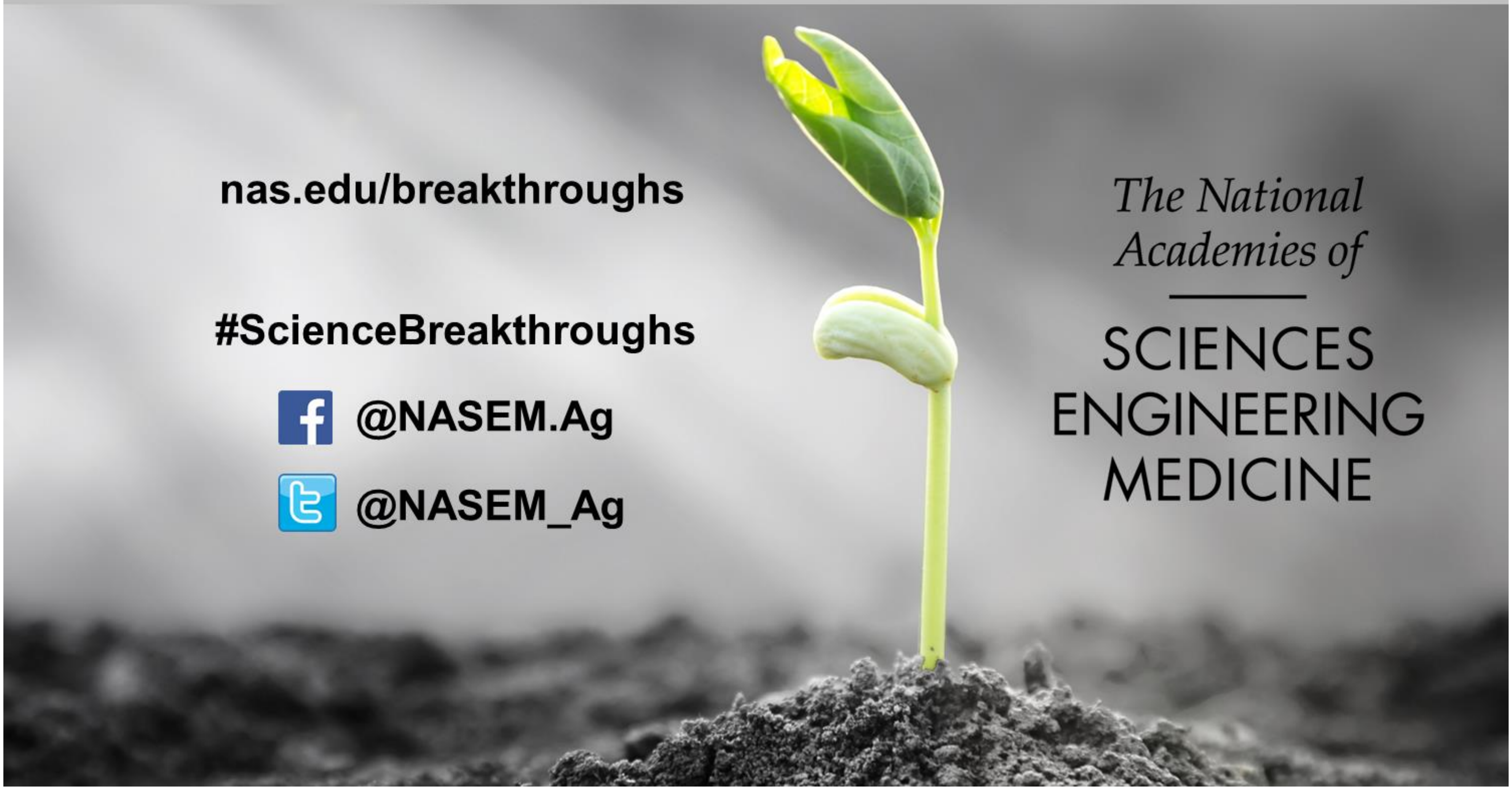


Higher sea level

Carnegie Mellon

Science Breakthroughs 2030

A Strategy for Food and Agricultural Research



Challenges to *Sustainable* Food Security

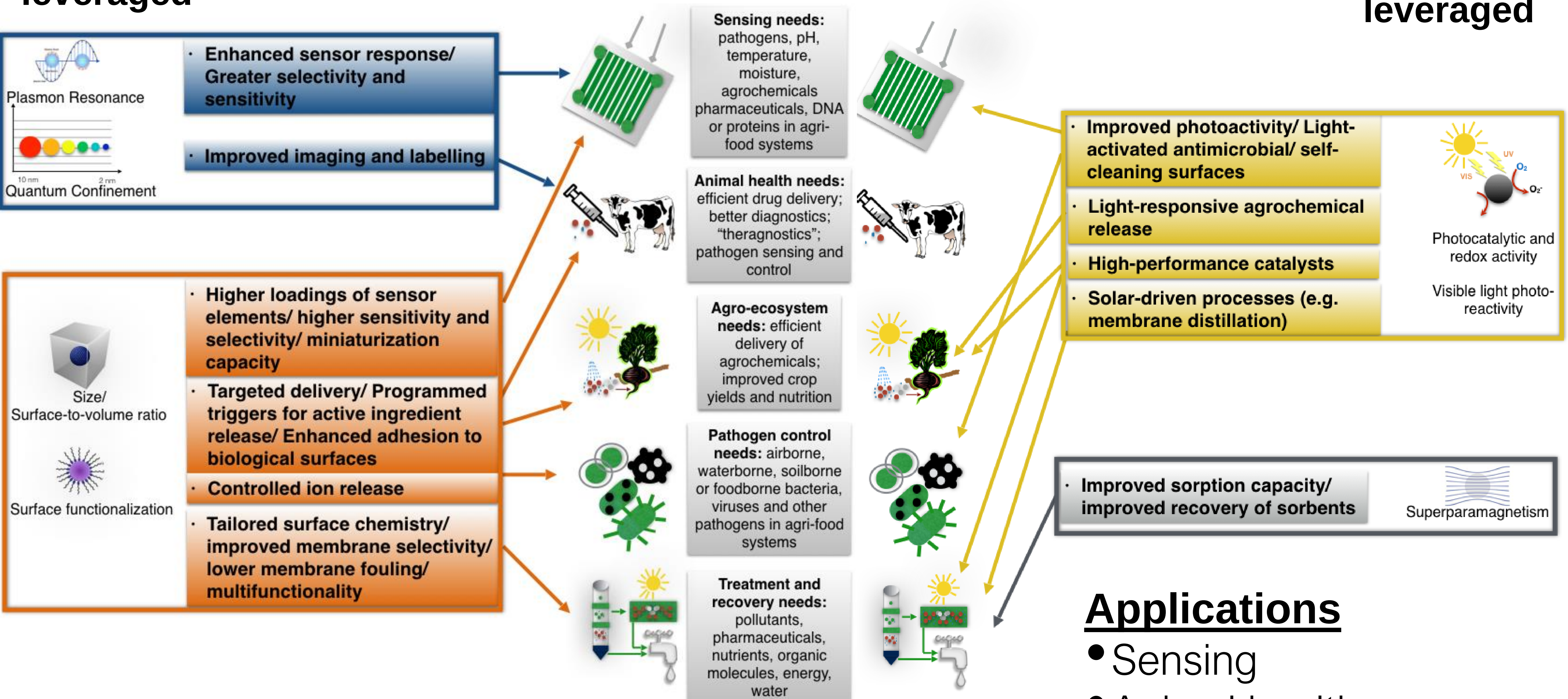
- **Water**
  - >70 % of global water <u>consumptive use</u>
- **Inefficiency**
  - Low agrochemical utilization rates
  - Food waste (40% in US) and food loss
- **Lack of Resilience**
  - Heat, salt, drought, or flood stress
  - Disease
- **Soil degradation and loss**
  - Poor nutritional value of foods
  - Declining yields
- **Insufficient workforce development**
- **Yet……Yields must increase by 60-100% by 2050 to meet demand and water use must decrease**

Carnegie Mellon

Foley et al., *Nature* 2011; Mueller et al., *Nature* 2012; UNESCO WWAP, 2012; UNESCO IHE, 2013

How can Nanotechnology Help?

Nanoscale properties leveraged | **Benefits** | **Benefits** | **Nanoscale properties leveraged**



Applications

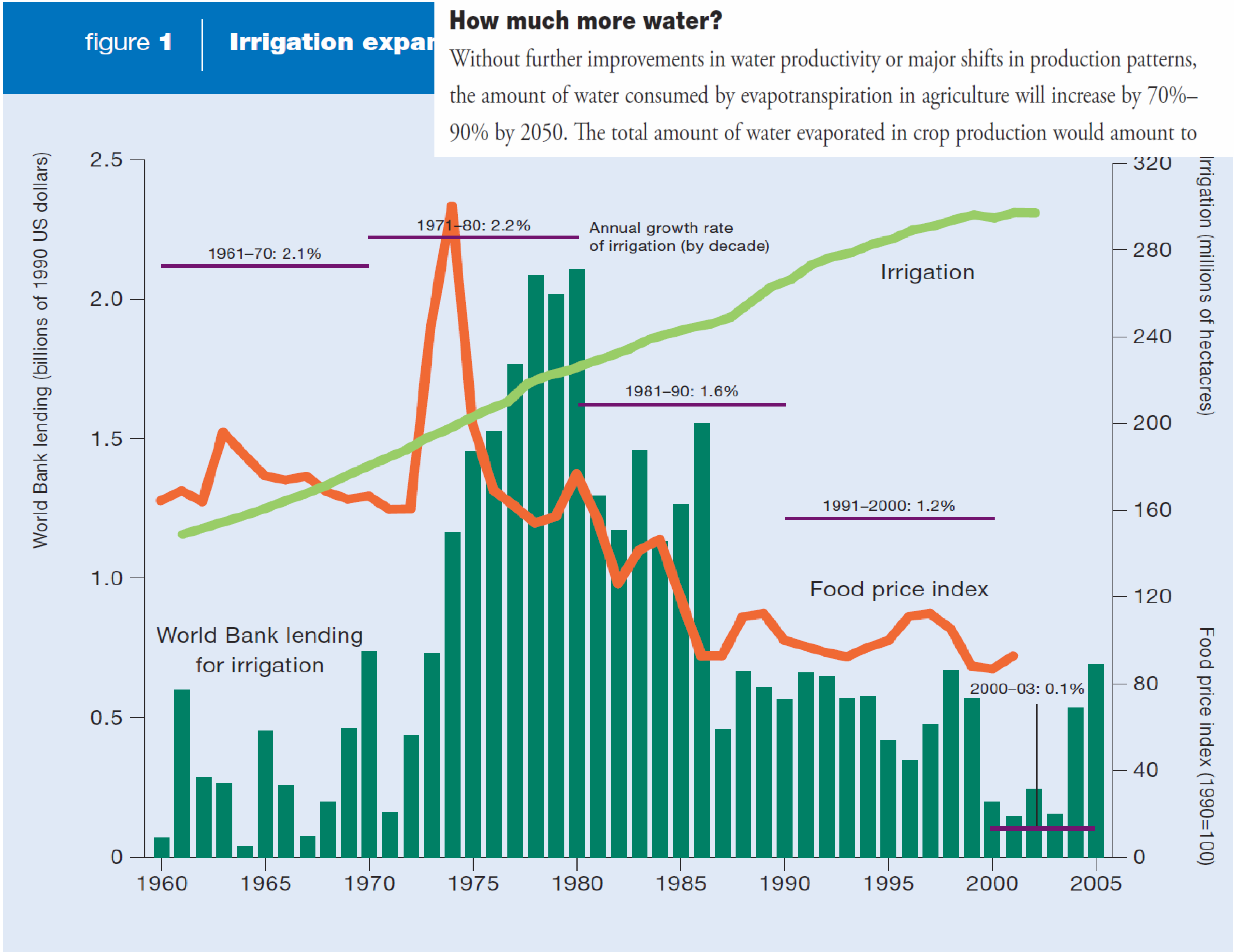
- Sensing
- Animal health
- Agriculture (crop)
- Pathogen Control
- Water treatment and nutrient recovery

Rodrigues et al. *ES Nano* 2017 DOI: 10.1039/C6EN00573J

Carnegie Mellon

How much more water?

Without further improvements in water productivity or major shifts in production patterns, the amount of water consumed by evapotranspiration in agriculture will increase by 70%–90% by 2050. The total amount of water evaporated in crop production would amount to



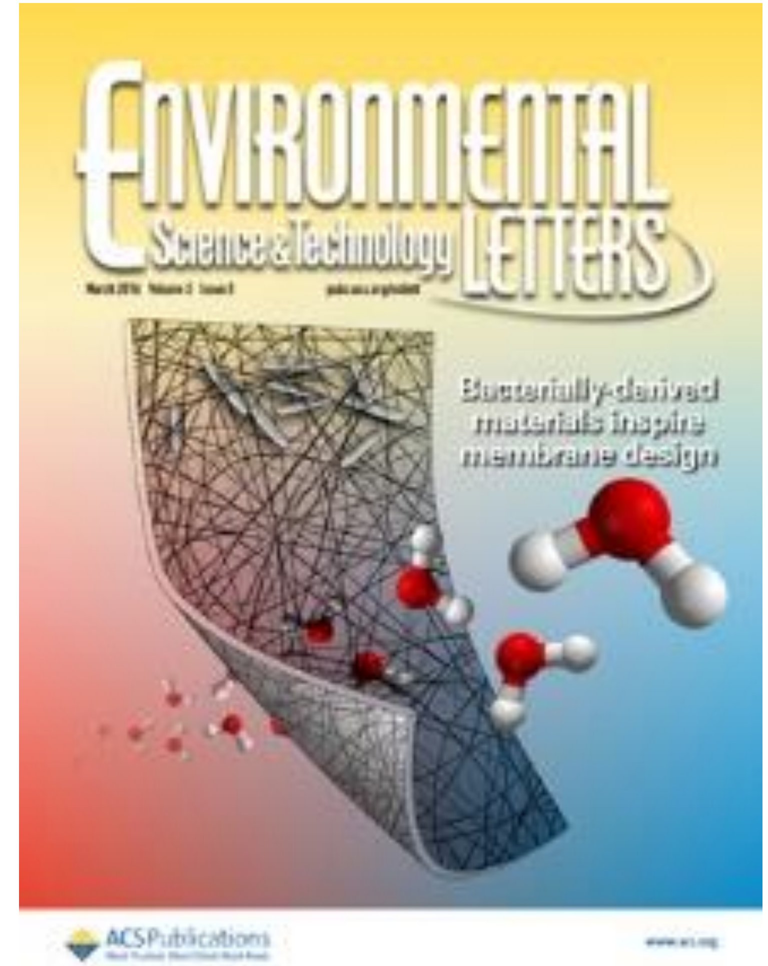
Source: Based on World Bank and Food and Agriculture Organization data; chapter 9.

Carnegie Mellon

Opportunities for Nanotech in Water

- Increase water availability
  - Non-traditional sources
  - Water reuse (e.g. wastewater)

- Use water wiser
  - **Smart plants**/soils/reservoirs
  - Sensors and data analytics



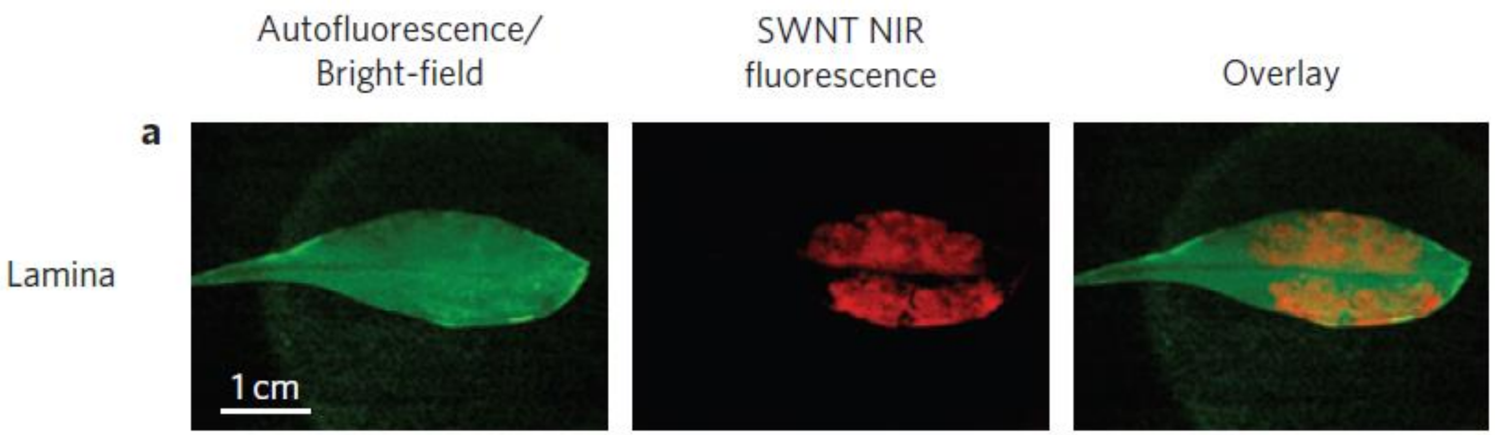
Carnegie Mellon

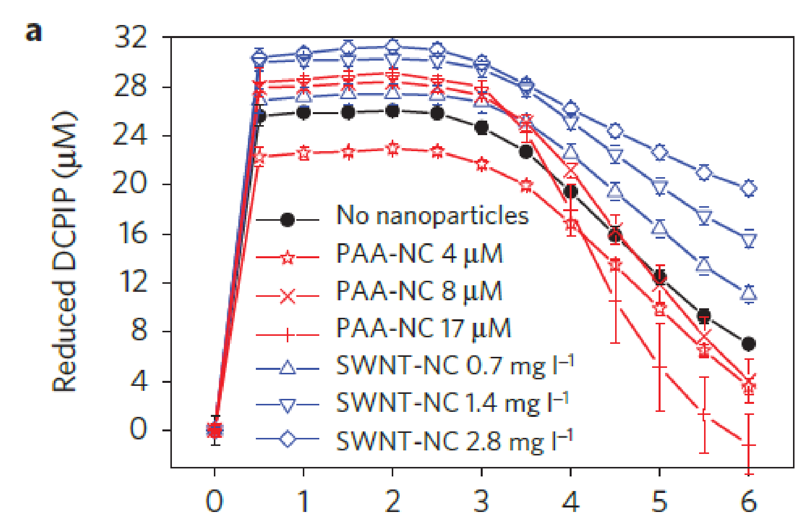
Bionic Plants

ARTICLES
PUBLISHED ONLINE: 16 MARCH 2014 | DOI: 10.1038/NMAT3890
nature materials

Plant nanobionics approach to augment photosynthesis and biochemical sensing

Juan Pablo Giraldo[1], Markita P. Landry[1], Sean M. Faltermeier[1], Thomas P. McNicholas[1], Nicole M. Iverson[1], Ardemis A. Boghossian[1,2], Nigel F. Reuel[1], Andrew J. Hilmer[1], Fatih Sen[1,3], Jacqueline A. Brew[1] and Michael S. Strano[1*]





Giraldo et al., 2014 *Nat Mat*. DOI: 10.1038/NMAT3890

Water delivery = Energy

Lowering Friction in Pipes for Water Delivery

Journal of Materials Chemistry A

ROYAL SOCIETY OF CHEMISTRY

PAPER

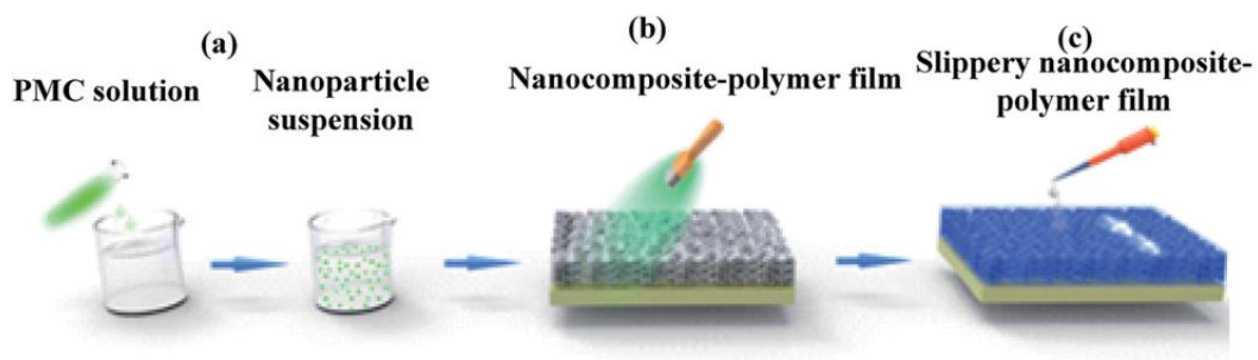
View Article Online
View Journal | View Issue

CrossMark click for updates

Cite this: *J. Mater. Chem. A*, 2016, 4, 2524

Slippery liquid-infused substrates: a versatile preparation, unique anti-wetting and drag-reduction effect on water†

Yang Wang, Haifeng Zhang,* Xiaowei Liu and Zhiping Zhou



Scheme 1 Schematic showing the fabrication of the SLIPS. (a) Nanoprecipitation in ethanol/water. (b) Nanocomposite–polymer formed on the substrate *via* the brushing method. (c) A liquid is infiltrated into the porous film. Droplets readily slide along the surface.

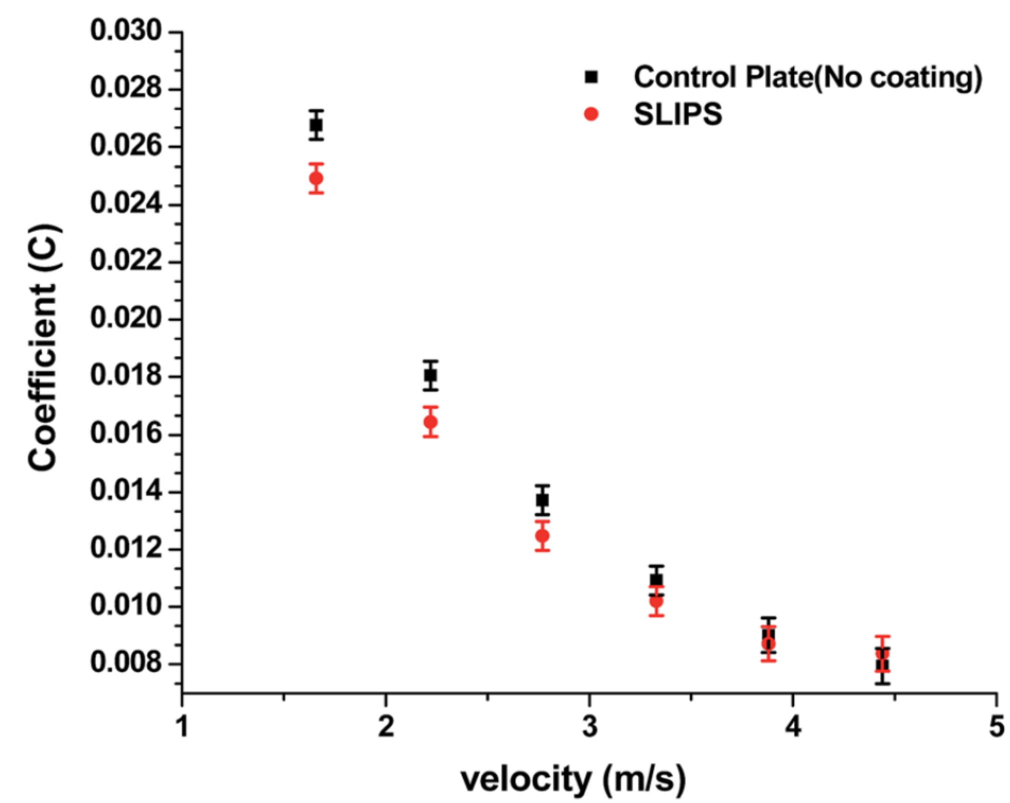
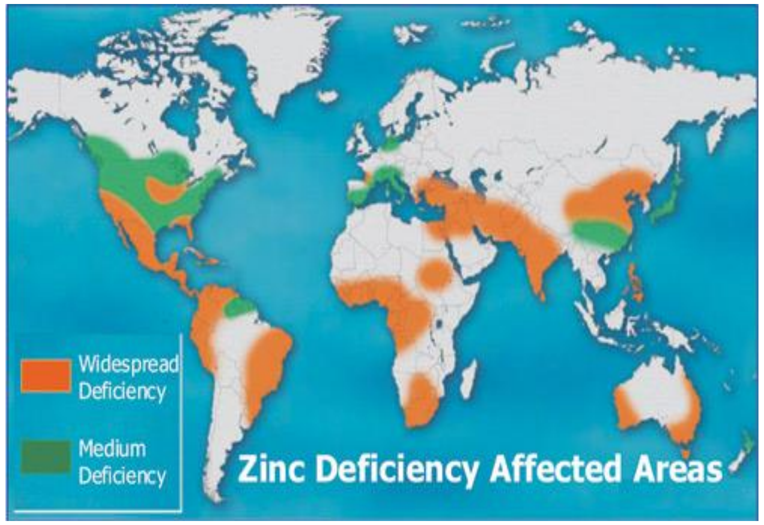


Fig. 4 Results of the drag test at different flow velocities. The error bar indicates ±3% for experimental uncertainty.

Inefficiency

- Agro-food system notoriously inefficient
  - Yield gap
  - Food loss (on farm)
    - Disease (e.g. wheat blast)
  - Food waste (from gate to table)
    - Waste to energy
  - Agrochemicals
    - <50% utilization of applied N & P
    - <5% for micronutrients and pesticides

Opportunities for nanomaterials to increase crop agriculture efficiency



- Improve yields and nutritional value of foods
  - Micronutrient deficient soils

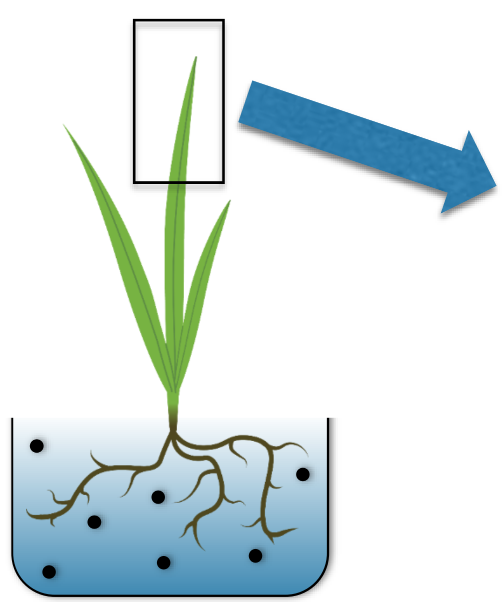
- Increase photosynthesis rates
  - Food and biofuels production
- Increase resistance to diseases and stress
  - Fungus, virus
  - Salt, drought, heat

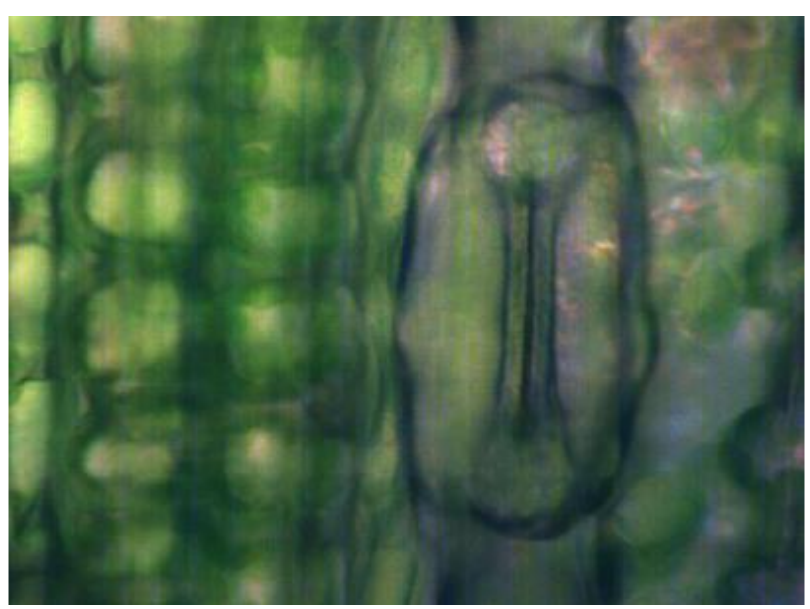
- Increase agrochemical utilization efficiency

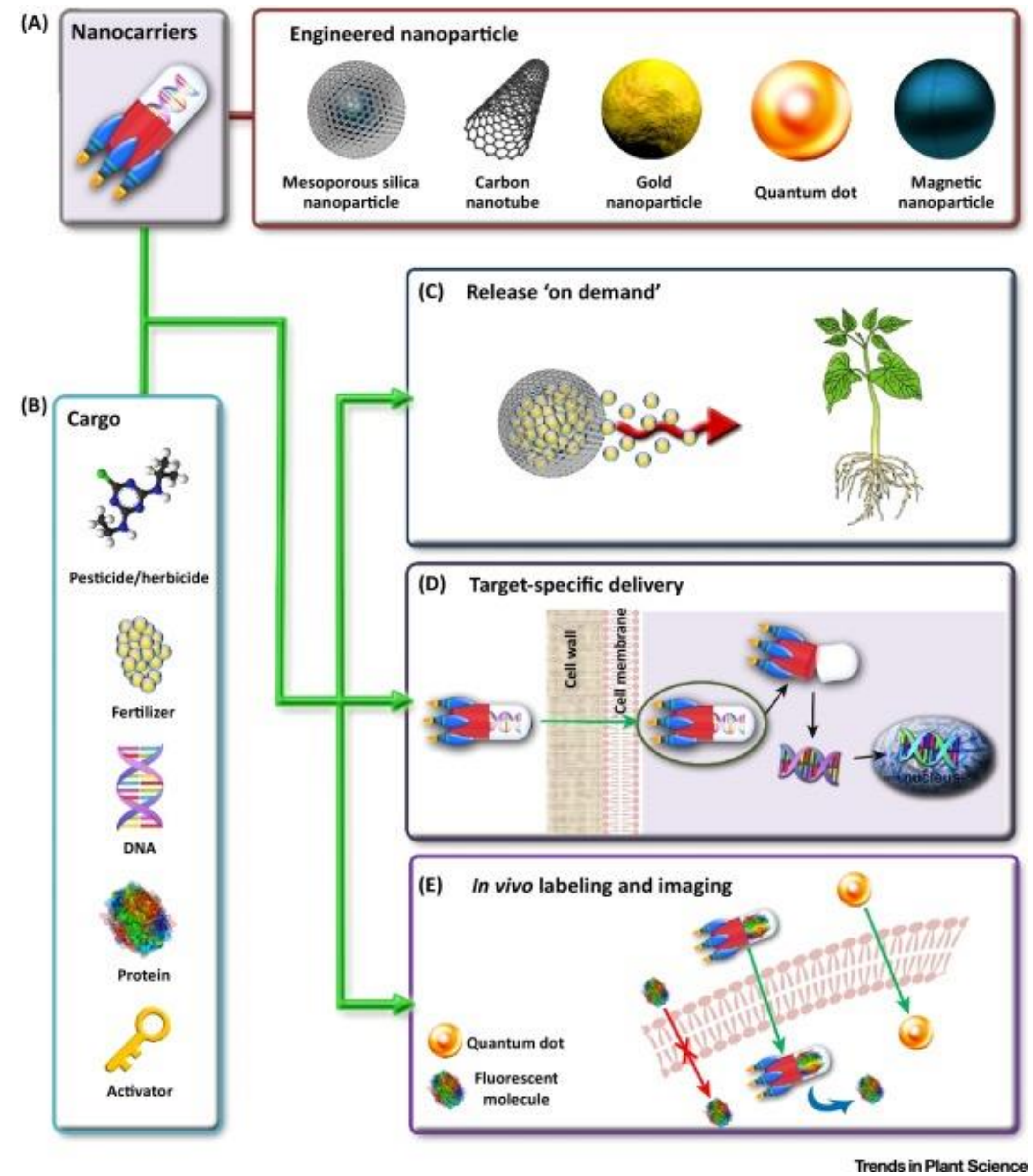
Carnegie Mellon

Why Nano?

- Small size enables entry into plants
  - Nutrient and pesticide delivery
- Inherent slow release mechanism
  - Timing and leaching
- Tunable surface properties
  - Targeting and adhesion







Wang et al., 2016 *Trends in Plant Science* 21(8), Pages 699–712

Carnegie Mellon

Rodrigues et al. *ES Nano* 2017 DOI: 10.1039/C6EN00573J

Key Question to Ask

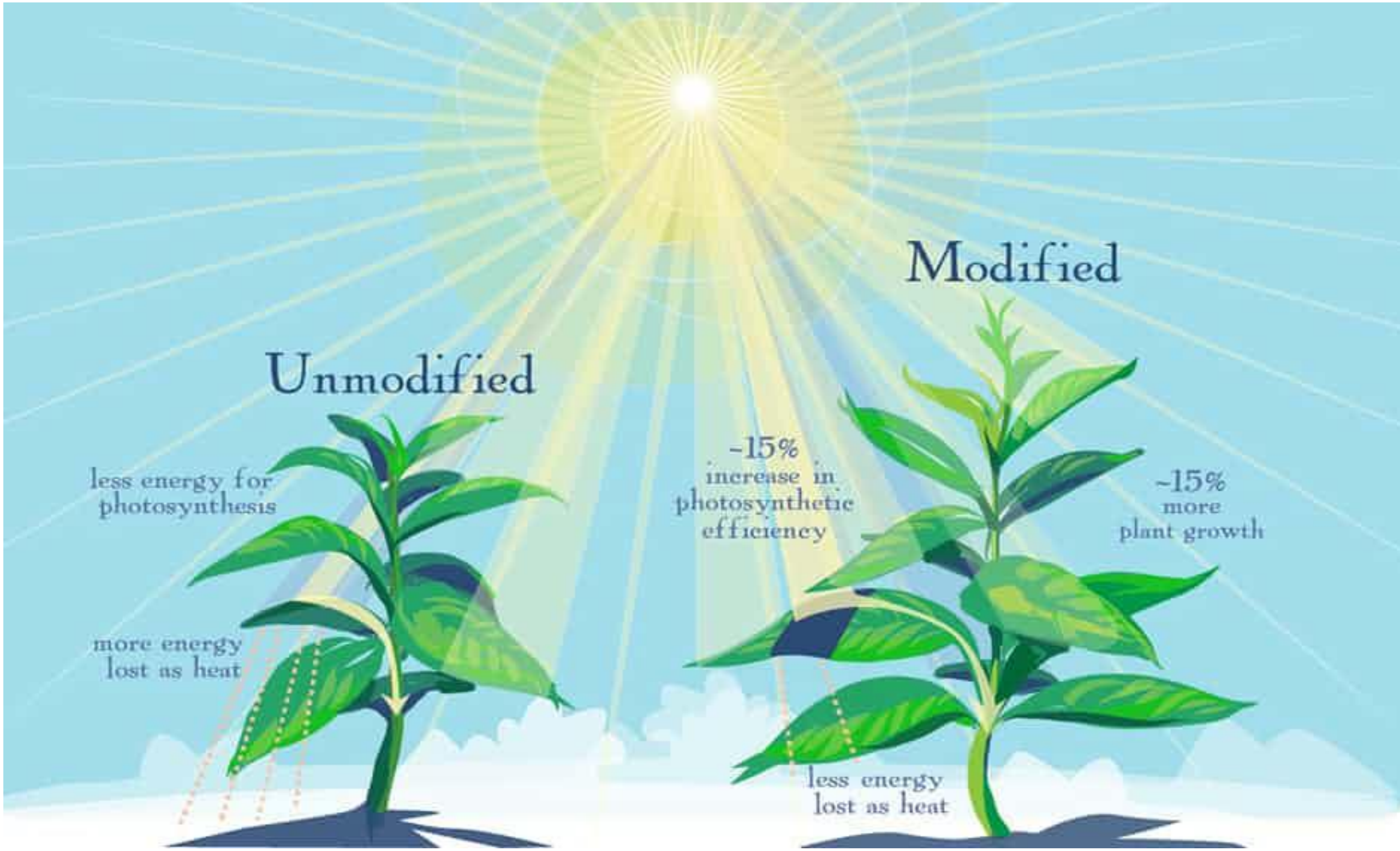
- Are nano-enabled technologies REALLY better than alternatives?

LOW COST SLOW-RELEASE FERTILIZER DEVELOPED
ALLEN, SE et al.
CROPS AND SOILS MAGAZINE
Volume: 21
Issue: 3
Pages: 13-&
Published: 1968

- Are you addressing the most important problems?
  - N inefficiency is a large problems (200 million tons/year)
  - Pesticides ($81B market by 2019)

Carnegie Mellon

Photosynthesis is inefficient



GM plants are more efficient

Nanomaterials Increase Plant Resistance to Soil Fungus

Environmental Science Nano

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

CrossMark
click for updates

Cite this: DOI: 10.1039/c6en00146g

The use of metallic oxide nanoparticles to enhance growth of tomatoes and eggplants in disease infested soil or soilless medium

Wade H. Elmer*[a] and Jason C. White[b]

Table 2 Effect of nanoparticles (NP) of Cu, Mn, and Zn oxides on growth of greenhouse-grown eggplant transplants in soil infested with *Verticillium dahliae*. Values are in g (dry weight)

	Non-inoculated	Inoculated with *V. dahliae*	
Treatment[a]	Fresh weight (g)	Fresh weight (g)	Area under the disease progress curve[c]
Control	14.2 ab	8.9 a[b]	114 a
CuO bulked	14.2 ab	10.6 ab	69 b
CuO NP	17.2 b	14.6 b	36 b
$CuSO_4$	14.7 ab	12.6 ab	69 b

- CuO NPs increased growth and fruit yield in fungus infested soil
- CuO NPs <u>did not</u> kill fungus in soil
- CuO NPs boosted plant's natural defense to fungus

Carnegie Mellon

CeO_2 NPs increases salt tolerance of Canola

Contents lists available at ScienceDirect

Environmental Pollution

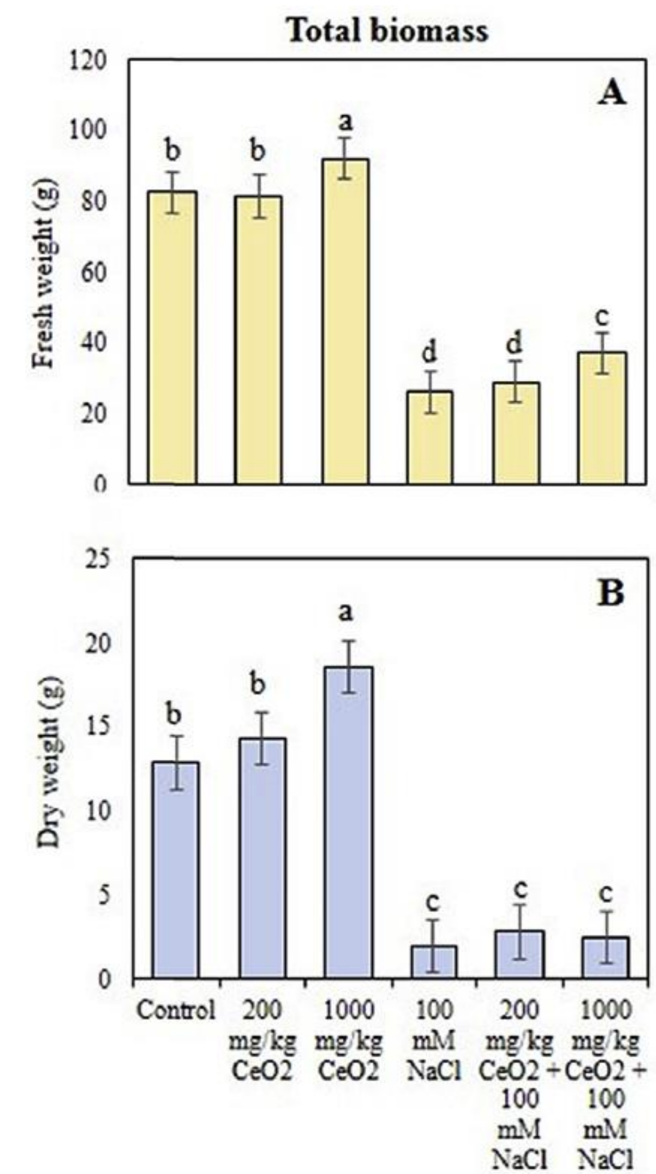
journal homepage: www.elsevier.com/locate/envpol

ELSEVIER

The impact of cerium oxide nanoparticles on the salt stress responses of *Brassica napus* L.☆

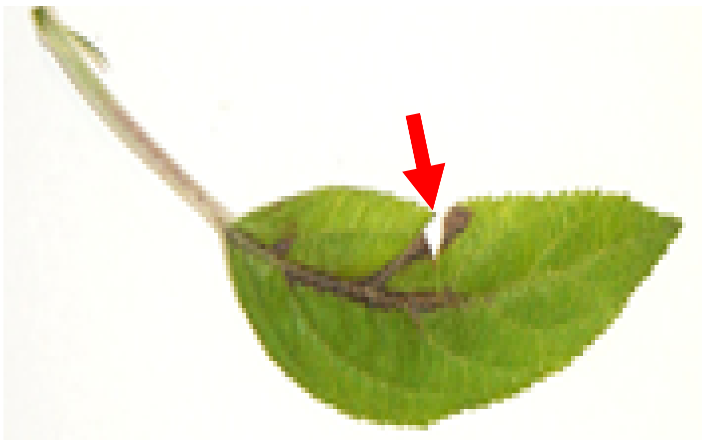
Lorenzo Rossi [a], Weilan Zhang [a], Leonardo Lombardini [b], Xingmao Ma [a, *]

[a] *Zachry Department of Civil Engineering, Texas A&M University, TAMU 3136, College Station, TX 77843-3136, USA*
[b] *Department of Horticultural Sciences, Texas A&M University, TAMU 2133, College Station, TX 77843-2133, USA*

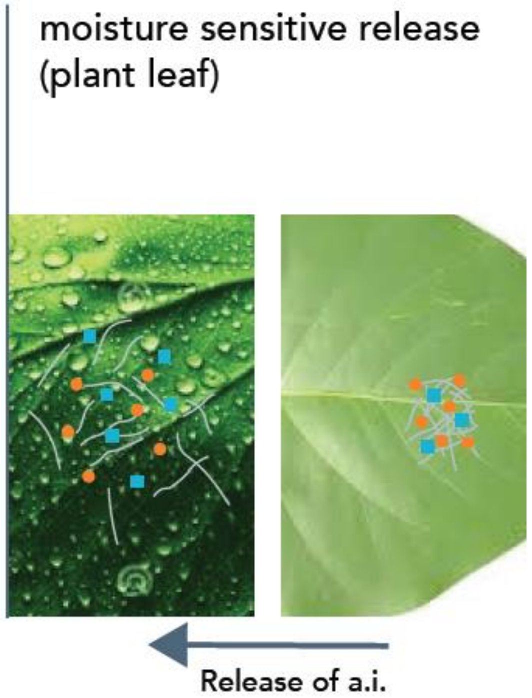


Rossi et al., 2016 *Env. Pollut*. 219

Fundamental Challenges to Deployment



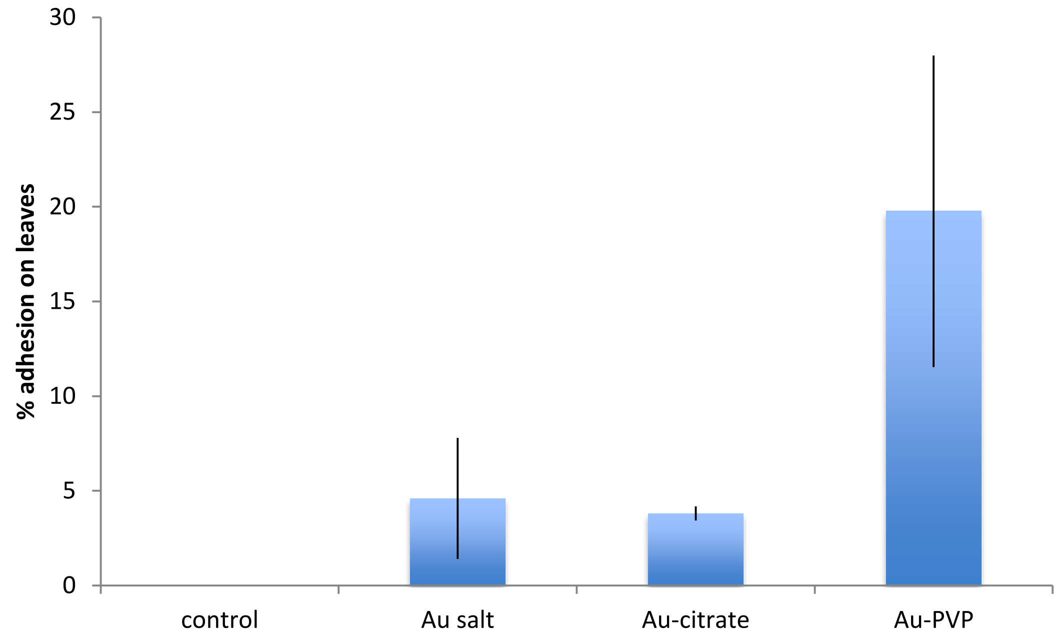
- Interfacial targeting and selectivity (Delivery)
  - **How do we get the NPs where they need to be?**
- Condition-specific availability (e.g. pH or moisture)
  - How can we release agrochemicals **where** and **when** needed?



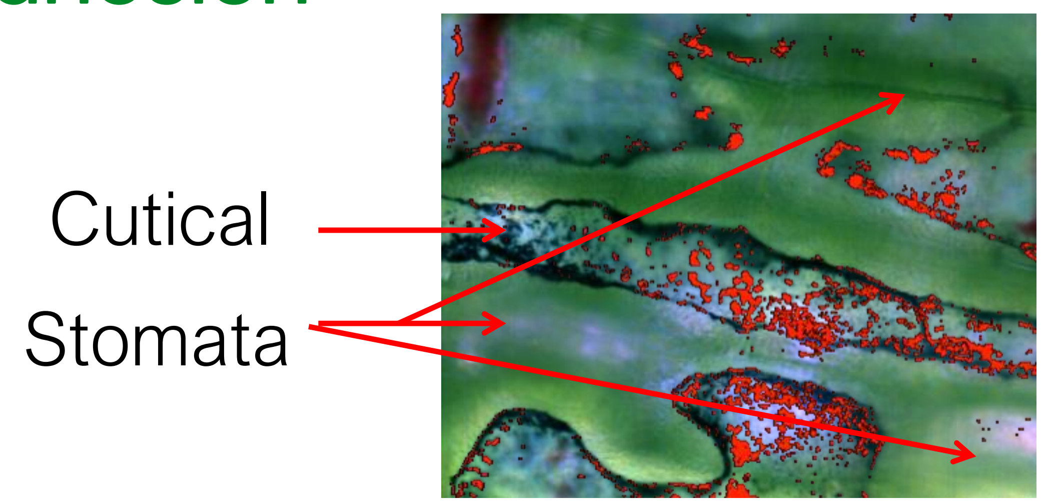
- Understand bioavailability in complex matrices
  - How to transformations affect bioavailability?
  - What are the ENP impacts on the phytobiome?
- Need to make the business case
  - LCA and economics

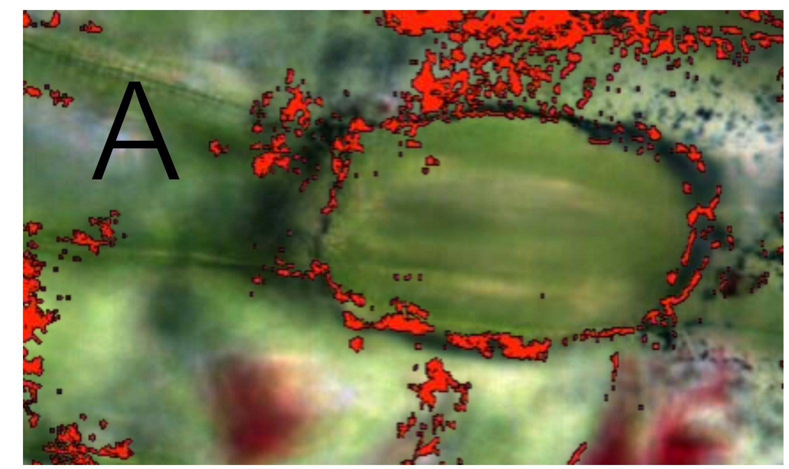
Carnegie Mellon

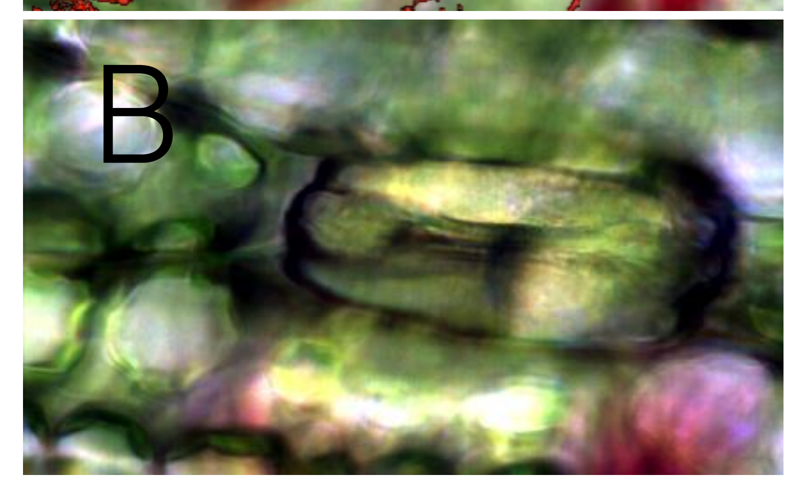
Effect of NP Coating on Leaf Adhesion



Au PVP

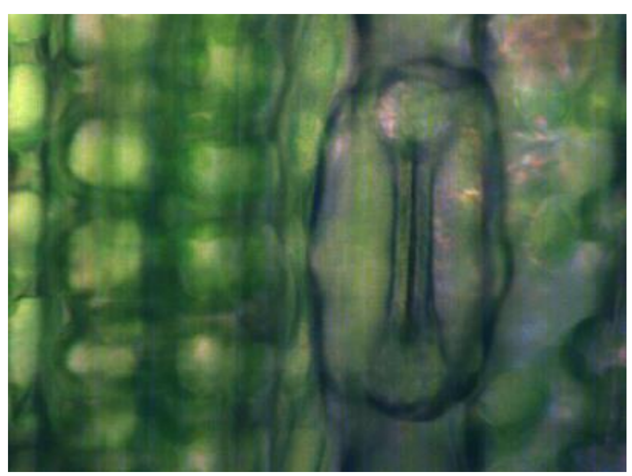




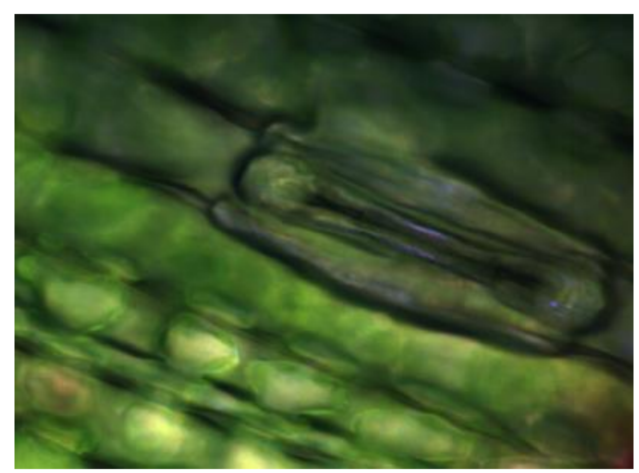


Control

Au salt



Au citrate



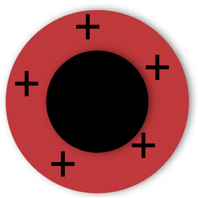
Key Variables: Size, charge, shape, coating, solubility
Plant species, organic matter, soil properties

Carnegie Mellon

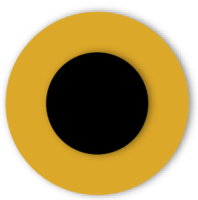
Avellan et al., (in prep)

Effect of NP Charge on Distribution in plants

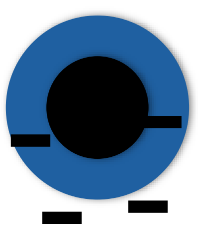
~4nm by TEM
~10nm DLS



Positively charged CeO_2

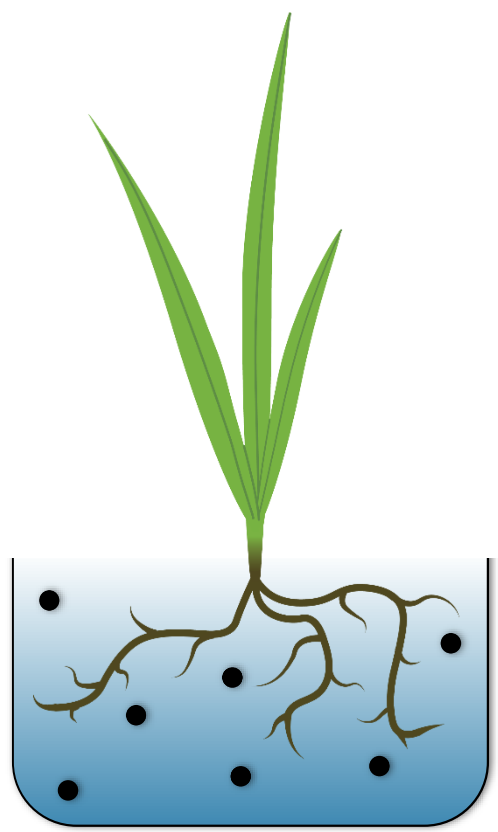


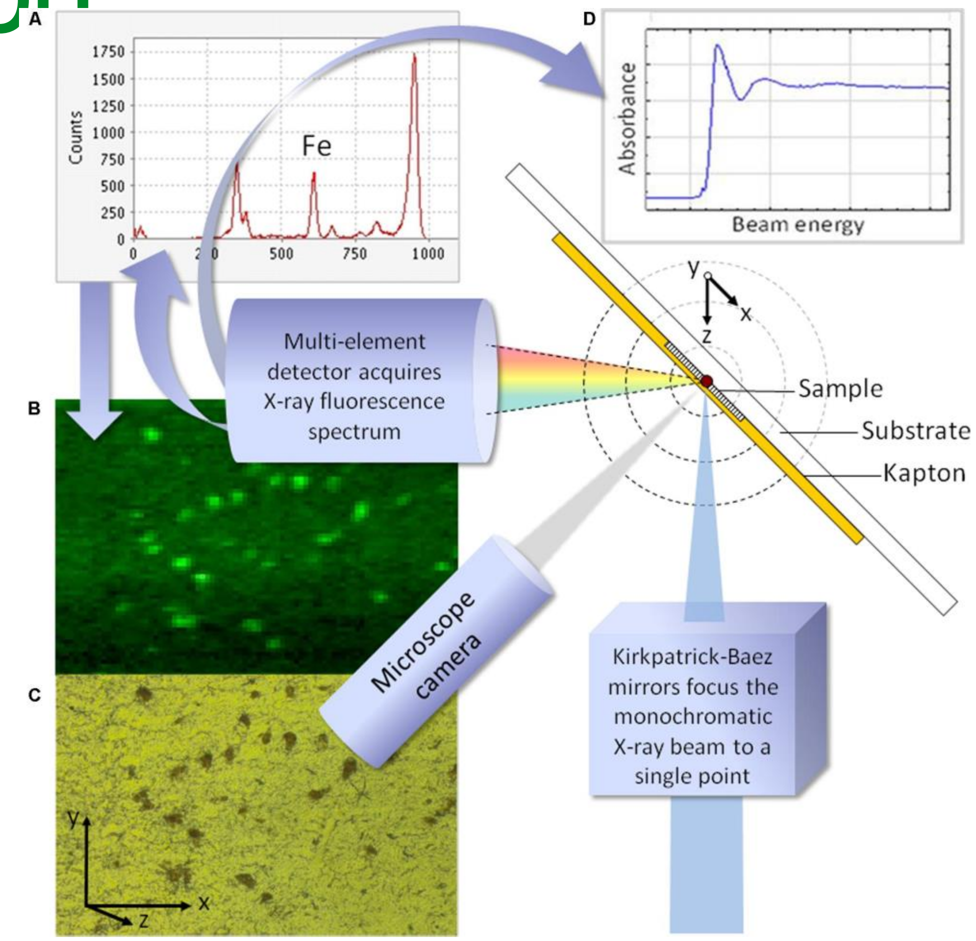
Neutral CeO_2



Negatively charged CeO_2

Expose plants hydroponically to 20 ppm CeO_2 NPs





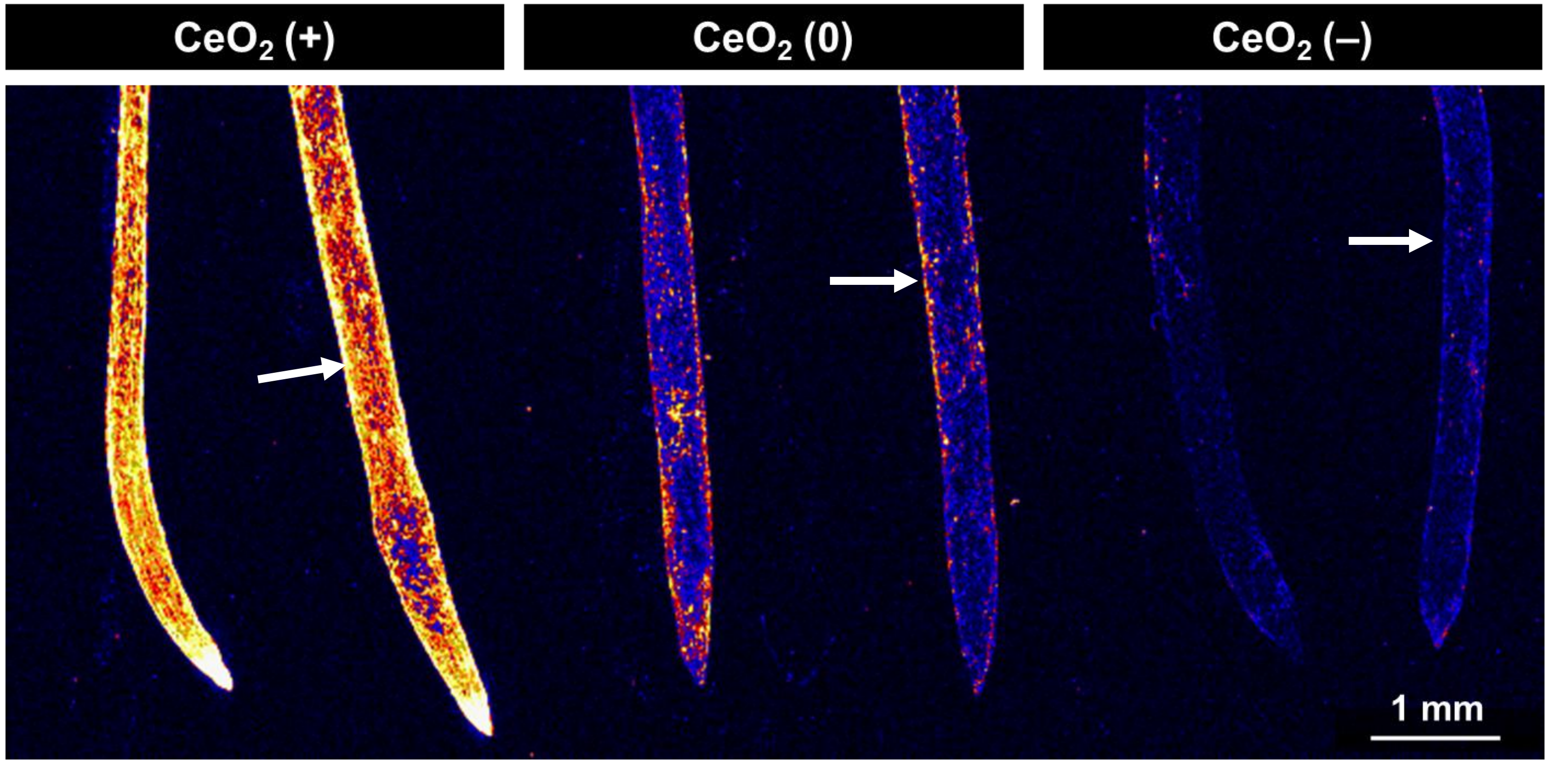
μ-XRF & XANES mapping

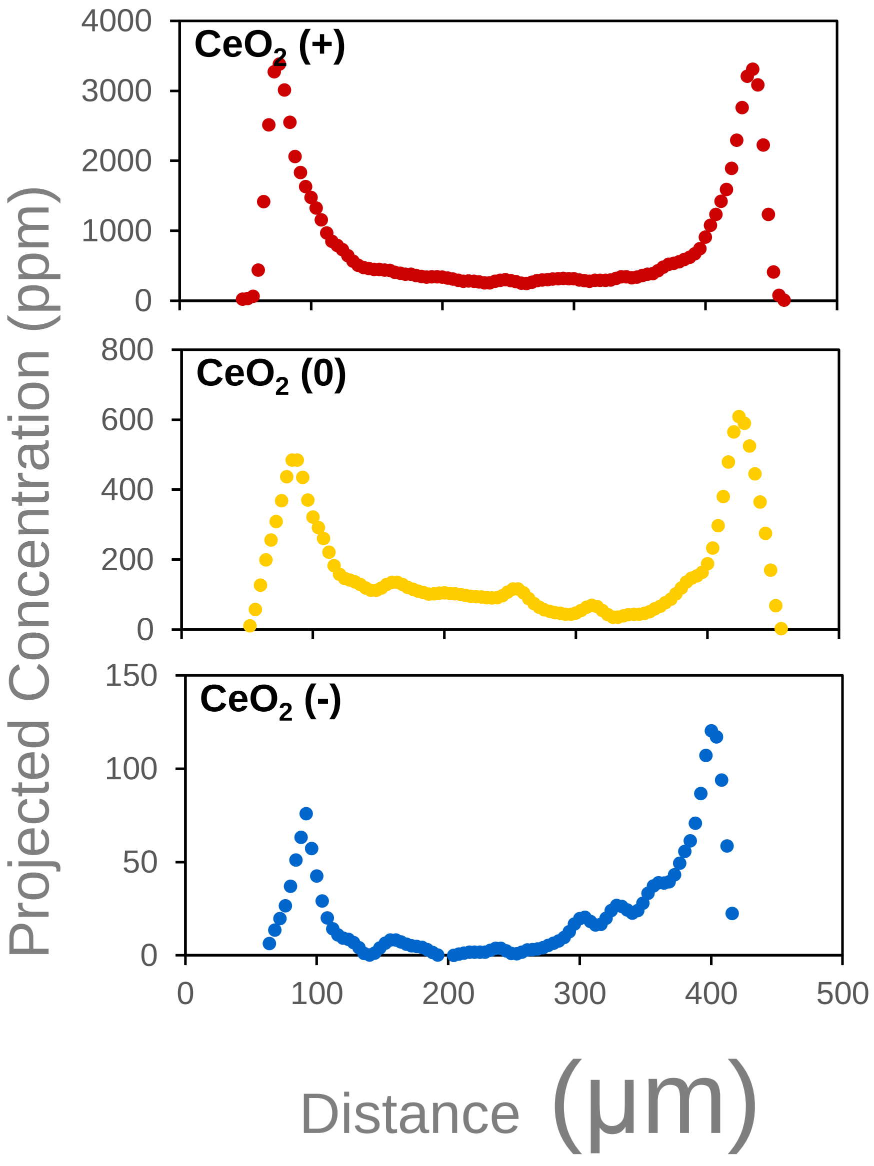
ICP-MS

Carnegie Mellon

Spielman-Sun et al., *ES&T* 51 (13) 7361

Charge affects amount of Ce on roots, but not its distribution





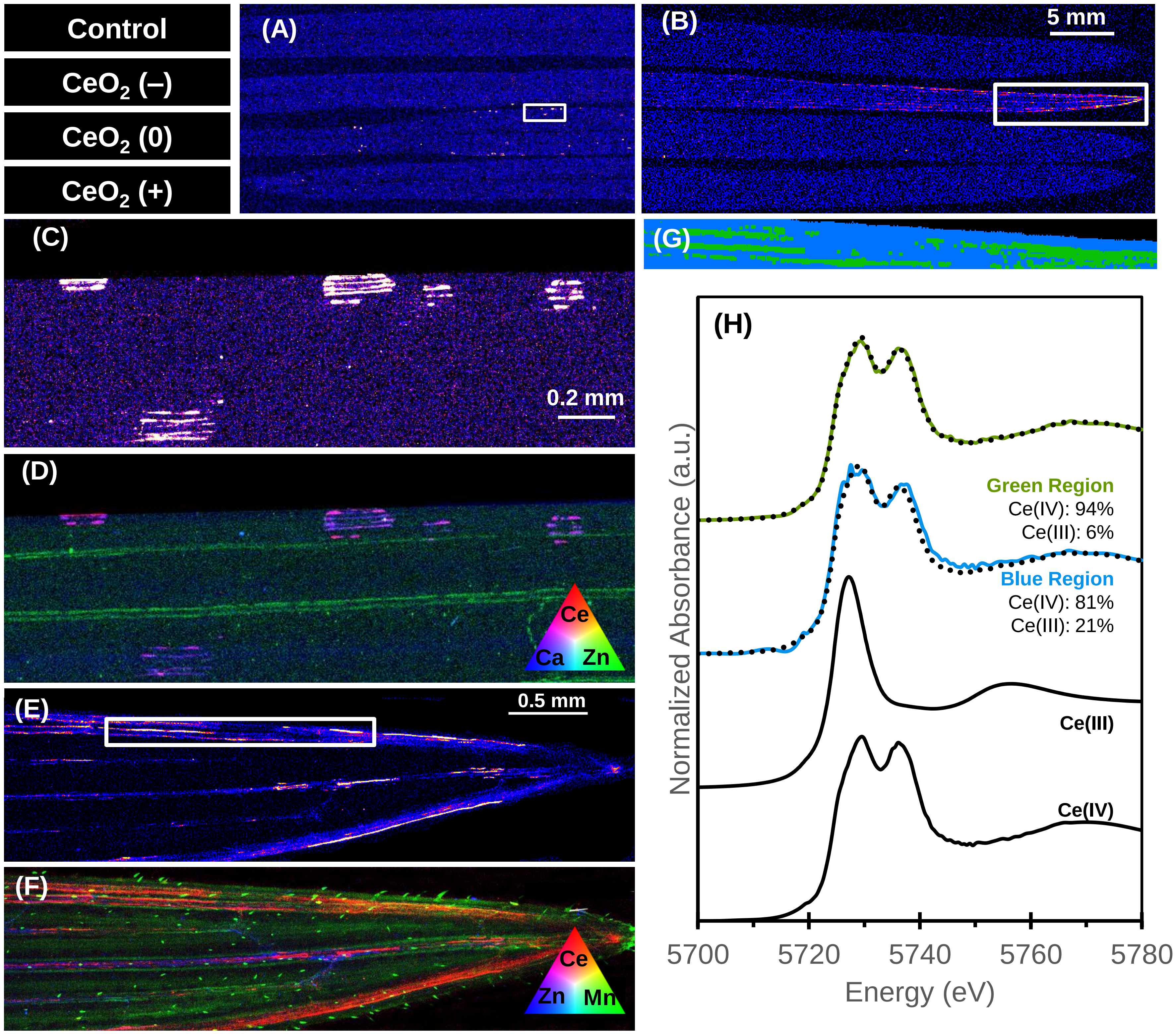
Spielman-Sun et al., *ES&T* 51 (13) 7361

Carnegie Mellon

Charge affects distribution of Ce in leaves

neutral

negative

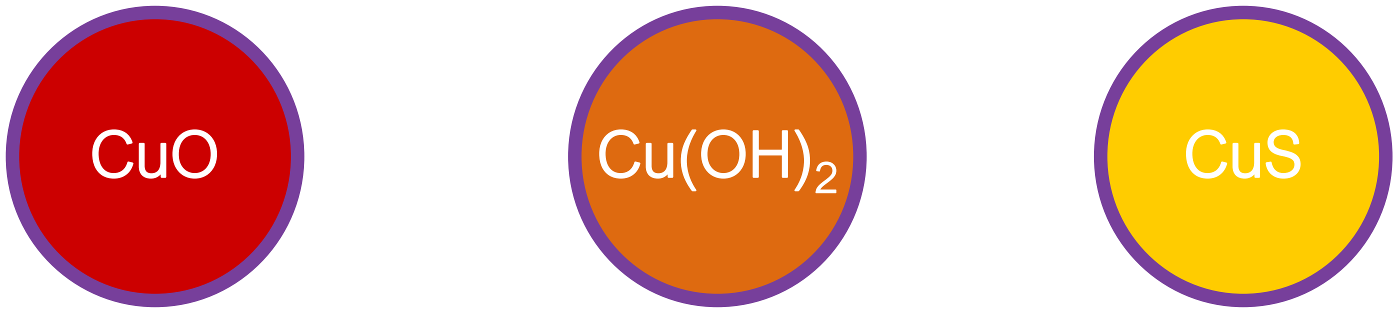


Carnegie Mellon

Spielman-Sun et al., *ES&T* 51 (13) 7361

Effect of Solubility on NP Interactions with Wheat Plants

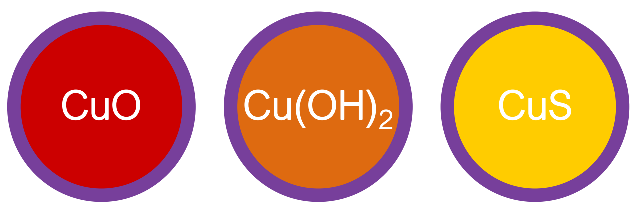
- Can the solubility of a NP be manipulated to provide long-term delivery of metal nutrients and/or fungicide?



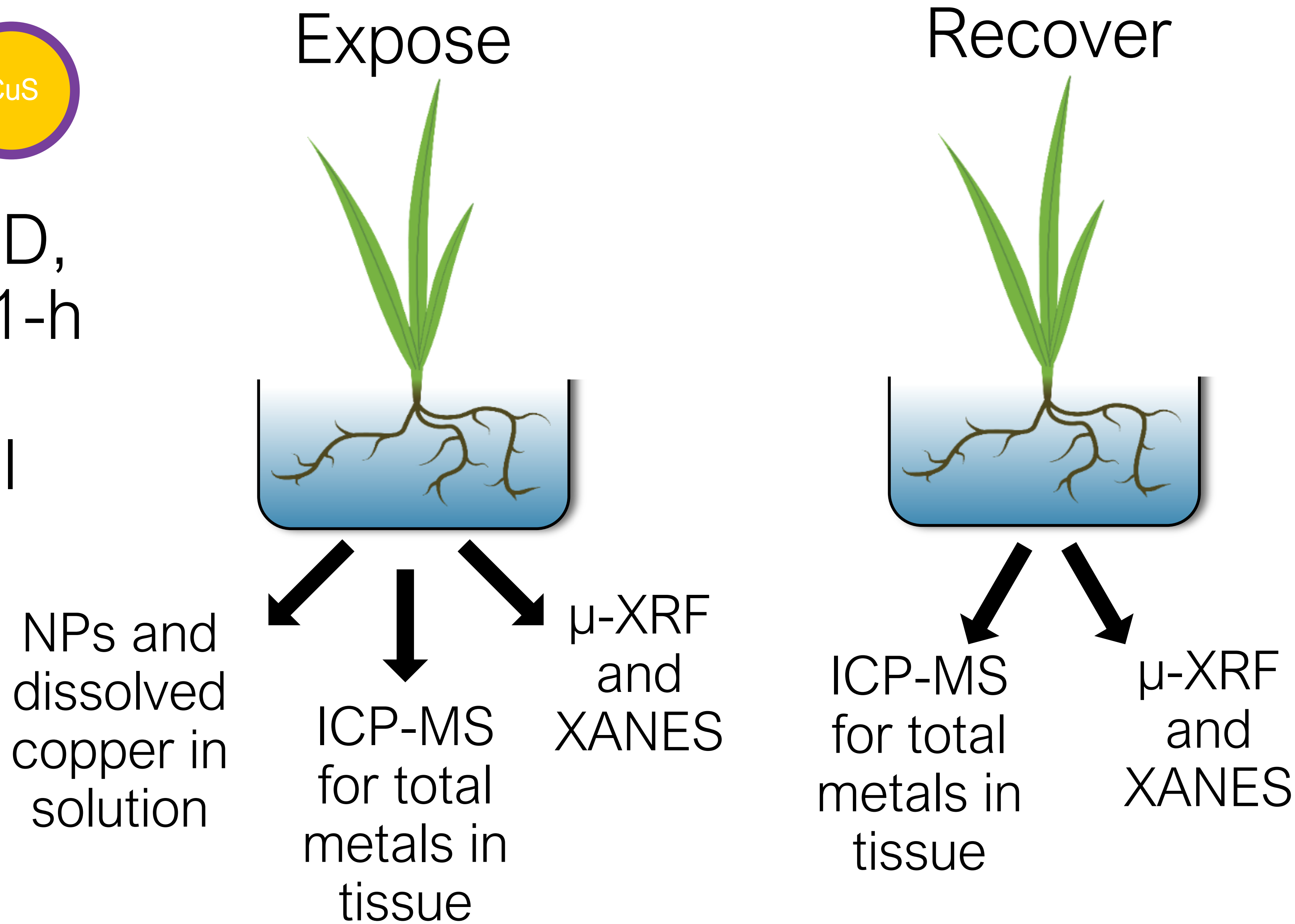
Carnegie Mellon

Experimental Design

Synthesize and characterize NPs → Expose plants to **1 ppm-Cu for 1 h** → Allow plants to **recover** in Cu-free solution



XANES, XRD, TEM, DLS, 1-h solubility, ζ-potential

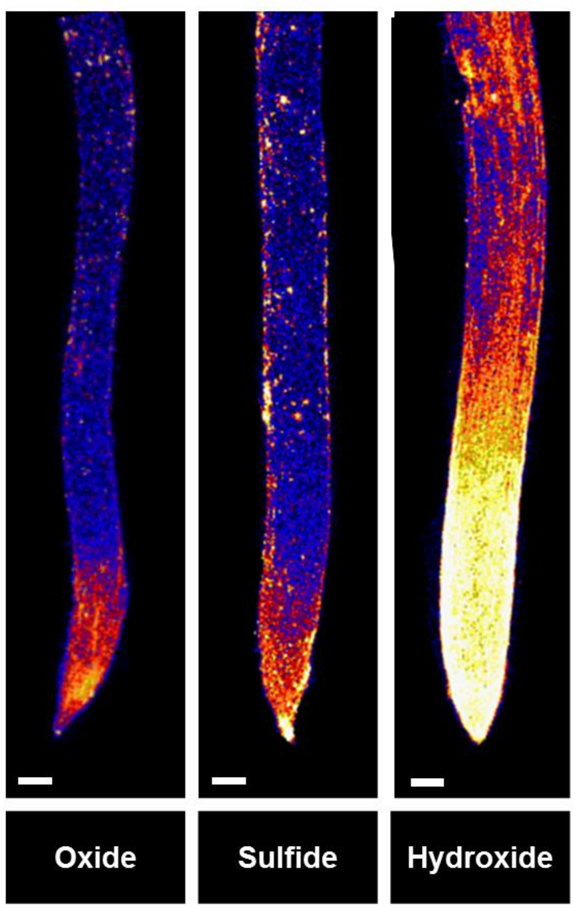


Carnegie Mellon

Spielman-Sun, *ES Nano* (in preparation)

Cu XRF Images of Wheat Roots Exposed to 1ppm Cu-based NPs

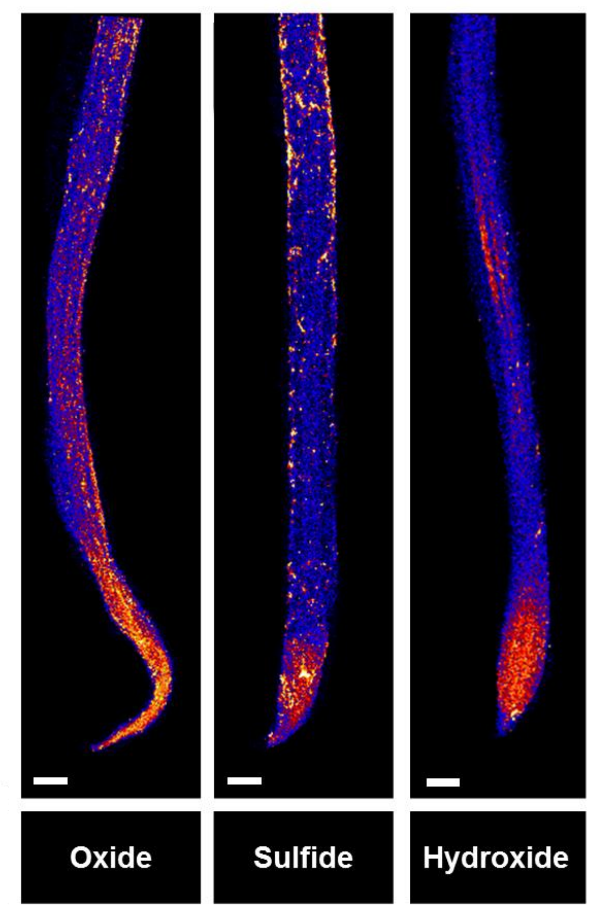
1 H EXPOSURE



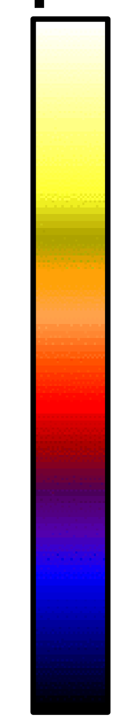
Increasing solubility

recovery

48 H RECOVERY SOLUTION



225 ppm



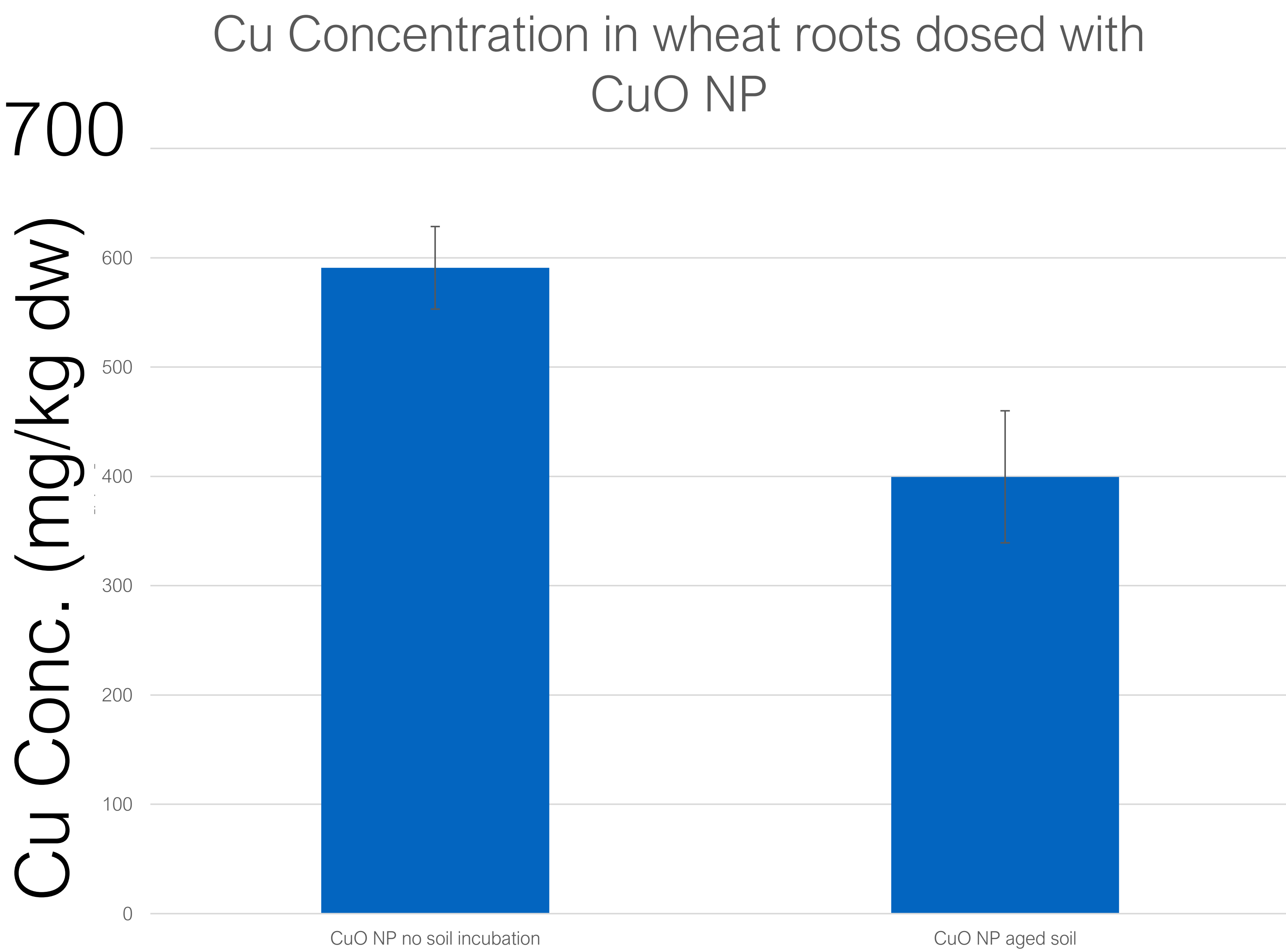
0 ppm

Scale bar=200 μm

Carnegie Mellon

Spielman-Sun, *ES Nano* (in preparation)

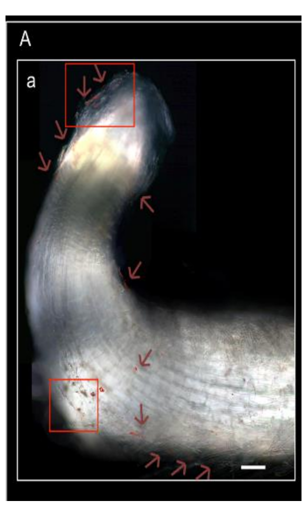
NPs increase Cu availability to wheat



Planted after no incubation

Planted after 30d incubation of CuO NPs in soils

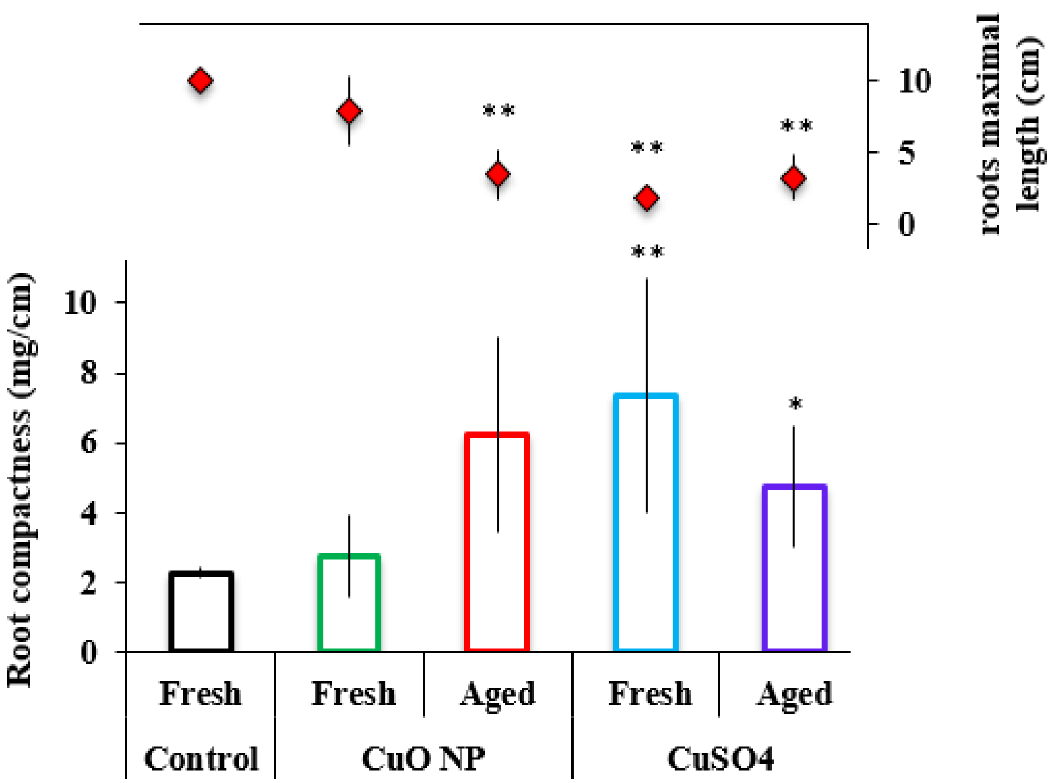
NPs associate with or are affected by plant roots to some degree

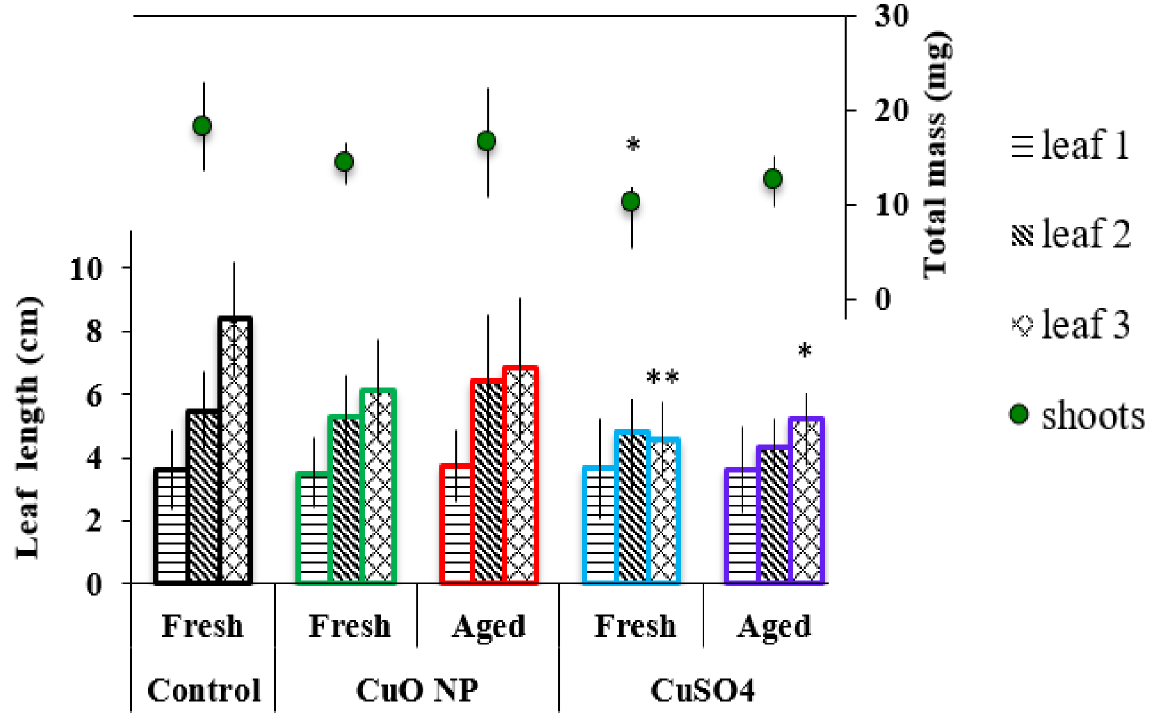


Carnegie Mellon

Gao et al *ES&T* (in preparation)

CuO NPs are LESS toxic to plants than $CuSO_4$





CuO NPs=500 ppm
$CuSO_4$=100 ppm

Carnegie Mellon

Gao et al *ES&T* (in preparation)

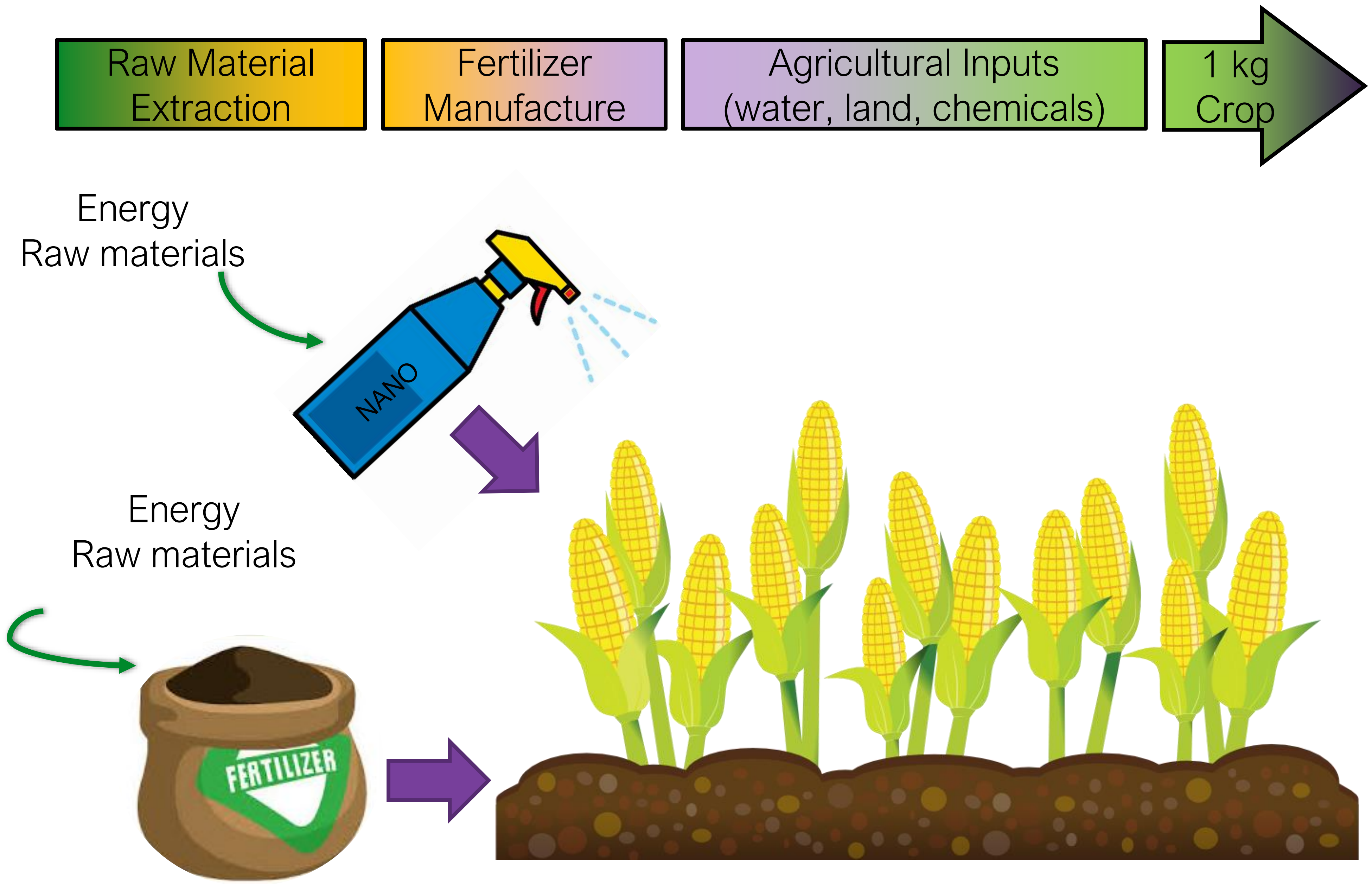
Summary

- Tremendous opportunities for ENMs in agriculture
  - Water, efficiency, soils, resilience
  - Make sure ENM solutions beat the alternatives
- Properties of ENMs can be controlled to provide
  - Targeted delivery
  - Roots and foliar
- Safety concerns will need to be addressed
  - Grower and consumer perceptions

- Soil-less
- Nutrient Delivery
- Nutrient Recovery
- Disease management

Carnegie Mellon

Cradle-to-Gate Lifecycle Assessment (LCA) and Technoeconomic Analysis



?

Which nano opportunities provide the most environmental life cycle benefits?

Carnegie Mellon

LC nano

Questions??

NSF

CBET-1541807
EF-1266252

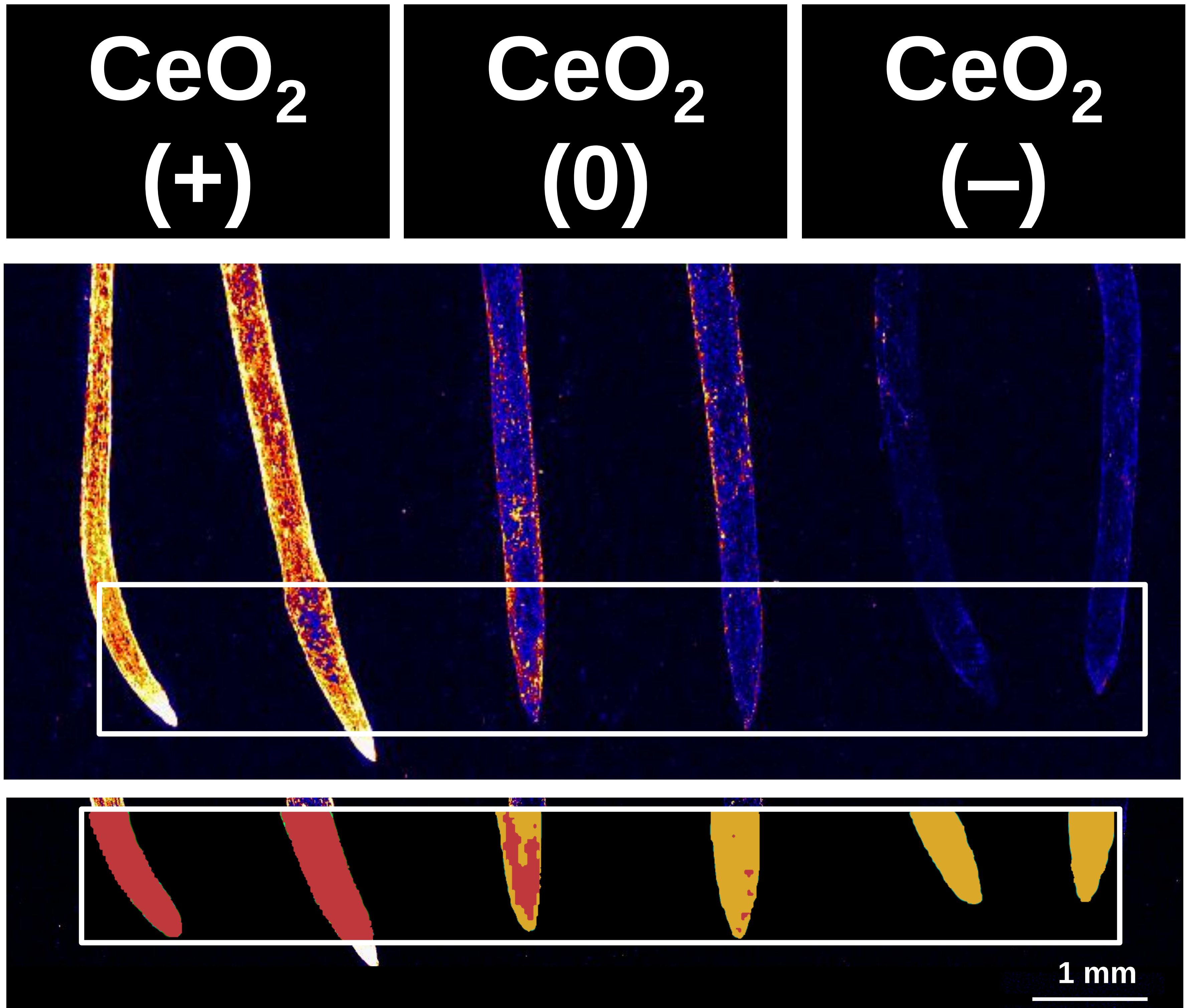
Australian Synchrotron
Turning bright ideas into brilliant outcomes

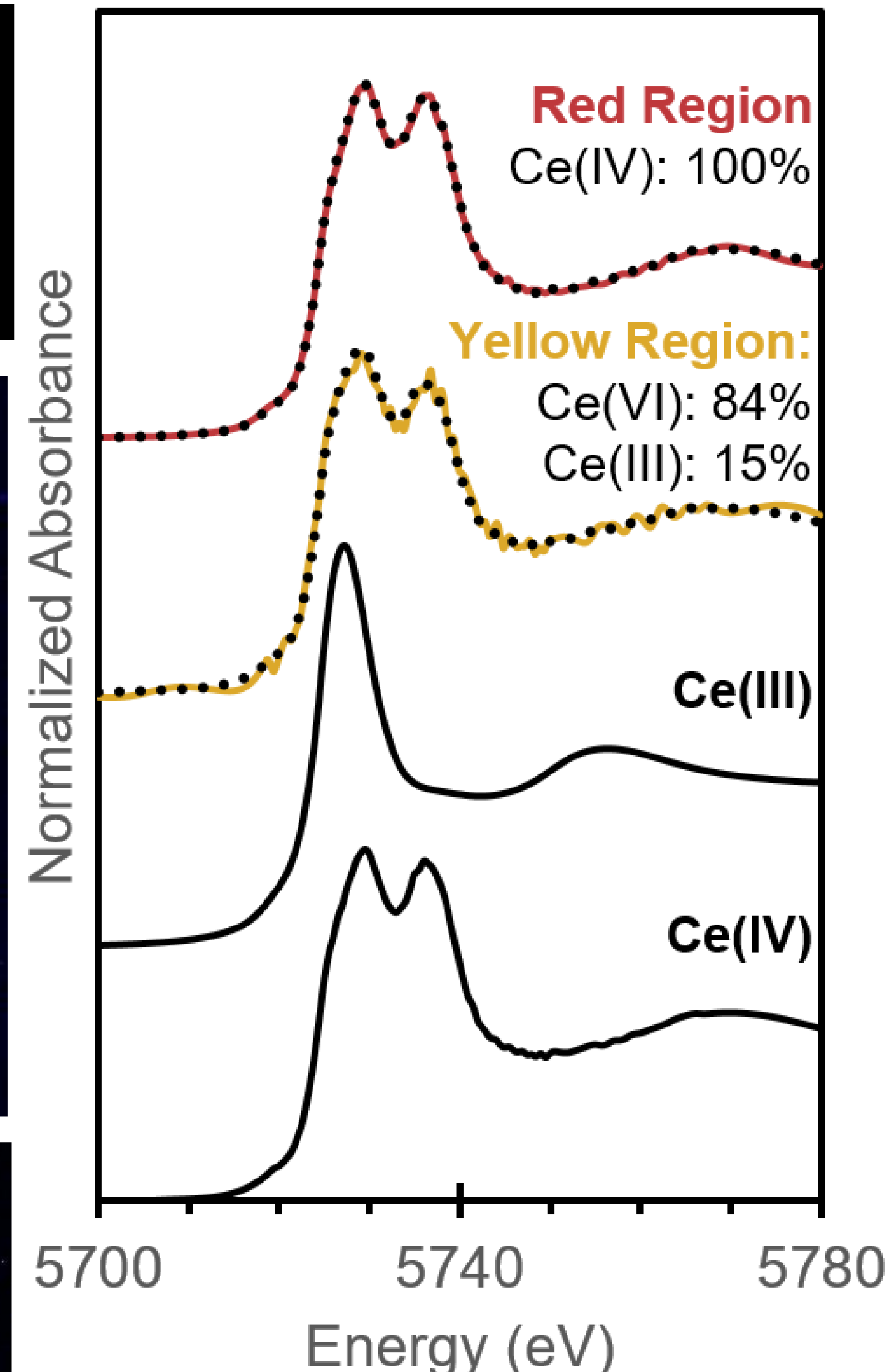
Carnegie Mellon

CEINT

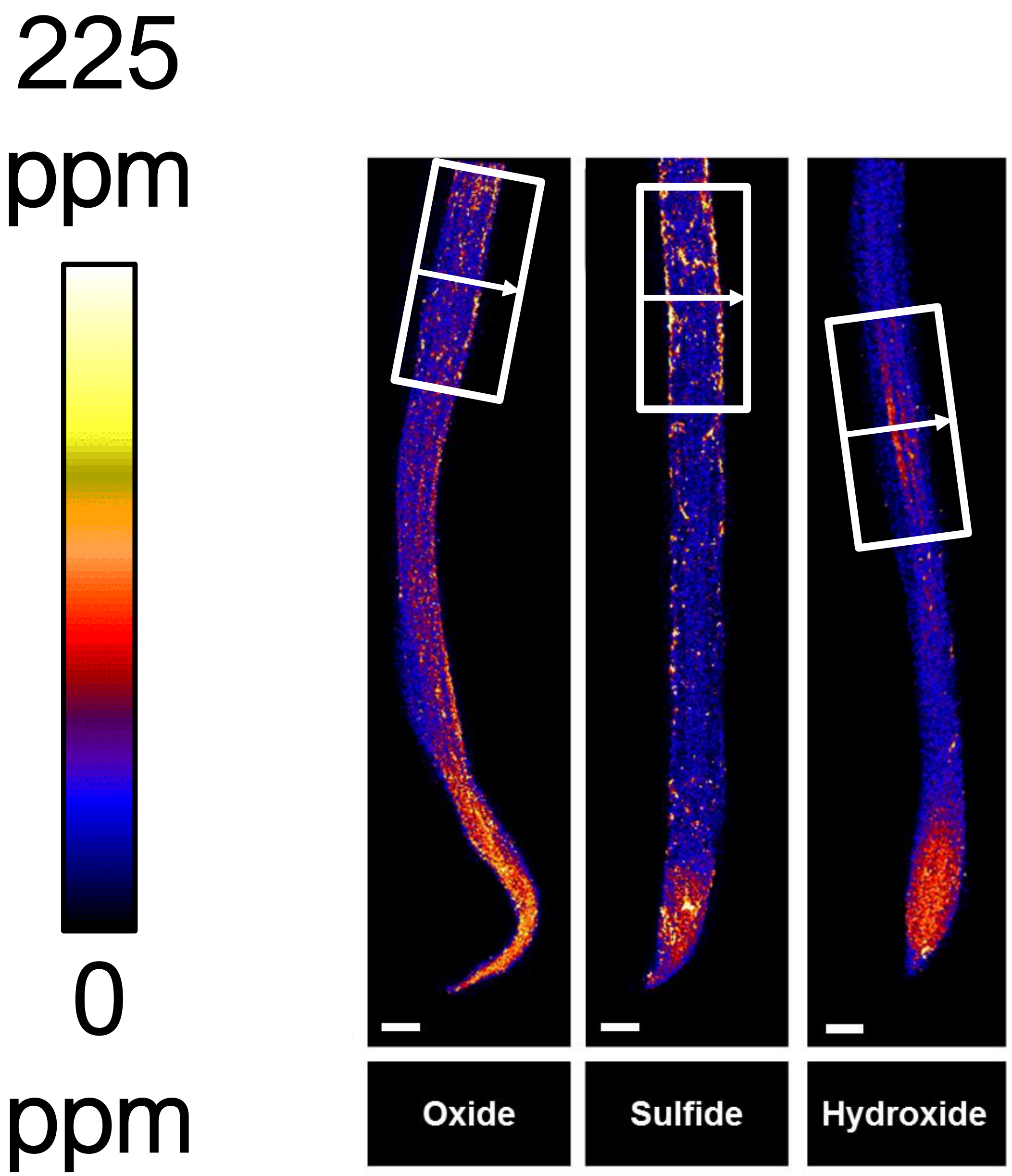
nano FARM

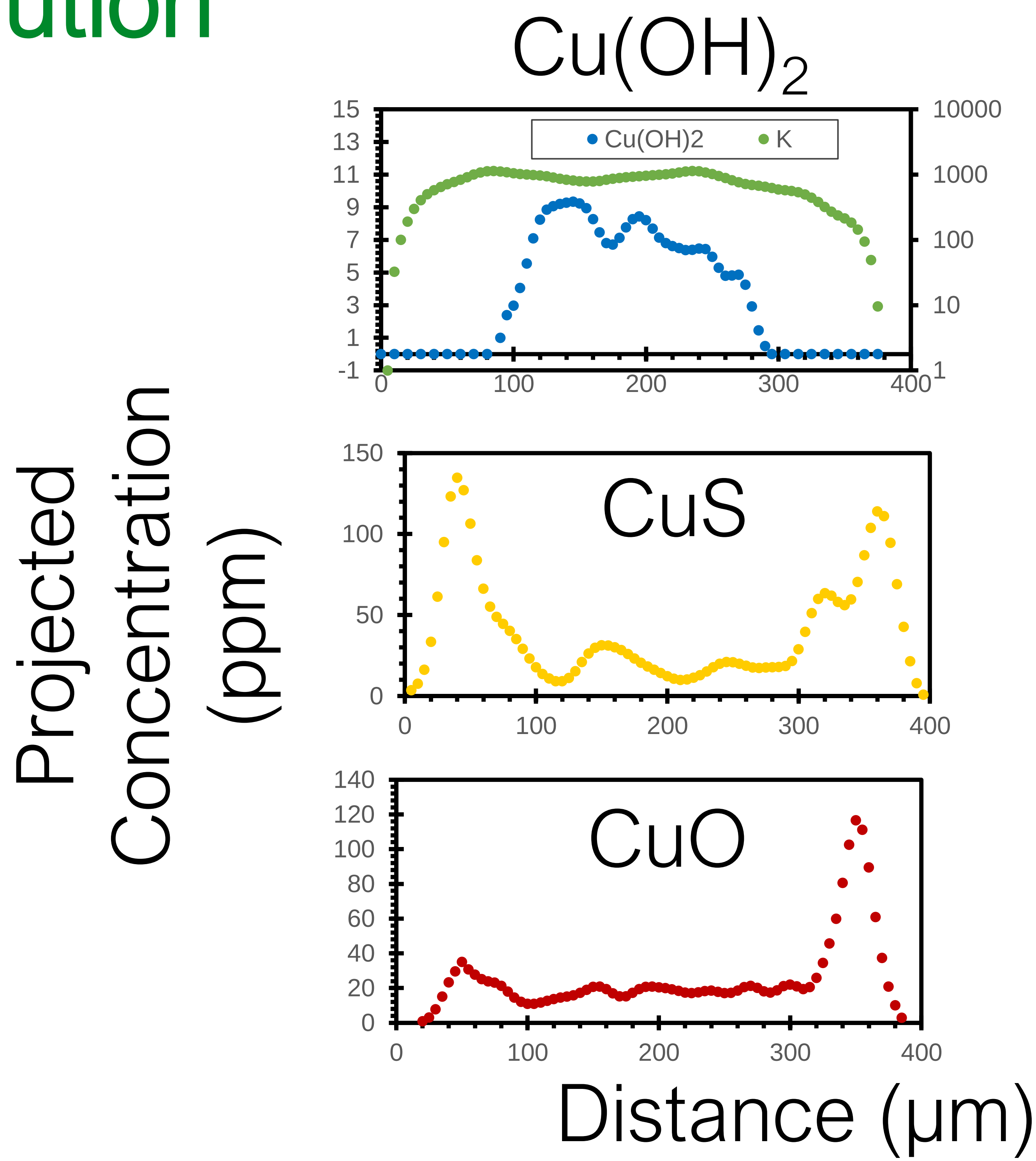
Ce XRF Maps after 34h Exposure to CeO_2 NPs





Cu distribution after 48 h Recovery in Cu-free Solution

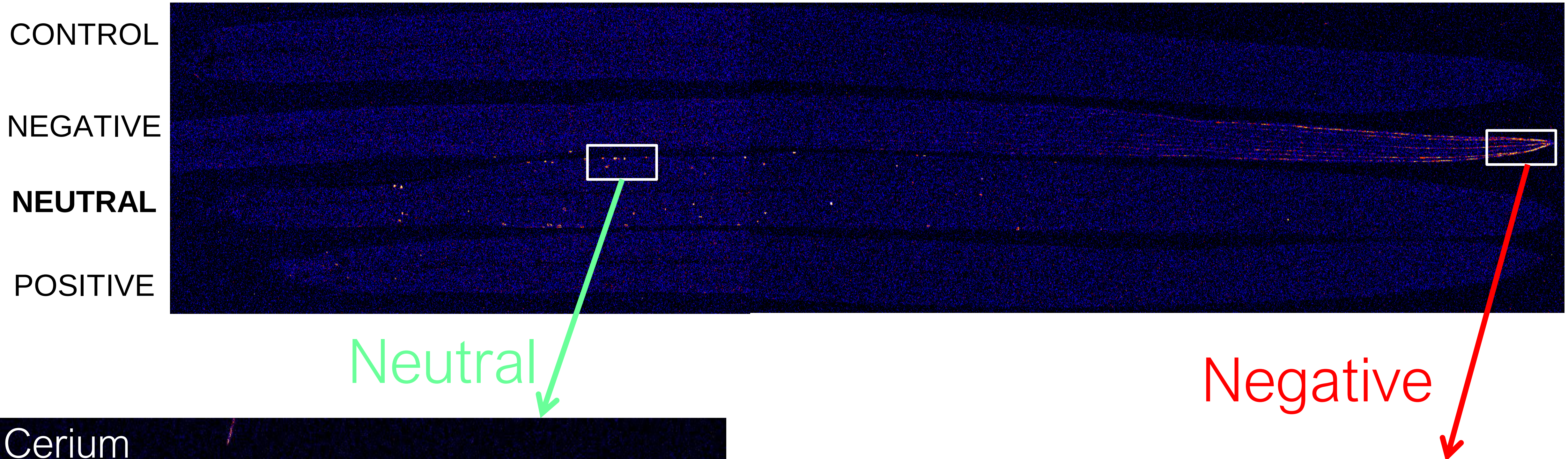


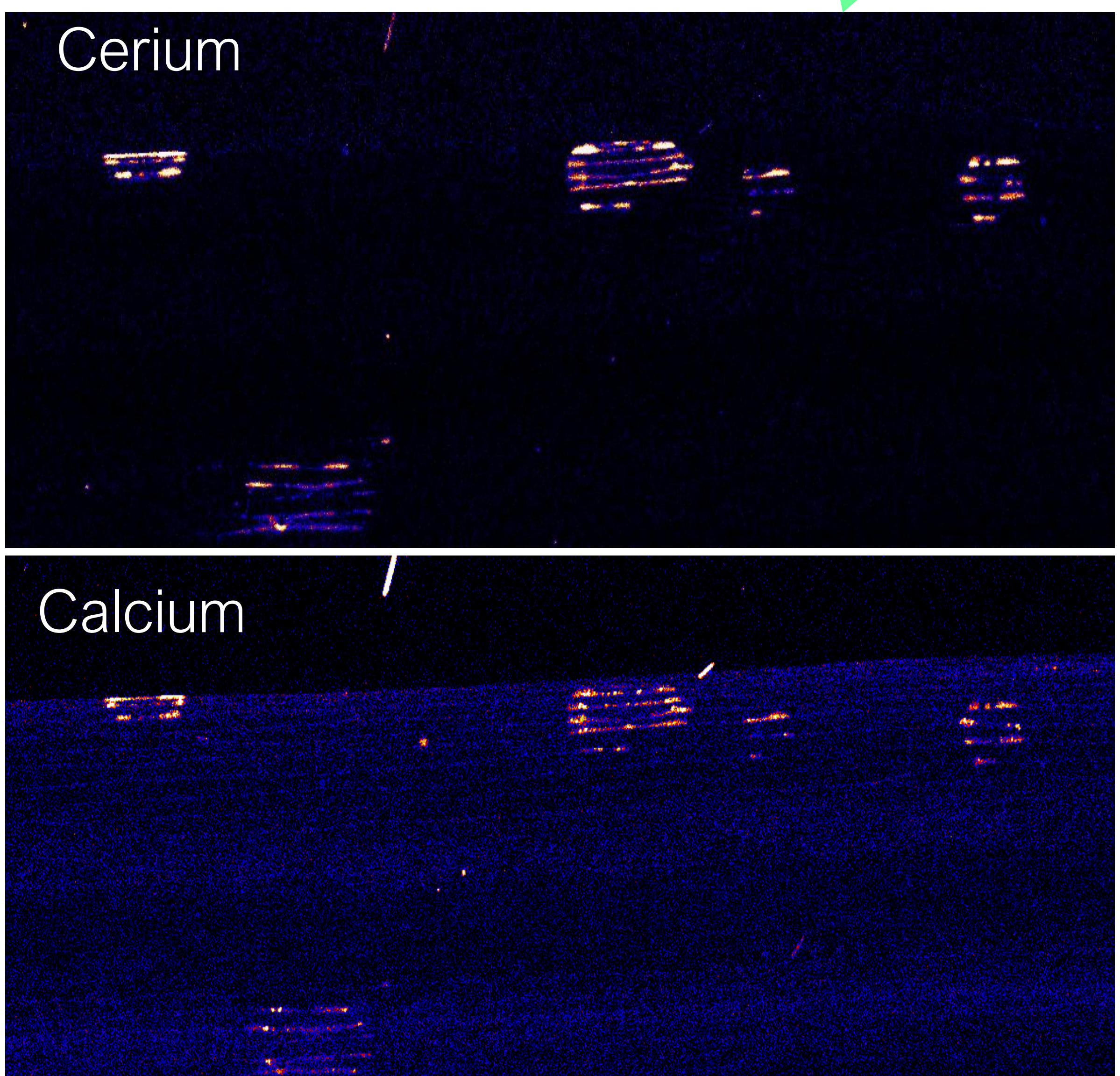


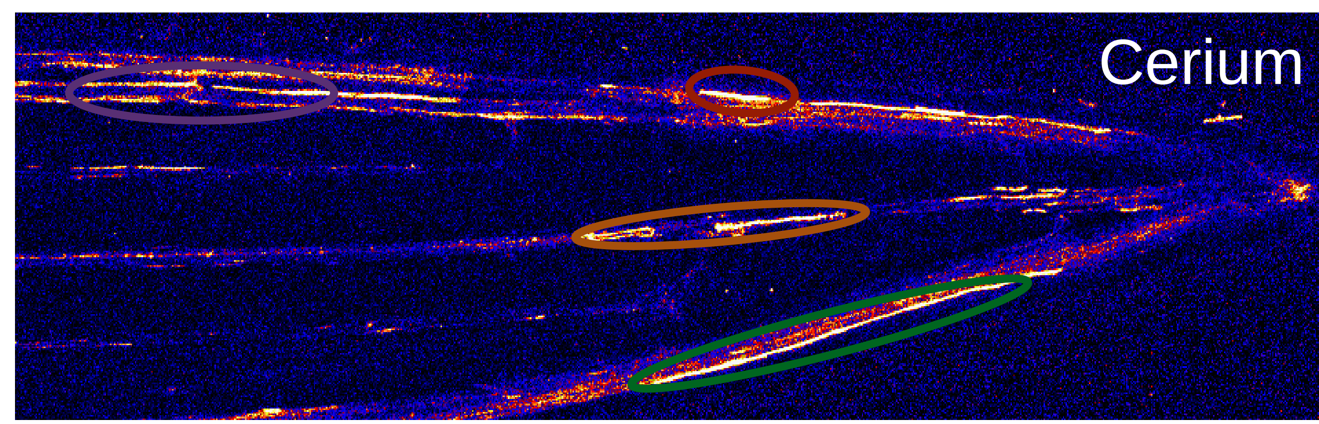
Carnegie Mellon

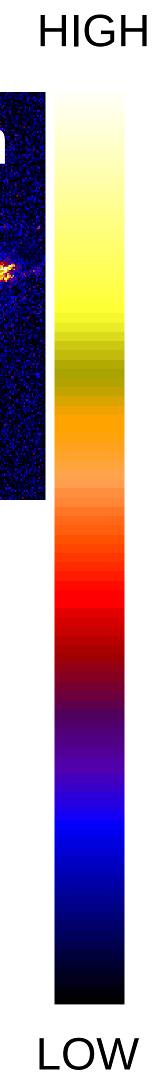
Spielman-Sun, *ES Nano* (in preparation)

Charge on CeO_2 NPs affects translocation pathways









Charge can be manipulated to deliver NPs to different places in the leaves