Investigating impacts of engineered nanoparticles on food safety & quality

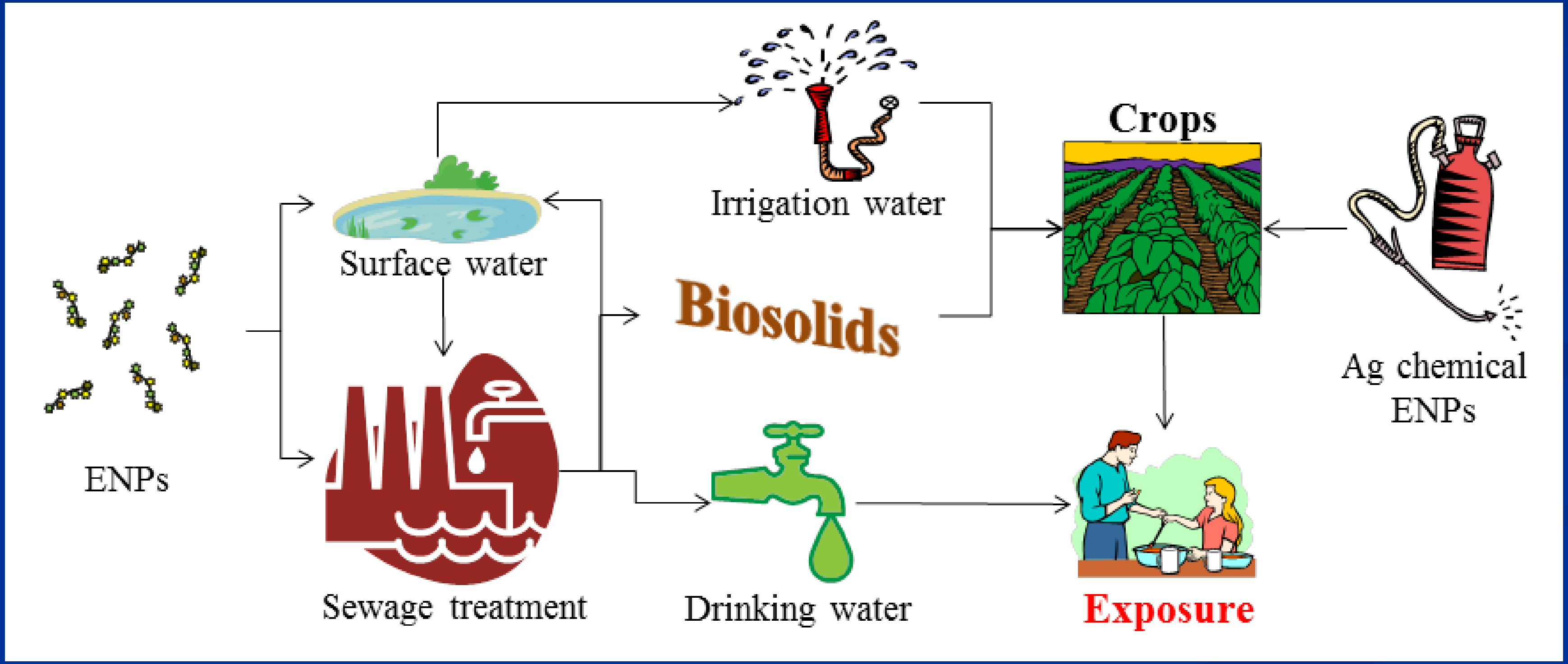
Stephen Ebbs[1], Scott Bradfield[1], Pawan Kumar[1], Weilan Zhang[2], Jason White[3] and Xingmao Ma[2]

[1] Dept. of Plant Biology Southern Illinois Univ.
[2] Dept. of Civil & Environ. Eng., Southern Illinois Univ.
[3] Dept. of Analytical Chemistry, The Conn. Ag. Expt. Station

Nano-research in the Ebbs Lab

- Primary emphasis on metal and metal oxide nanoparticles
- Plant nanotoxicology
- Nanoparticles, food safety, & food quality
- Beneficial applications of nanomaterials for plant & crop production

Potential pathways for nanoparticle entry into plant foods



Nanoparticles, food safety, & food quality

- Belowground vegetables and tubers grown in direct contact with the soil will have a higher concentration than other plant foods.

- Quantitative data on dietary exposure is needed to assess risks (or benefits?) to human health.

- Nanoparticle metals could compromise safety or could improve micronutrient density and/or quality.

Nanoparticle exposure studies

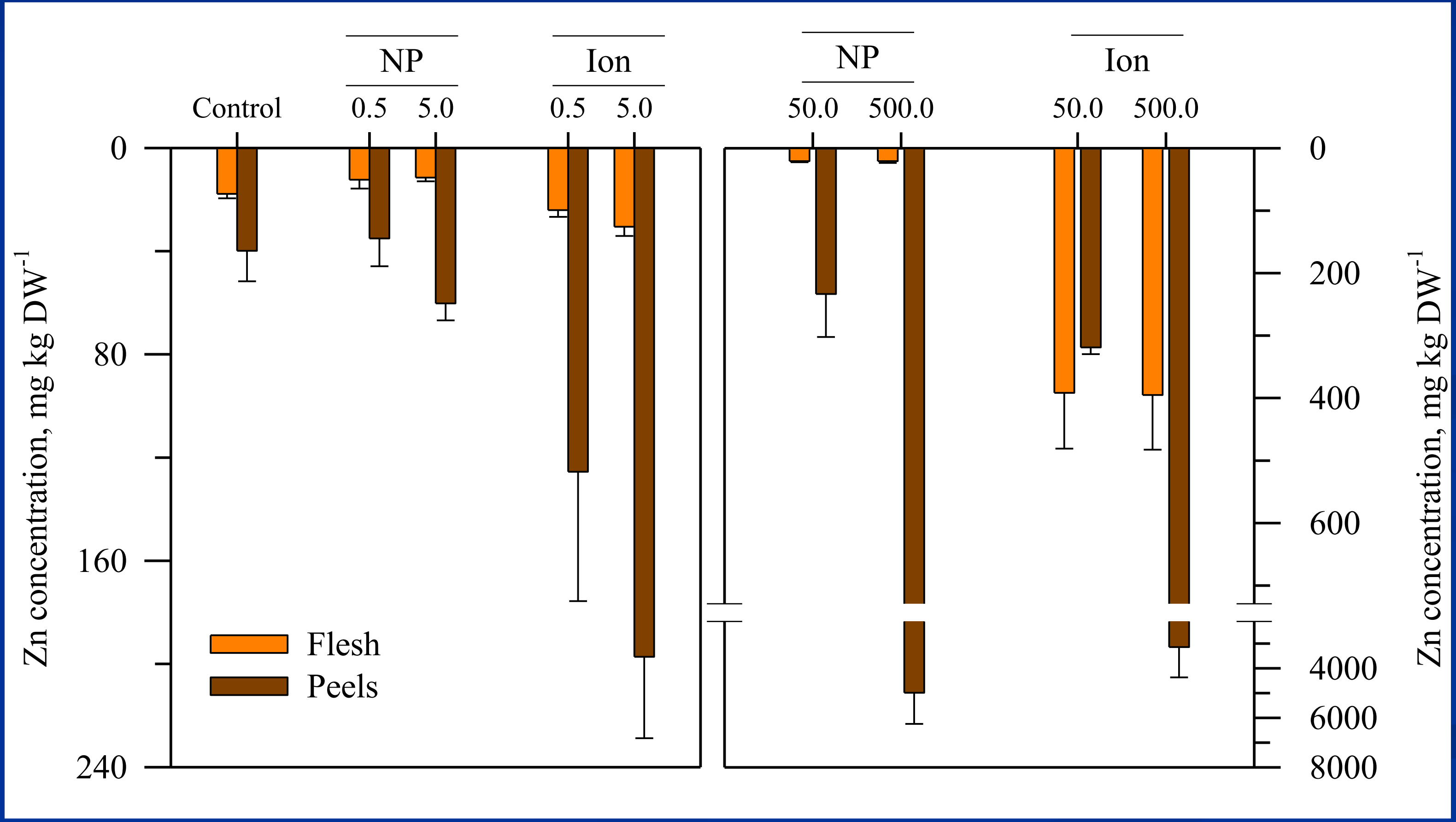
- Plants germinated and grown in sand, soil, or hydroponic cultures containing NPs

- Harvest at or near maturity, process (e.g., typical food prep), and analyze for metal.

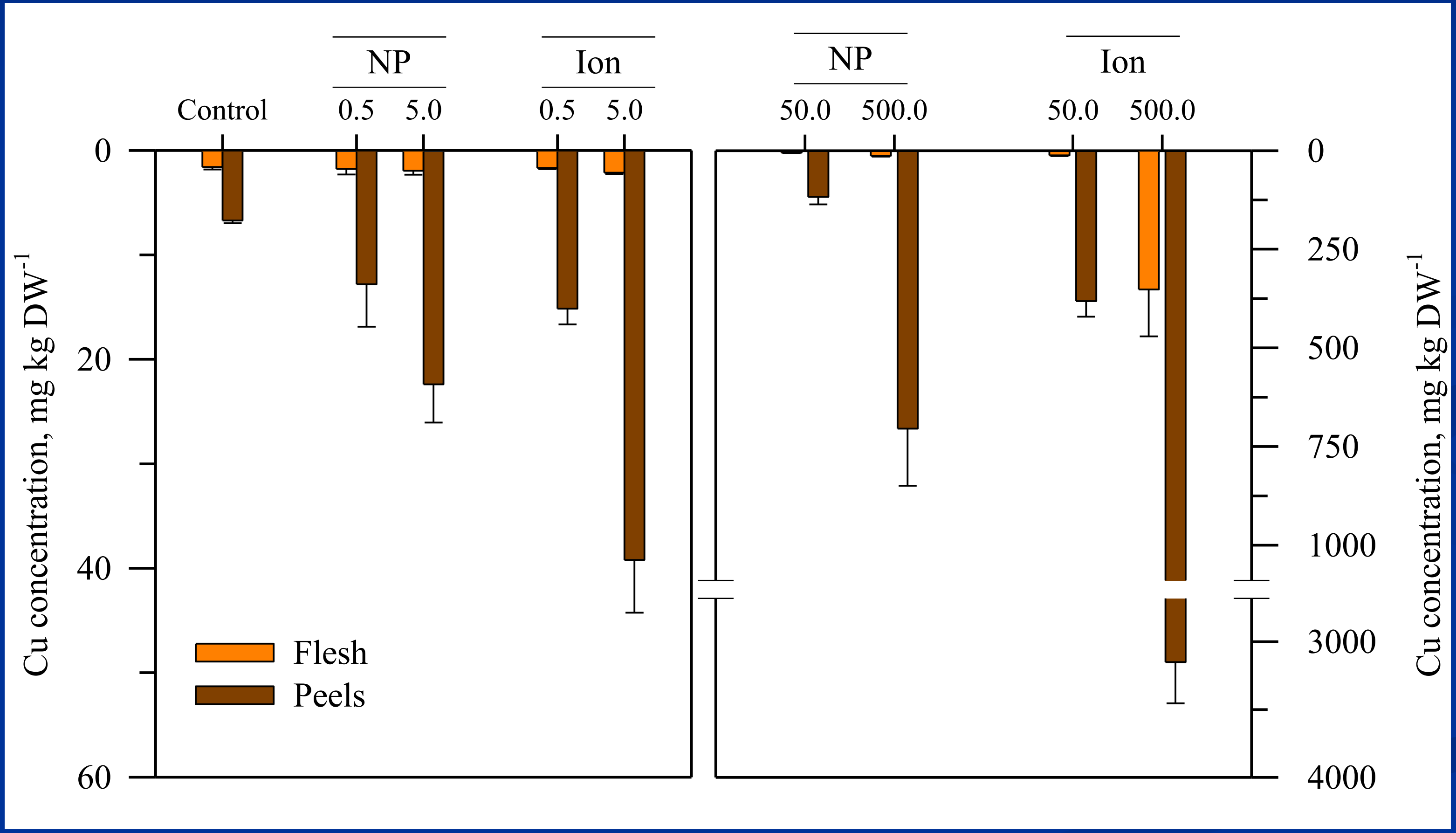
Carrot as a model for concentration-dependent NP penetration and dietary exposure modeling

- Carrots grown in sand culture and treated with an NP and the ionic counterpart
  - Copper (CuO or $CuSO_4$)
  - Cerium (CeO_2 or $CeSO_4$)
  - Zinc (ZnO or $ZnSO_4$)
- Harvest, peel with common kitchen peeler, and analyze for element of interest.
- Develop age-mass dietary exposure models.

Accumulation of Zn in carrot tissues from watering with ZnO NPs or with ionic Zn



Accumulation of Cu in carrot tissues from watering with CuO NPs or with ionic Cu



Results

- Accumulation from the ionic form of Cu or Zn was generally greater than for the NP form.
- There was greater accumulation in the peels than in the flesh of the carrot.
- Cu or Zn from the nanoparticle accumulated primarily in the peel, but not in the flesh.
- Cu or Zn from the nanoparticle decreased in flesh at the higher concentrations.

Dietary exposure Cu or Ce scenarios: Unpeeled v. peeled fresh carrot

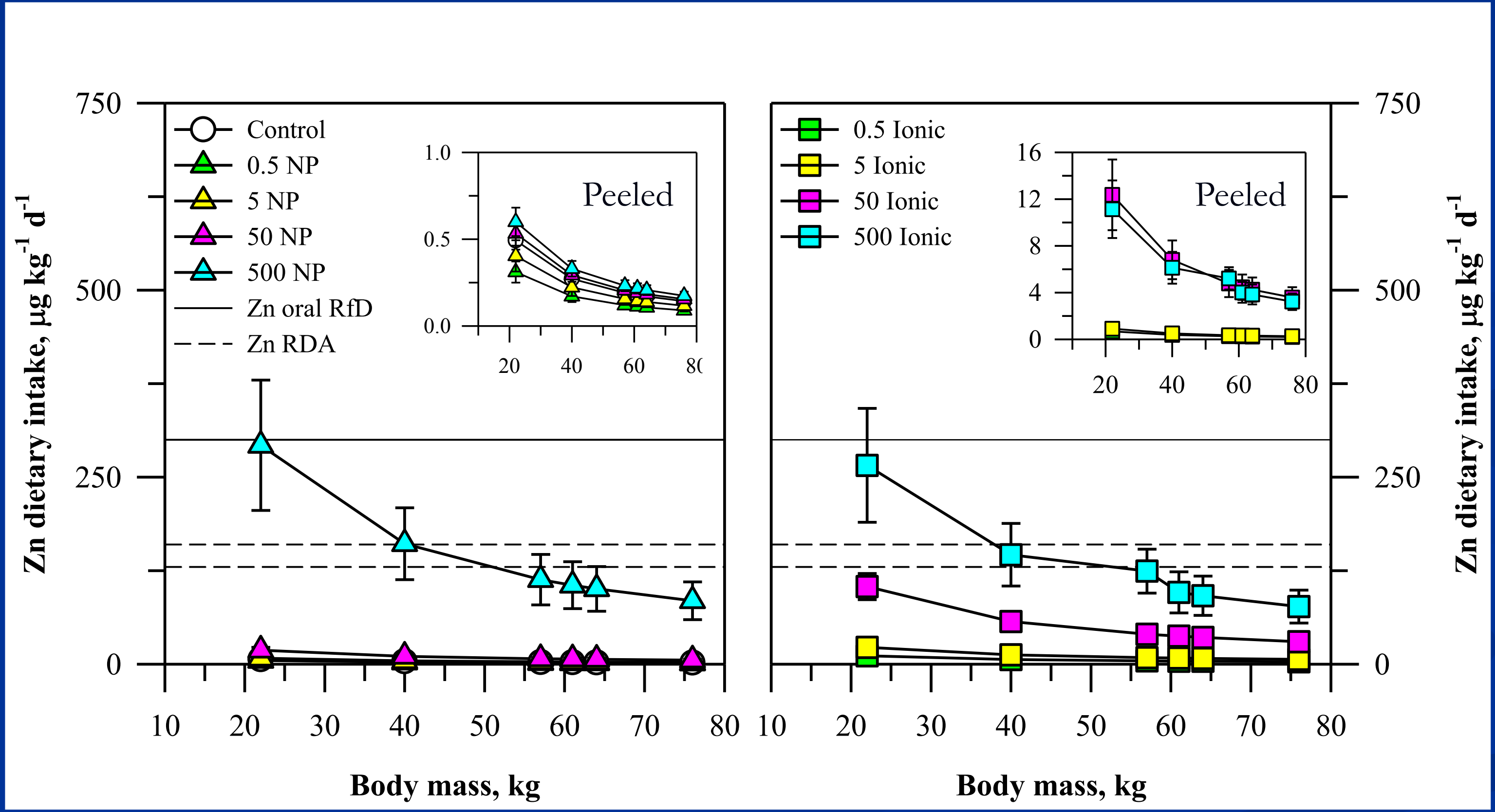
- Scenario: Consumption of one serving of fresh carrot across six age-mass classes, child to adult.

- Four possible fresh carrot tissues for each metal:
  - Unpeeled carrot, treated with ionic Cu^{2+} or Ce^{4+}
  - Unpeeled carrot, treated with NP CuO or CeO_2
  - Peeled carrot, treated with ionic Cu^{2+} or Ce^{4+}
  - Peeled carrot, treated with NP CuO or CeO_2

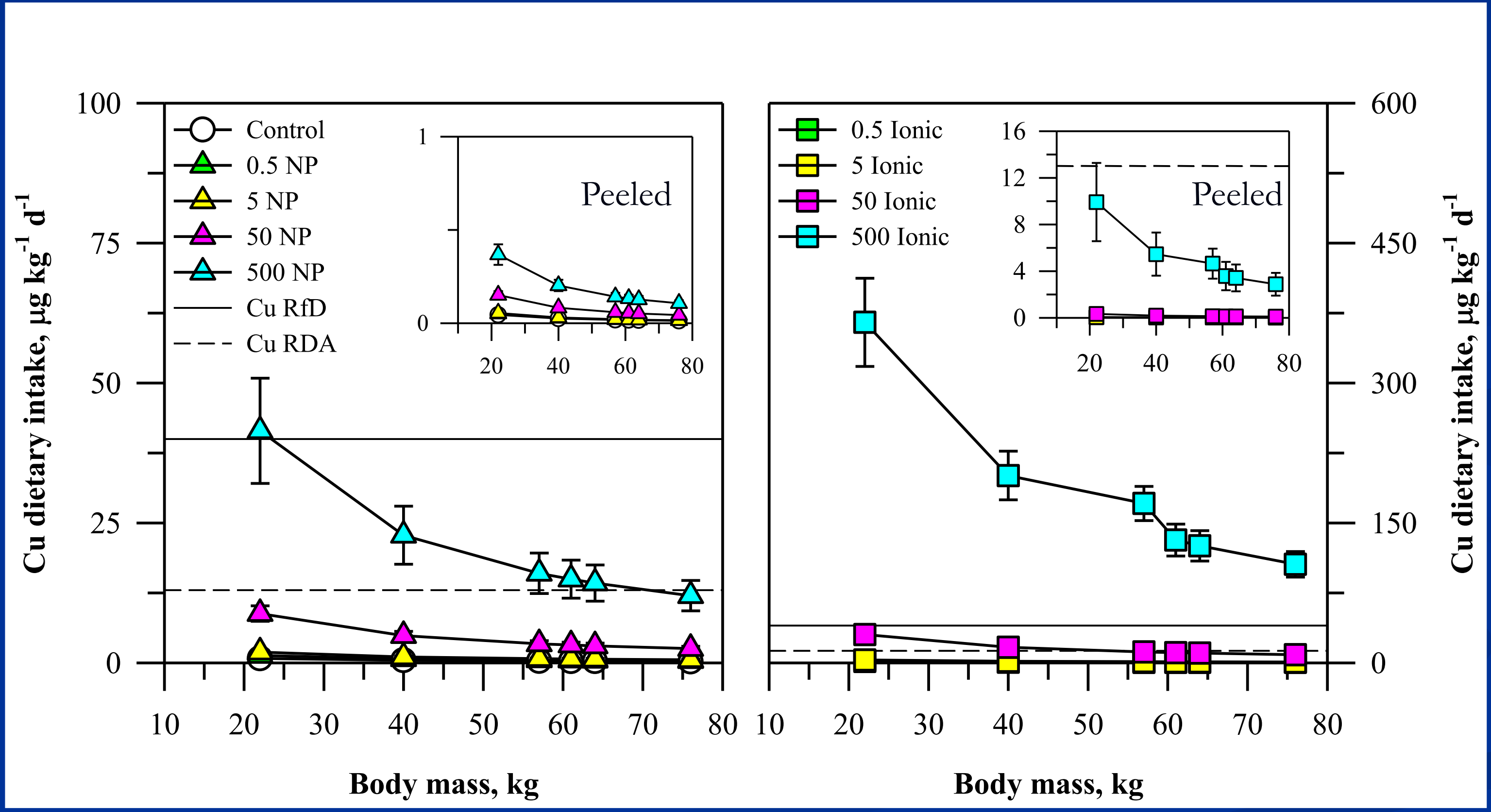
Dietary exposure Cu or Ce scenarios: Unpeeled v. peeled fresh carrot

- Dietary intake was calculated and expressed on a $\mu g\ kg^{-1}\ d^{-1}$ basis.
- Data obtained compared to reference values:
  - Oral reference dose (Oral RfD)
  - Recommended daily allowance (RDA)
- These example do not incorporate bioaccessibility or absorption in the GI tract.

Projected dietary intake of Zn from consumption of carrot



Projected dietary intake of Cu from consumption of carrot



Reverse-modeling of dietary intake

- Based on the models developed, we can back-calculate for each age-mass class:
  - The number of servings needed to reach the oral RfD
  - The mass of fresh carrot that would have to be consumed to reach the oral RfD
  - The fresh weight tissue concentration necessary to reach the oral RfD

How many servings per day to reach oral RfD for Zn of 300 µg kg^{-1} d^{-1}

		Treatment, concentration (mg kg^{-1} DW) and form (NP or Ion)							
UNPEELED	**Body mass, (kg)**	**0.5 NP**	**5 NP**	**50 NP**	**500 NP**	**0.5 Ion**	**5 Ion**	**50 Ion**	**500 Ion**
age 1-3	13	44.3	24.6	11.7	1.0	18.6	12.3	1.8	0.81
age 4-8	22	75.0	41.6	19.8	1.6	31.5	20.8	3.1	1.38
age 9-13	40	136.4	75.6	36.0	2.9	57.2	37.7	5.6	2.50
F, age 14-18	57	194.4	107.8	51.3	4.2	81.5	53.8	8.0	3.03
F, age 19-30	61	208.1	115.3	54.9	4.5	87.2	57.6	8.6	3.82
M, age 14-18	64	218.3	121.0	57.6	4.7	91.5	60.4	9.0	4.00
M, age 19-30	76	259.2	143.7	68.4	5.6	108.6	71.7	10.7	4.76
PEELED									
age 1-3	13	643.9	517.1	359.3	330.8	267.3	211.9	14.3	19.4
age 4-8	22	1089.6	875.0	608.0	559.8	452.4	358.5	24.1	32.8
age 9-13	40	1981.1	1590.9	1105.5	1017.7	822.5	651.9	43.9	59.6
F, age 14-18	57	2823.1	2267.1	1575.4	1450.3	1172.1	928.9	62.5	72.2
F, age 19-30	61	3021.2	2426.2	1685.9	1552.1	1254.4	994.1	66.9	90.8
M, age 14-18	64	3169.7	2545.5	1768.8	1628.4	1316.1	1043.0	70.2	95.3
M, age 19-30	76	3764.1	3022.8	2100.5	1933.7	1562.8	1238.5	83.4	113.1

How much fresh carrot (in kg) to consume to reach oral RfD for Zn of 300 µg kg^{-1} d^{-1}

		Treatment, concentration (mg kg^{-1} DW) and form (NP or Ion)							
UNPEELED	**Body mass, (kg)**	**0.5 NP**	**5 NP**	**50 NP**	**500 NP**	**0.5 Ion**	**5 Ion**	**50 Ion**	**500 Ion**
age 1-3	13	2.7	1.5	0.7	0.06	1.2	0.8	0.1	0.05
age 4-8	22	4.7	2.6	1.2	0.10	1.9	1.3	0.2	0.09
age 9-13	40	8.5	4.7	2.2	0.18	3.5	2.3	0.4	0.16
F, age 14-18	57	12.1	6.7	3.2	0.26	5.1	3.3	0.5	0.19
F, age 19-30	61	12.9	7.2	3.4	0.28	5.4	3.6	0.5	0.24
M, age 14-18	64	13.5	7.5	3.6	0.29	5.7	3.7	0.6	0.25
M, age 19-30	76	16.1	8.9	4.2	0.35	6.7	4.4	0.7	0.29
PEELED									
age 1-3	13	39.9	32.1	22.3	20.5	16.6	13.1	0.9	1.2
age 4-8	22	67.6	54.3	37.7	34.7	28.0	22.2	1.5	2.0
age 9-13	40	122.8	98.6	68.5	63.1	51.0	40.4	2.7	3.7
F, age 14-18	57	175.0	140.6	97.7	89.9	72.7	57.6	3.9	4.5
F, age 19-30	61	187.3	150.4	104.5	96.2	77.8	61.6	4.1	5.6
M, age 14-18	64	196.5	157.8	109.7	101.0	81.6	64.7	4.4	5.9
M, age 19-30	76	233.4	187.4	130.2	119.9	96.9	76.8	5.2	7.0

What fresh weight tissue concentration necessary to reach the oral RfD for Cu?

Age-Mass class	Body mass, (kg)	Fresh weight Cu concentration (mg kg FW^{-1})
age 1-3	13	62.9
age 4-8	22	106.5
age 9-13	40	193.6
F, age 14-18	57	275.8
F, age 19-30	61	295.2
M, age 14-18	64	309.7
M, age 19-30	76	367.7

Range of FW concentrations observed across all treatments for unpeeled carrot:

Nanoparticle: 0.8 – 180.5 mg kg FW^{-1}

Ionic: 2.5 – 173.0 mg kg FW^{-1}

How many servings per day to reach oral RfD for Cu of 40 µg kg^{-1} d^{-1}

		Treatment, concentration (mg kg^{-1} DW) and form (NP or Ion)							
UNPEELED	**Body mass, (kg)**	**0.5 NP**	**5 NP**	**50 NP**	**500 NP**	**0.5 Ion**	**5 Ion**	**50 Ion**	**500 Ion**
age 1-3	13	27.3	13.9	2.9	0.7	17.5	7.8	0.8	0.07
age 4-8	22	46.3	23.5	5.0	1.1	29.6	13.3	1.4	0.12
age 9-13	40	84.1	42.8	9.1	2.0	53.9	24.1	2.5	0.21
F, age 14-18	57	119.8	61.0	12.9	2.9	76.8	34.4	3.6	0.26
F, age 19-30	61	128.3	65.3	13.8	3.1	82.2	36.8	3.8	0.33
M, age 14-18	64	134.6	68.5	14.5	3.2	86.2	38.6	4.0	0.34
M, age 19-30	76	159.8	81.3	17.2	3.9	102.4	45.8	4.8	0.41
PEELED									
age 1-3	13	587.3	594.0	229.2	89.6	504.1	412.6	155.4	24.7
age 4-8	22	993.9	1005.2	387.8	151.7	853.0	698.2	263.0	41.8
age 9-13	40	1807.1	1827.6	705.1	275.7	1551.0	1269.5	478.1	76.1
F, age 14-18	57	2575.1	2604.4	1004.8	392.9	2210.1	1809.0	681.4	92.2
F, age 19-30	61	2755.8	2787.1	1075.3	420.5	2365.2	1936.0	729.2	116.0
M, age 14-18	64	2891.4	2924.2	1128.2	441.2	2481.6	2031.2	765.0	121.7
M, age 19-30	76	3433.5	3472.5	1339.8	523.9	2946.9	2412.0	908.5	144.5

How much fresh carrot (in kg) to consume to reach oral RfD for Cu of 40 µg kg^{-1} d^{-1}

		Treatment, concentration (mg kg^{-1} DW) and form (NP or Ion)							
UNPEELED	**Body mass, (kg)**	**0.5 NP**	**5 NP**	**50 NP**	**500 NP**	**0.5 Ion**	**5 Ion**	**50 Ion**	**500 Ion**
age 1-3	13	1.7	0.9	0.2	0.0	1.2	0.5	0.05	0.004
age 4-8	22	2.9	1.5	0.3	0.1	2.0	0.8	0.09	0.01
age 9-13	40	5.2	2.7	0.6	0.1	3.6	1.5	0.16	0.01
F, age 14-18	57	7.4	3.8	0.8	0.2	5.2	2.1	0.22	0.02
F, age 19-30	61	8.0	4.0	0.9	0.2	5.5	2.3	0.24	0.02
M, age 14-18	64	8.3	4.2	0.9	0.2	5.8	2.4	0.25	0.02
M, age 19-30	76	9.9	5.0	1.1	0.2	6.9	2.9	0.30	0.03
PEELED									
age 1-3	13	36.4	36.8	14.2	5.6	31.1	26.2	4.6	1.9
age 4-8	22	61.6	62.3	24.0	9.4	52.6	44.3	7.7	3.2
age 9-13	40	112.0	113.3	43.7	17.1	95.6	80.6	14.1	5.8
F, age 14-18	57	159.7	161.5	62.3	24.4	136.2	114.9	20.0	7.1
F, age 19-30	61	170.9	172.8	66.7	26.1	145.8	122.9	21.5	8.9
M, age 14-18	64	179.3	181.3	70.0	27.4	152.9	129.0	22.5	9.3
M, age 19-30	76	212.9	215.3	83.1	32.5	181.6	153.2	26.7	11.1

What fresh weight tissue concentration necessary to reach the oral RfD for Cu?

Age-Mass class	Body mass, (kg)	Fresh weight Cu concentration ($mg\ kg\ FW^{-1}$)
age 1-3	13	8.4
age 4-8	22	14.2
age 9-13	40	25.8
F, age 14-18	57	36.8
F, age 19-30	61	39.4
M, age 14-18	64	41.3
M, age 19-30	76	49.0

Range of FW concentrations observed across all treatments for unpeeled carrot:

Nanoparticle:	0.2 – 27.7 mg kg FW^{-1}
Ionic:	0.4 – 178.4 mg kg FW^{-1}

Dietary intake scenarios: General model interpretations

- Dietary intake from the ionic treatment higher than the NP treatment, except for unpeeled carrot at highest concentration of ZnO/ Zn^{2+}.
- Dietary intake from unpeeled carrot higher than for peeled carrot.

- Peeling would reduce potential intake to below the oral RfD for all age-mass classes.
- No apparent nanofertilizer effect in terms of either biomass production or nutritional value.

Conclusions to date

- For carrot, the peel is an effective screen reducing the metal concentration in edible flesh.
- For unpeeled carrots, dietary exposure modeling for Cu and Zn indicates that oral RfD values would be exceeded only in limited scenarios.
- Reverse modeling demonstrated the degree of consumption or tissue concentrations that would theoretically be needed to reach the oral RfD.

Additional research efforts

- Broader scale efforts with more crops, more ENPs, and different size classes.
- ENP stability, speciation, and spatial distribution.
- Bioaccessibility assays and dietary exposure modeling for our plants and those from collaborators.
- Additional efforts with trophic transfer.
- Continued efforts on nanotoxicology and beneficial uses

Acknowledgments

- Ebbs lab
  - Scott Bradfield, Pawan Kumar, Marylou Machingura, Laxmi Sagwan, Shayla Gunn, Tony Sabella, Cassie Turner
- Ma lab
  - Weilan Zhang, Qiang (Dennis) Wang, Haochun (Stan) Pei, Yahui Zheng, Byran Quah
- White Lab
  - Craig Musante
- Funding
  - USDA-AFRI Food Safety