Assessing the Effects of Levee Setbacks on Floods, Ecosystem Services, and Biodiversity on the Lower Missouri River

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Upper Mississippi River Conference
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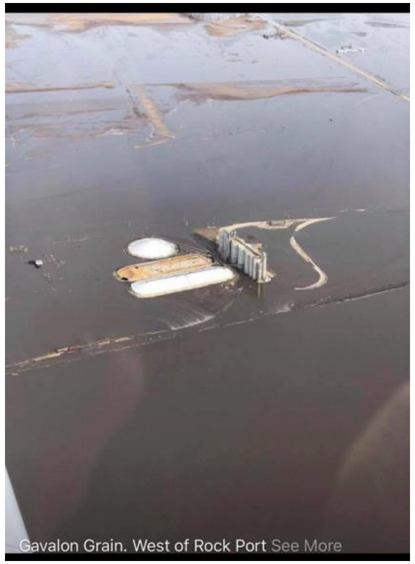
Moline, IL

River Management Challenges

- Flooding
- Aging infrastructure
- Biodiversity declines, endangered species
- Other lost ecosystem services
- Uncertainties of future climate

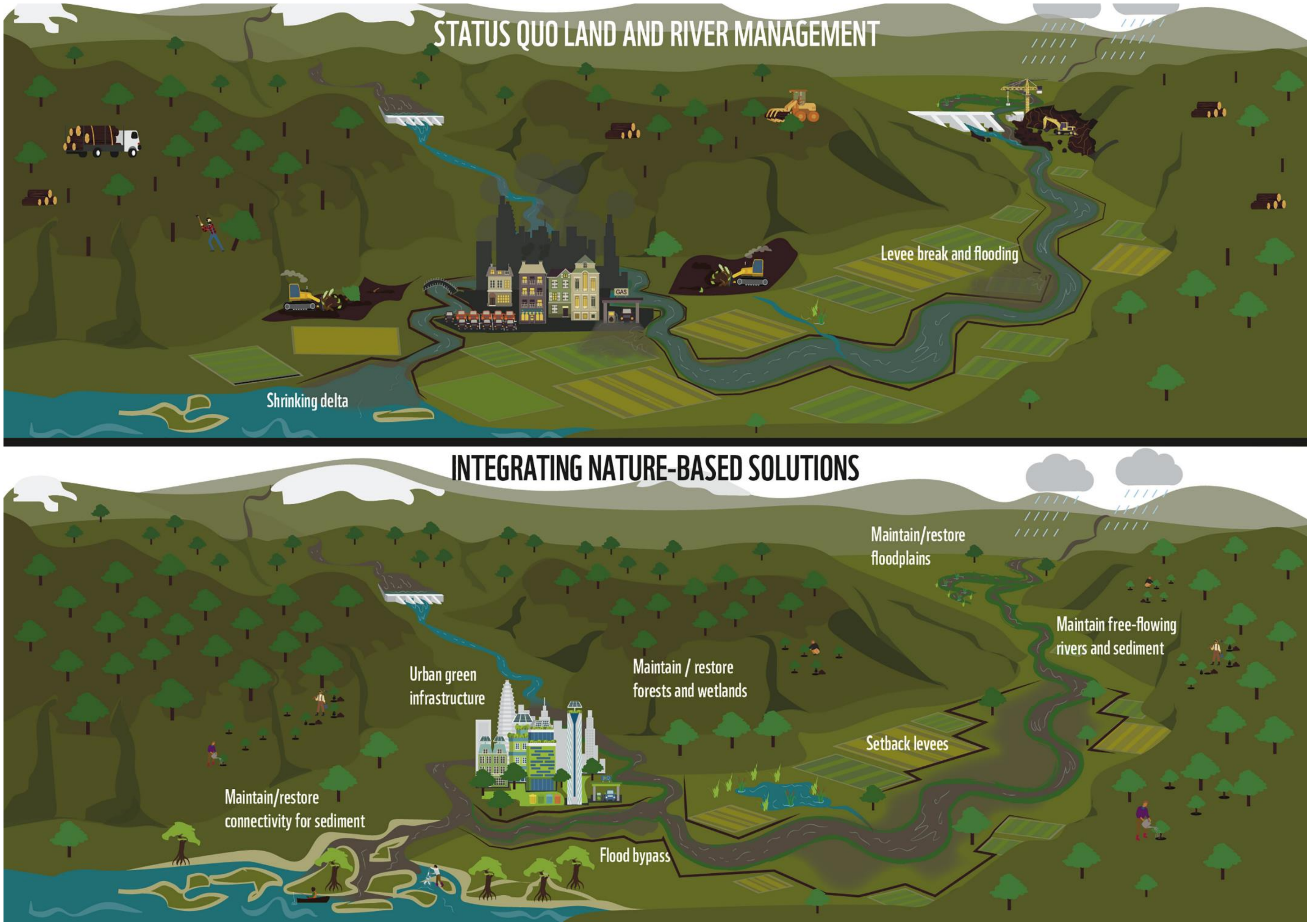
- Need more resilient, adaptable infrastructure to deal with uncertainty and to deliver "co-benefits" like biodiversity conservation and ecosystem services
  - "**Nature-based solutions (NBS)** are civil works features or management actions that leverage extant, created, or rehabilitated ecosystems to deliver infrastructure functions along with multiple co-benefits like biodiversity conservation."


Gavalon Grain. West of Rock Port See More

NbS & River Management

NbS & River Management

Opperman and Galloway (2022)



NbS and Freshwater Biodiversity

Can NbS boost the Emergency Recovery Plan for Freshwater Biodiversity?

- Improve water quality
- Protect & restore critical habitats
- Safeguard & restore freshwater connectivity

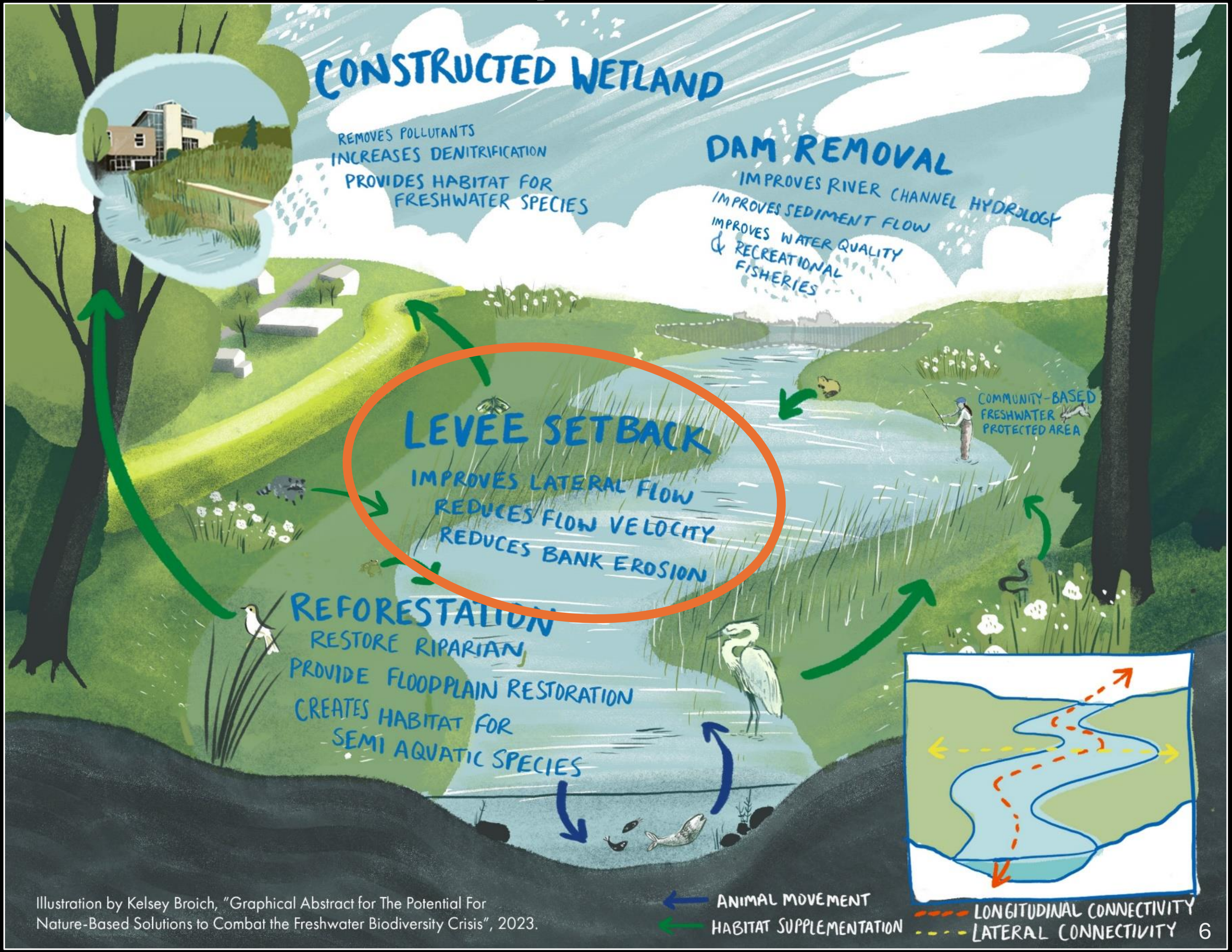


Illustration by Kelsey Broich, "Graphical Abstract for The Potential For Nature-Based Solutions to Combat the Freshwater Biodiversity Crisis", 2023.

Tickner et al., 2020 *BioScience*
van Rees et al., 2021 *Conservation Letters*
van Rees et al., 2023 *PLoS Water*

LEVEE SETBACK CO-BENEFITS AND SERVICES

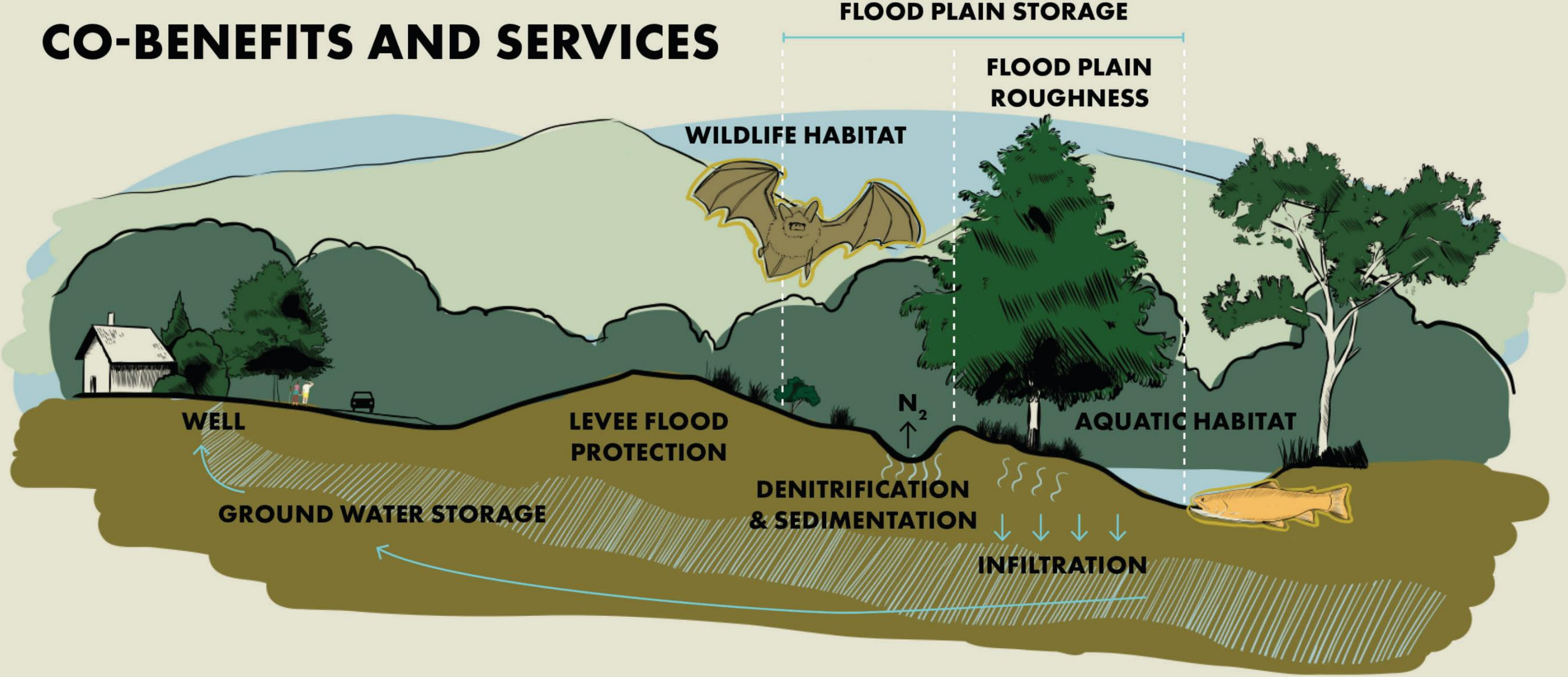


Illustration by Kelsey Broich, "Levee Setback Co-Benefits and Services Graphic" for "Strategic Planning of Freshwater Nature-based Solutions: An Interdisciplinary Synthesis for Implementing Levee Setbacks", 2023.

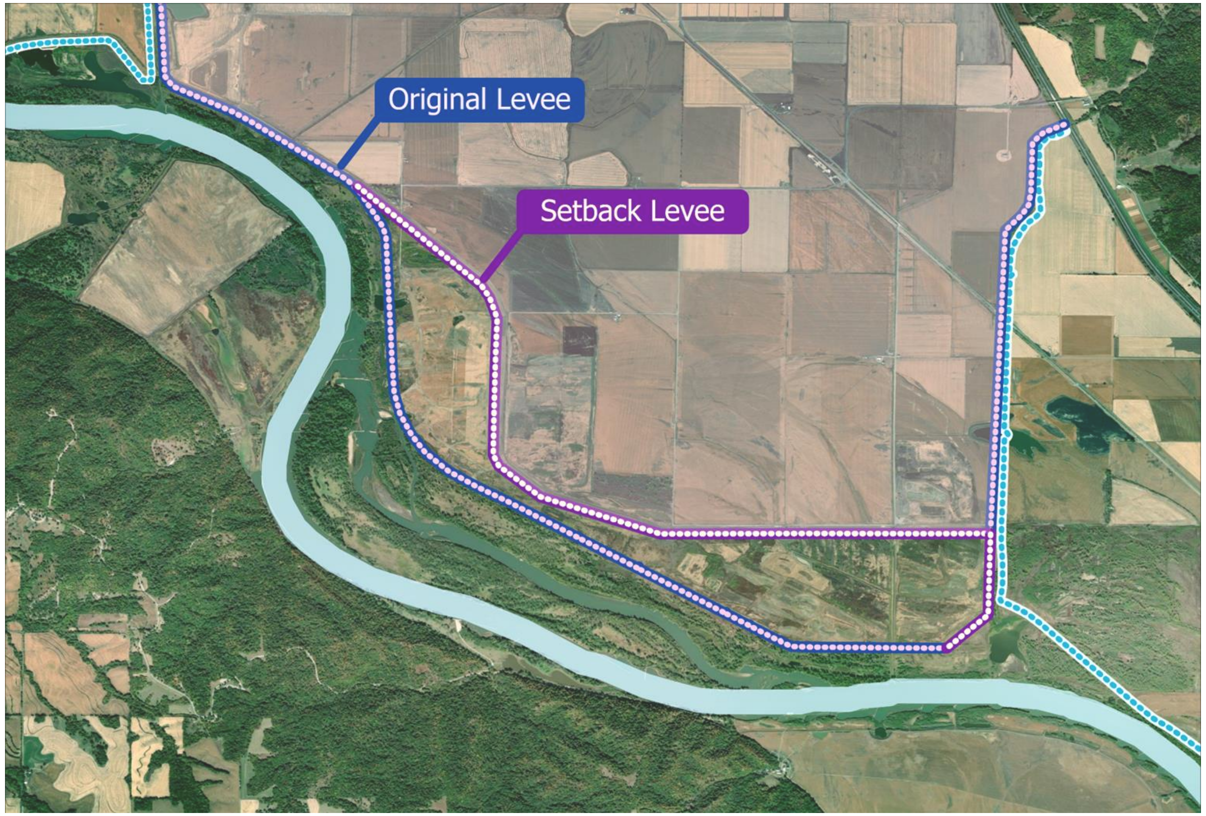
van Rees et al. *in revision, WIREs Water*

Why Focus on Levees?

- Growing social pressure to change river corridor management practices
  - Freshwater biodiversity crisis
  - FRM, the “levee effect”
- Historical levee engineering practice may be contributing
- Massive number and spatial scales
- Test NbS like levee setbacks
  - Variety of contexts
  - At large spatial scales
  - Broadly meaningful impacts

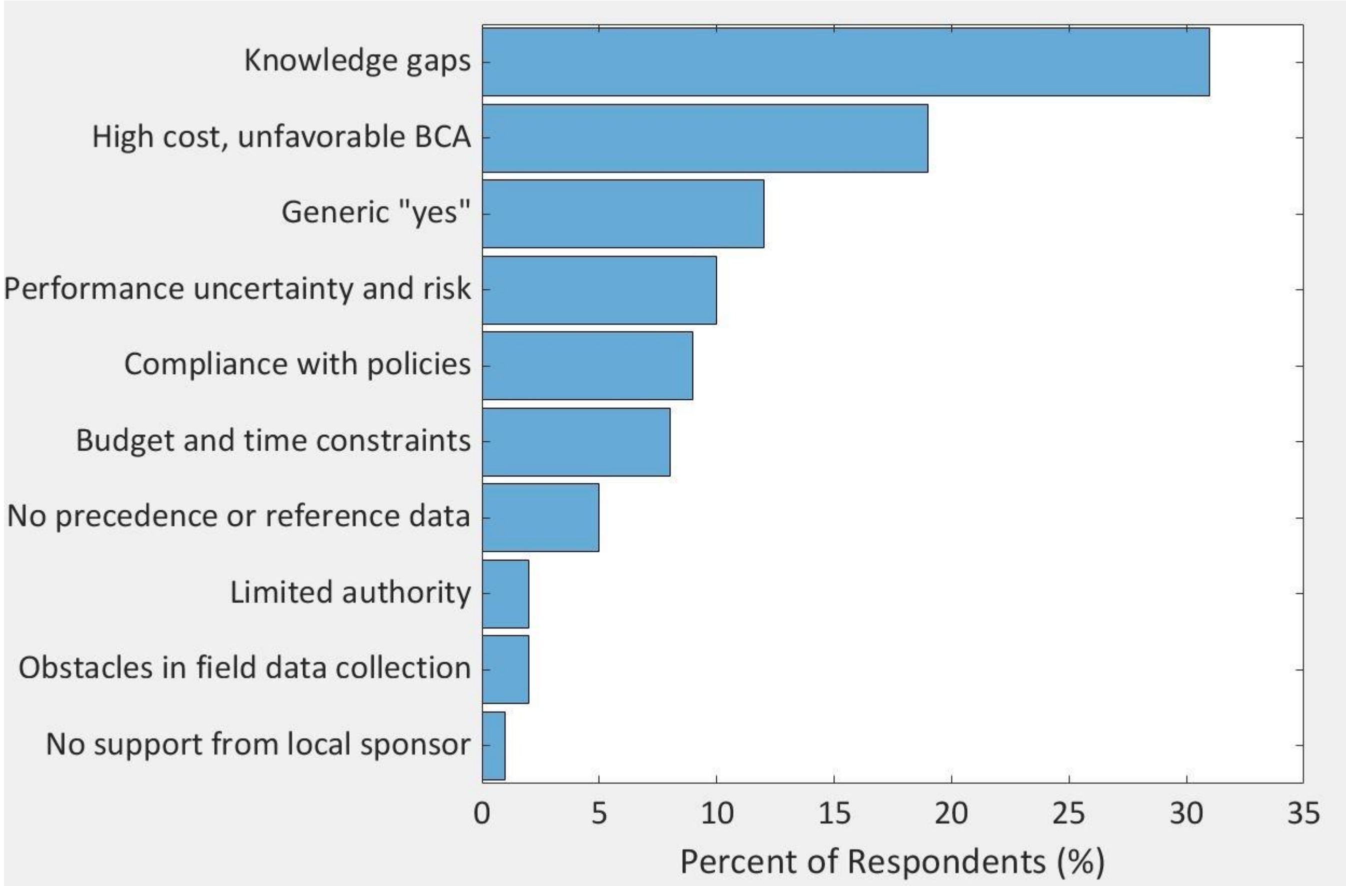
Levee Setbacks

- Setbacks are a NbS
- Floodplain conveyance is a FRM (flood risk management) service
  - Reduce the severity of flood hazards
  - Improve level of protection and reliability
  - Risk mitigation through relocation
- Alleviate ecological stressors and drivers of biodiversity loss
- Regulation of water quality and climate



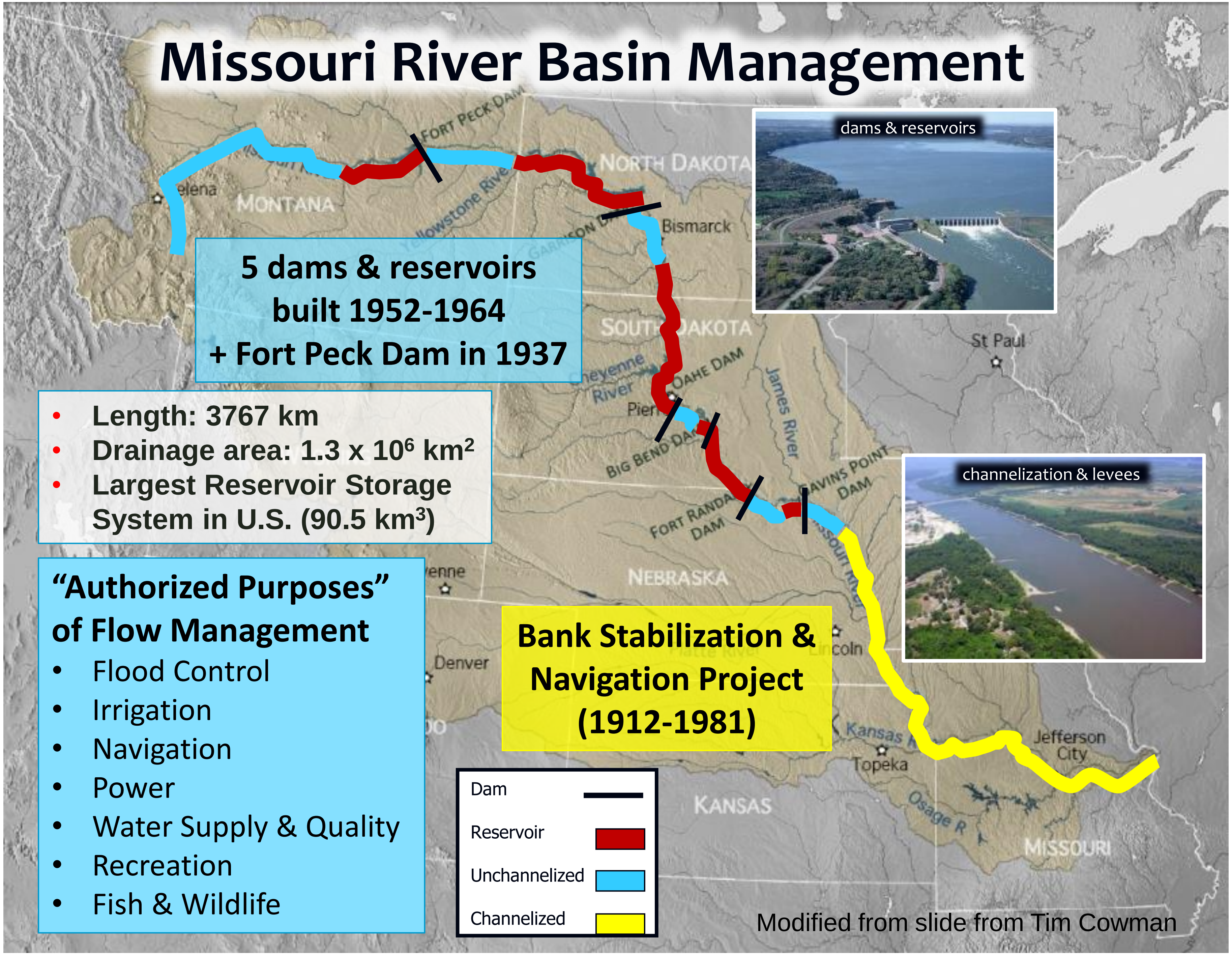
What is limiting their application?

- *Outside the obvious…*
  - Expensive
  - Differing land use interests
- *Where there is political will…*
  - Knowledge gaps
  - Uncertain performance
  - Limited guidance
- USACE is embracing NbS, will then implement more setbacks?



Chambers et al., 2023

Missouri River Basin Management



5 dams & reservoirs built 1952-1964 + Fort Peck Dam in 1937

- Length: 3767 km
- Drainage area: 1.3 x 10^6 km^2
- Largest Reservoir Storage System in U.S. (90.5 km^3)

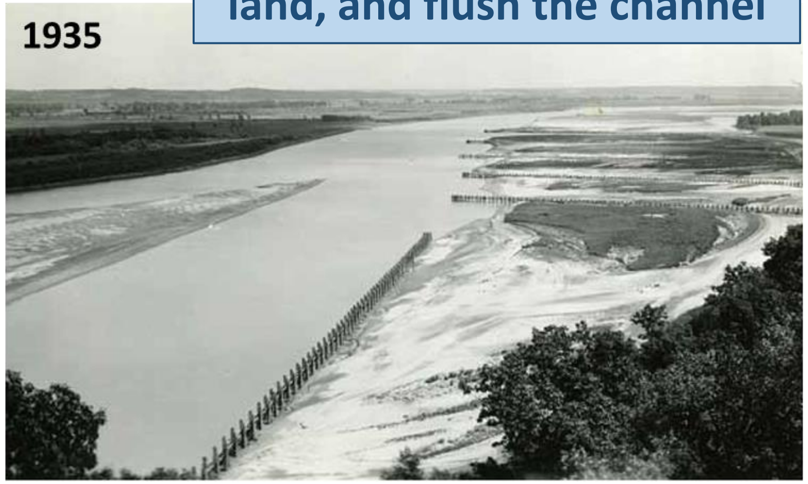
"Authorized Purposes" of Flow Management

- Flood Control
- Irrigation
- Navigation
- Power
- Water Supply & Quality
- Recreation
- Fish & Wildlife

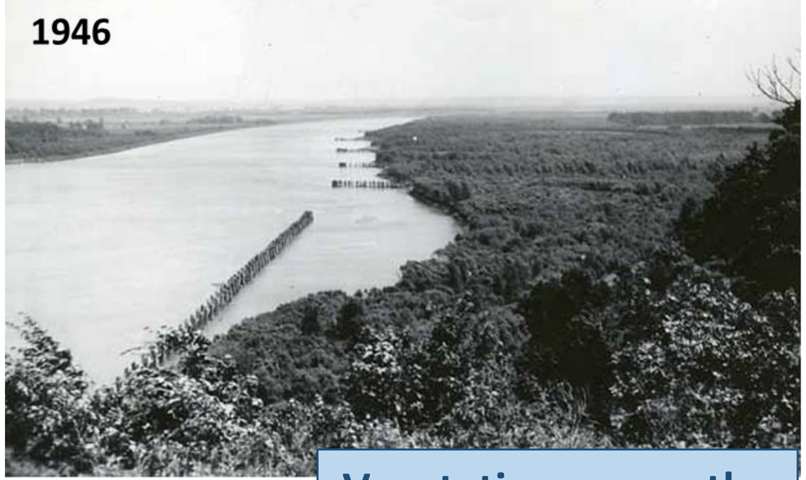
Bank Stabilization & Navigation Project (1912-1981)

Modified from slide from Tim Cowman

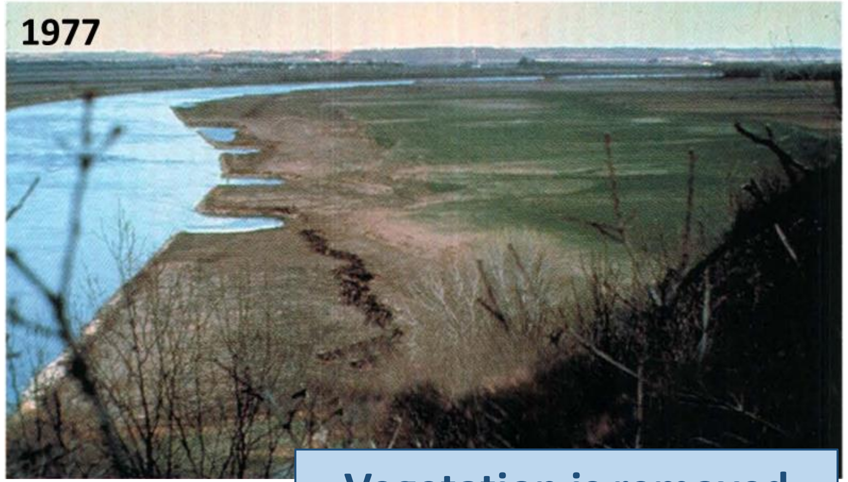
Pre-engineering



Dikes trap sediment, accrete land, and flush the channel



Vegetation covers the accreted floodplain



Vegetation is removed for agriculture

Levee construction on accreted land

Loss of Aquatic Habitat Complexity from Channelization on Lower Missouri River

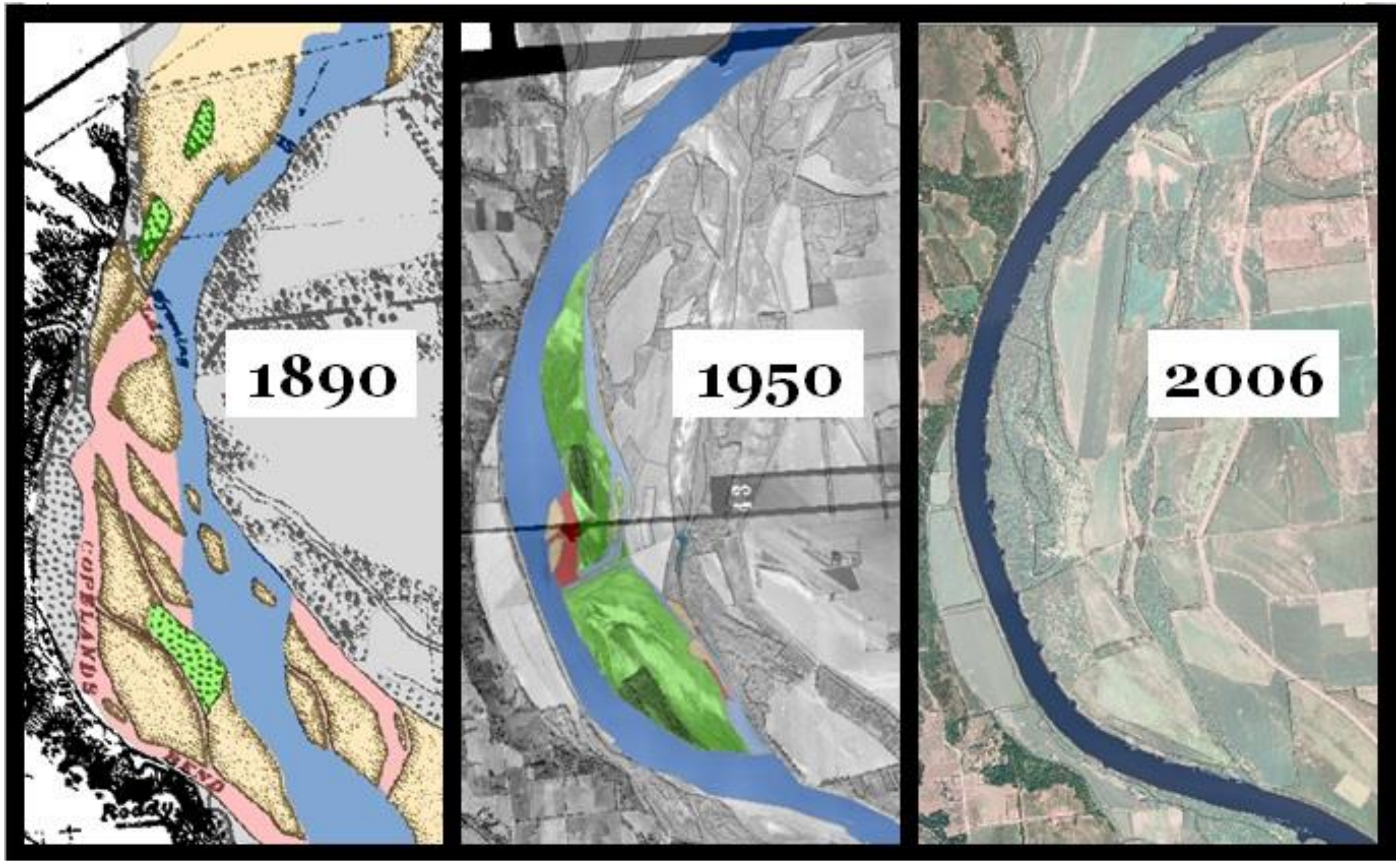
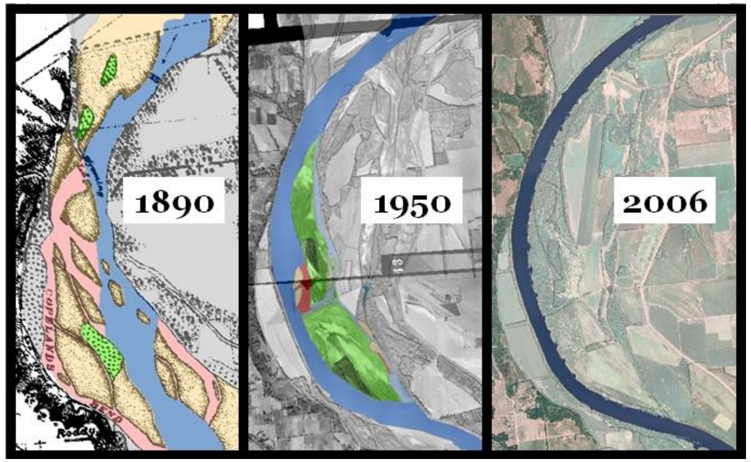
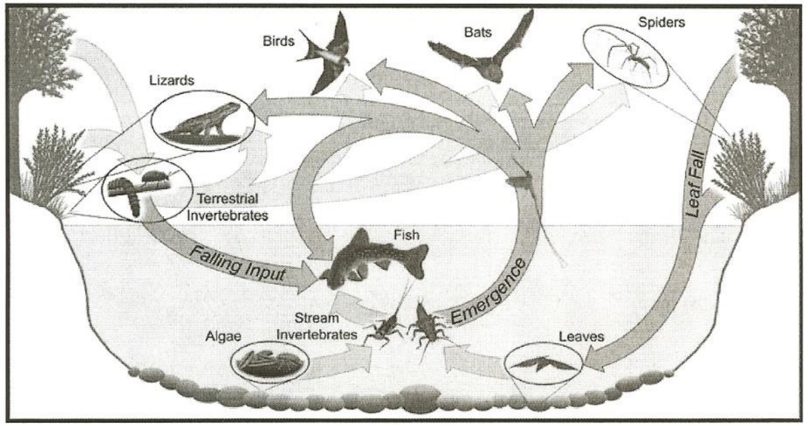


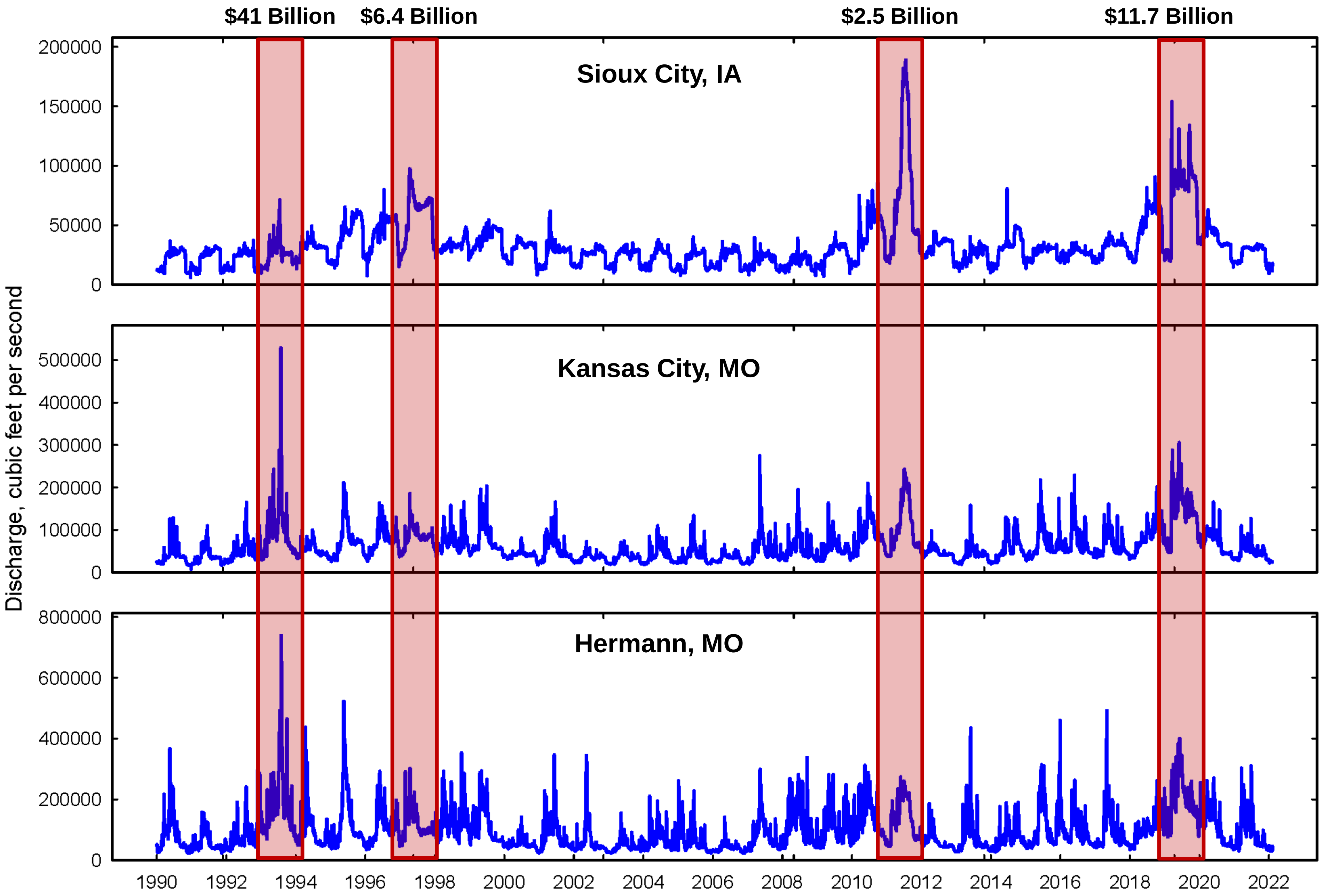
Figure by Danielle Quist

Biodiversity Issues on the Missouri River

- Loss of aquatic & floodplain habitat and connectivity from dams and channelization
  - Federally listed species
    - Pallid sturgeon, Piping Plover
  - ~90% of floodplains in the Lower Missouri were disconnected by levees during the 20th century (NRC 2002)
  - Possible loss of energy subsidies from aquatic to terrestrial ecosystem (Wesner et al. 2020)

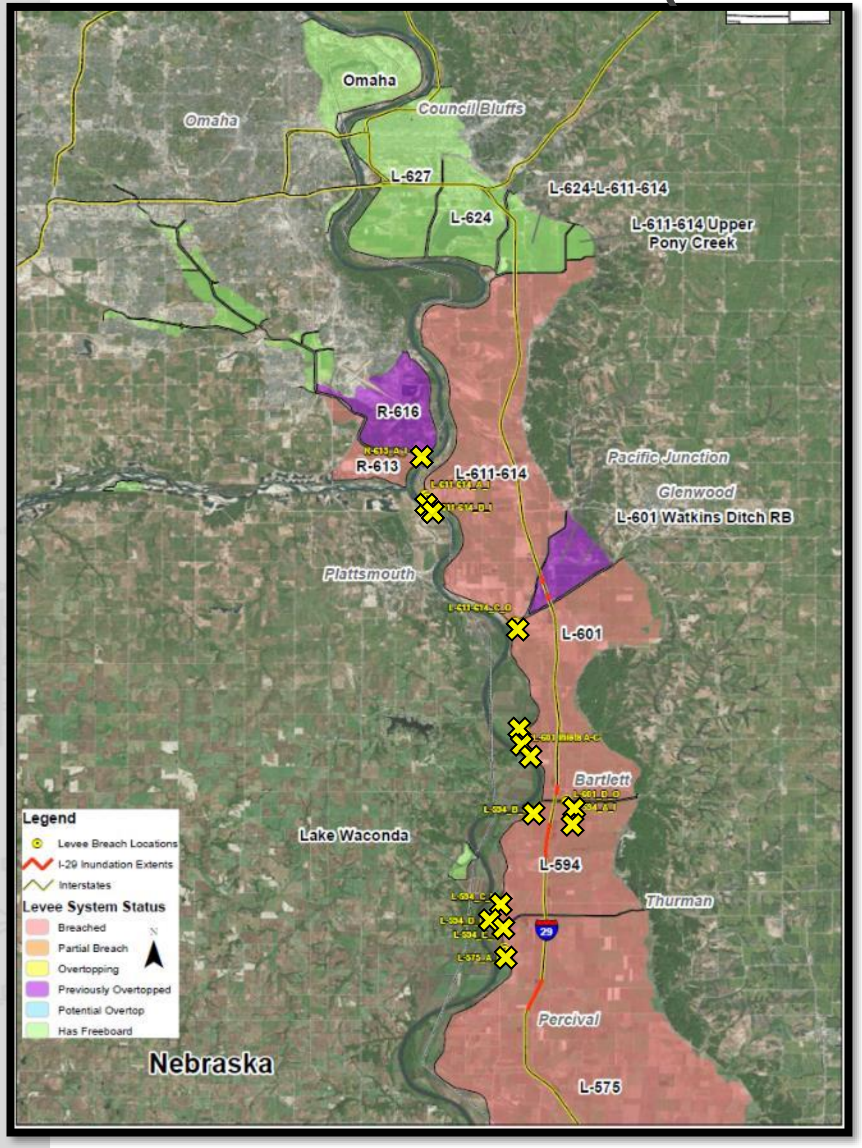


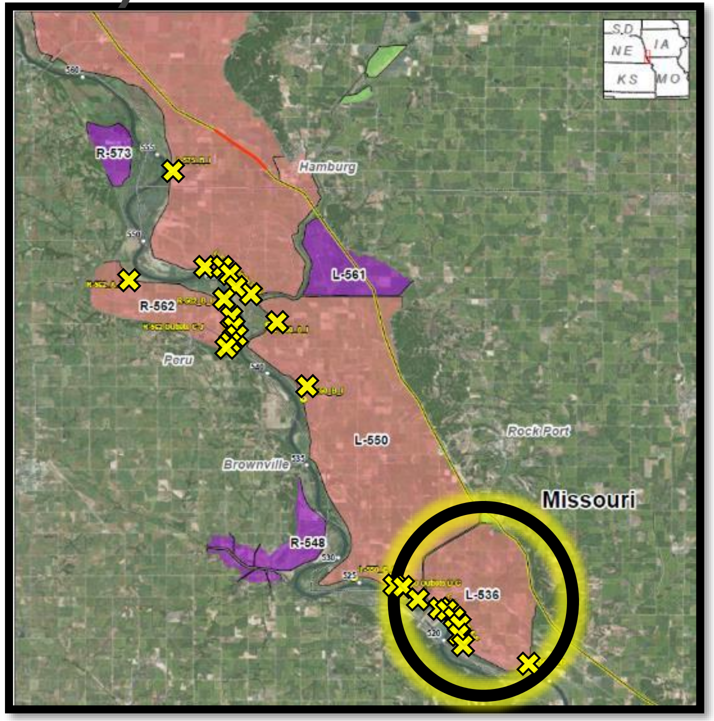




***NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2022). https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73**

LEVEE SYSTEMS ON THE MISSOURI RIVER RM 626 – 516 (15 APRIL 19)





L536 LEVEE SYSTEM

2019 OVERALL DAMAGE

- Over 50 Breaches (widespread, unprecedented damage)
  - 17 breaches on systems inactive in PL 84-99
- Failure mode primarily overtopping
  - Short duration events
  - Reloading of levees on Memorial Day
- Requests for assistance on levee systems active in PL 84-99
  - 60 levee and channel systems (60 completed Project Information Reports)
  - 352 miles of levees

FLOOD DAMAGES – L536

Category	Length (FT)	Length (Miles)
Breaches (5 full, 2 partial)	2,120	0.40
Damaged	56,738	10.75
Scour hole, max depth	60 FT	

Breach, July 2019

F Breach, July 2020 *(with temp ring levee to prevent site from flooding)*

13 Aug 2019 Imagery

B Breach, July 2019

Extensive floodplains in the Midwest are highly valued for development, agriculture, transportation, and conservation benefits.

Can resiliency be improved?


Kansas City, Missouri

Engineering resilient

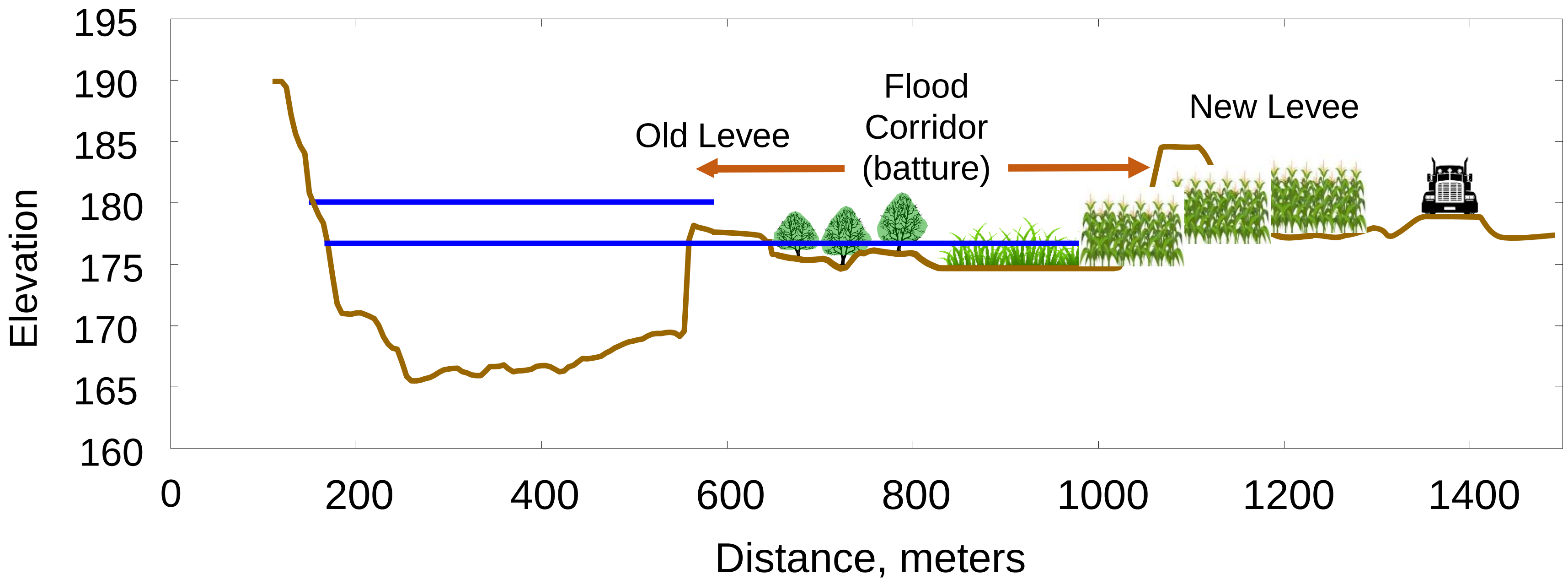

Agricultural land, near Bartlett, Iowa

Not resilient


Big Muddy NWR, Arrow Rock, Missouri

Ecologically resilient

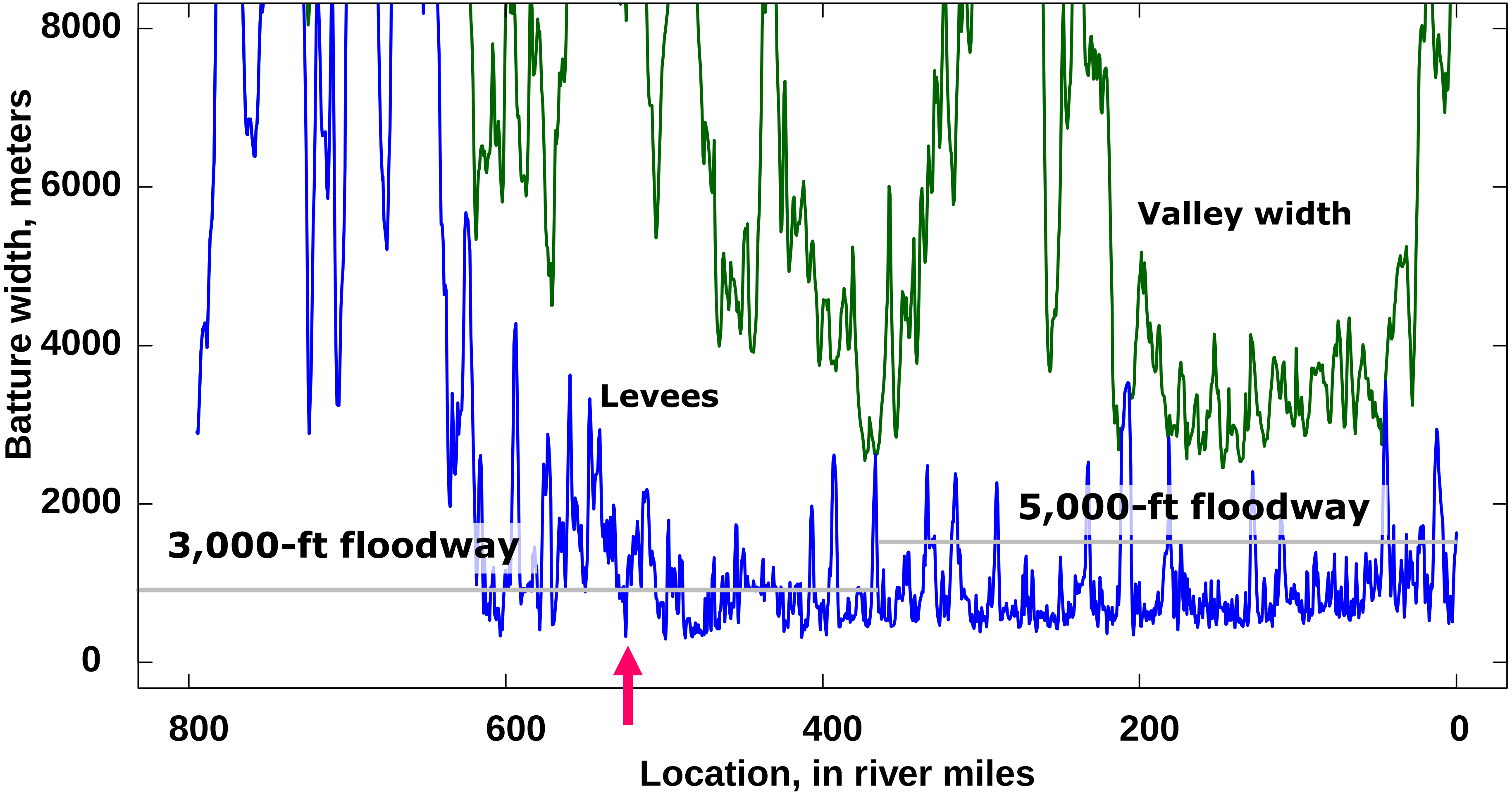
USGS



Design objectives for setbacks and increased resilience:

- Decrease flood hazard, local river stages
- Maximize revenue in flood corridor – flood-compatible crops, hunting easements, flowage or conservation easements…
- Minimize long-term maintenance costs, sedimentation.
- Potentially increase ecosystem services through provision of diverse, dynamic habitats, nutrient processing, carbon sequestration…

Opportunities for levee setbacks – “pinch points”



Floodplain insights

After the devastating flood of 2019, some levee districts pushed for higher, stronger levees. One (L-536) pushed for a levee setback.

An interagency effort with strong support from TNC, USACE, USFWS, MDC.

- www.nature.org/moriverlevee

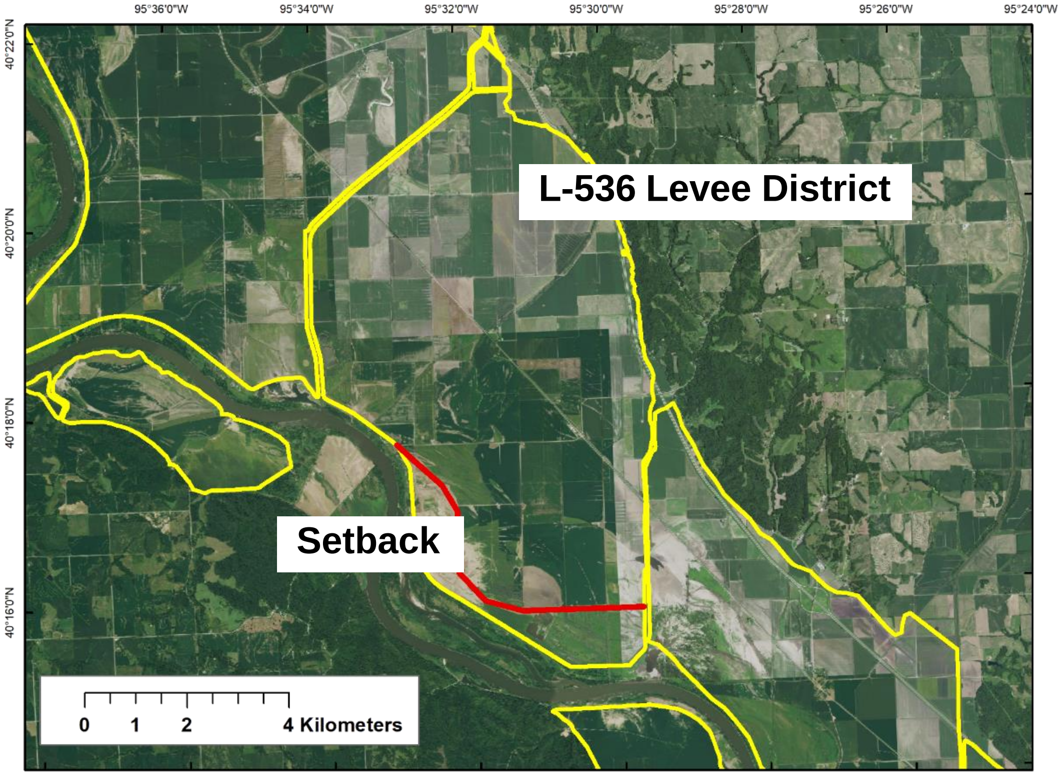
Unique and promising BUT expensive and small:

$103 million, $24 million /mile for a 4.3 mile realignment.

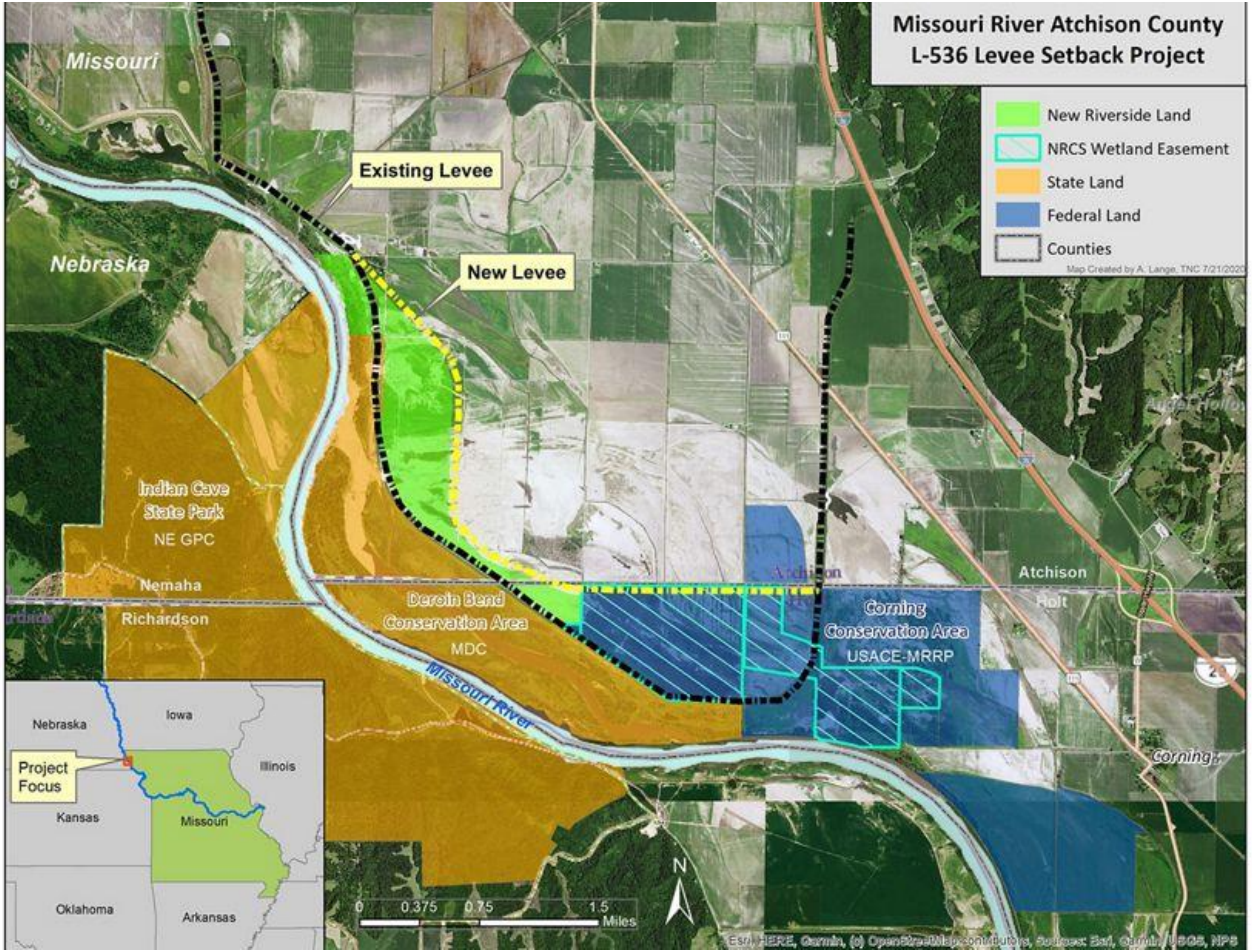
Connected 1,040 acres at a cost of $100,000/ac, 10x the usual per acre cost of restoration.

The connected area amounts to about 0.02% of the 2019 flood volume.

Minimum monitoring and evaluation (so far).



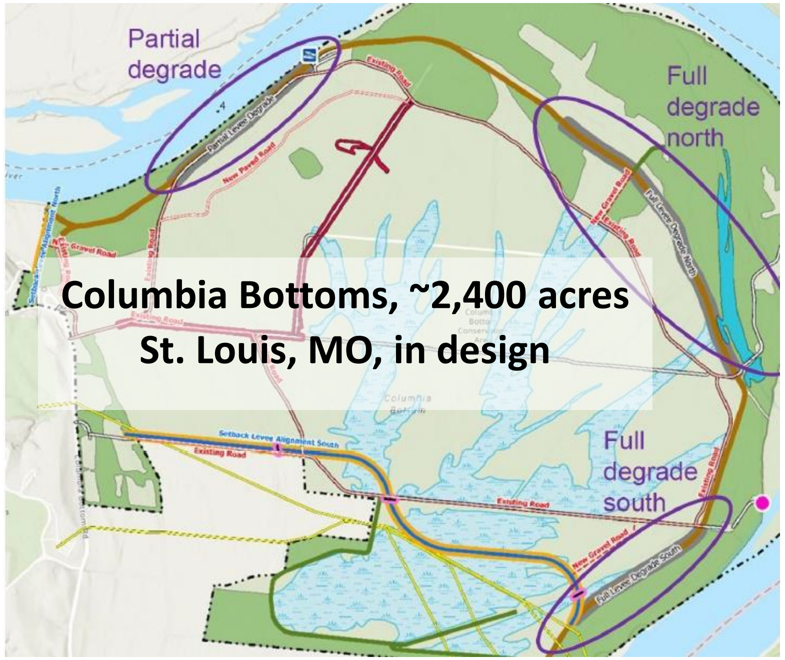

USACE Omaha

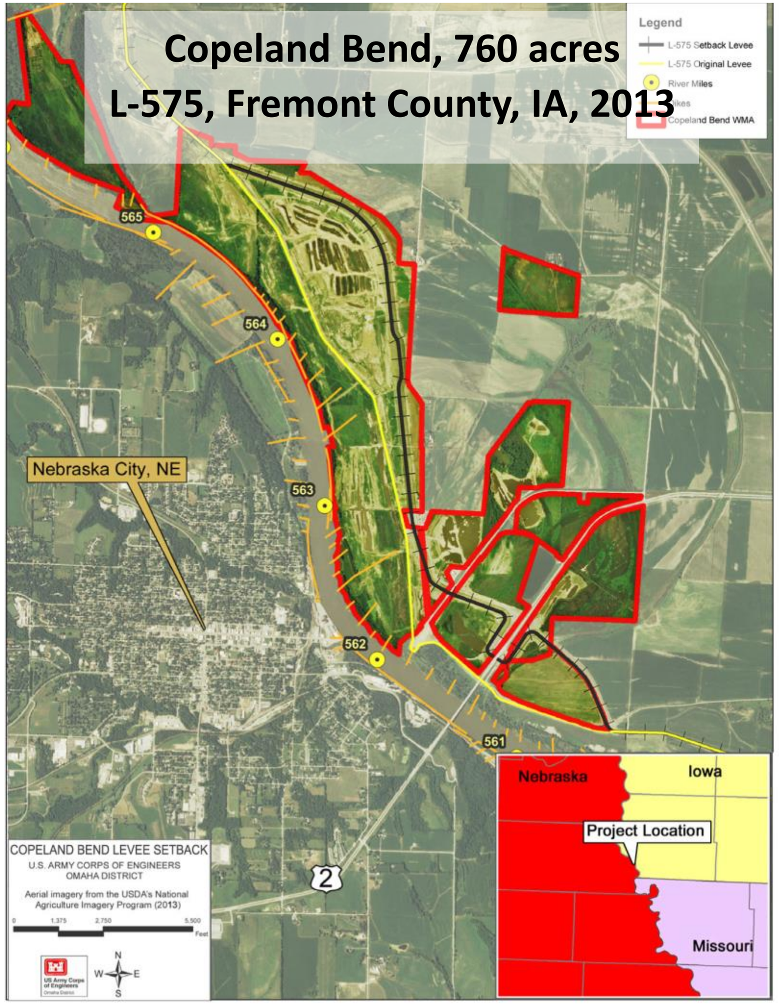


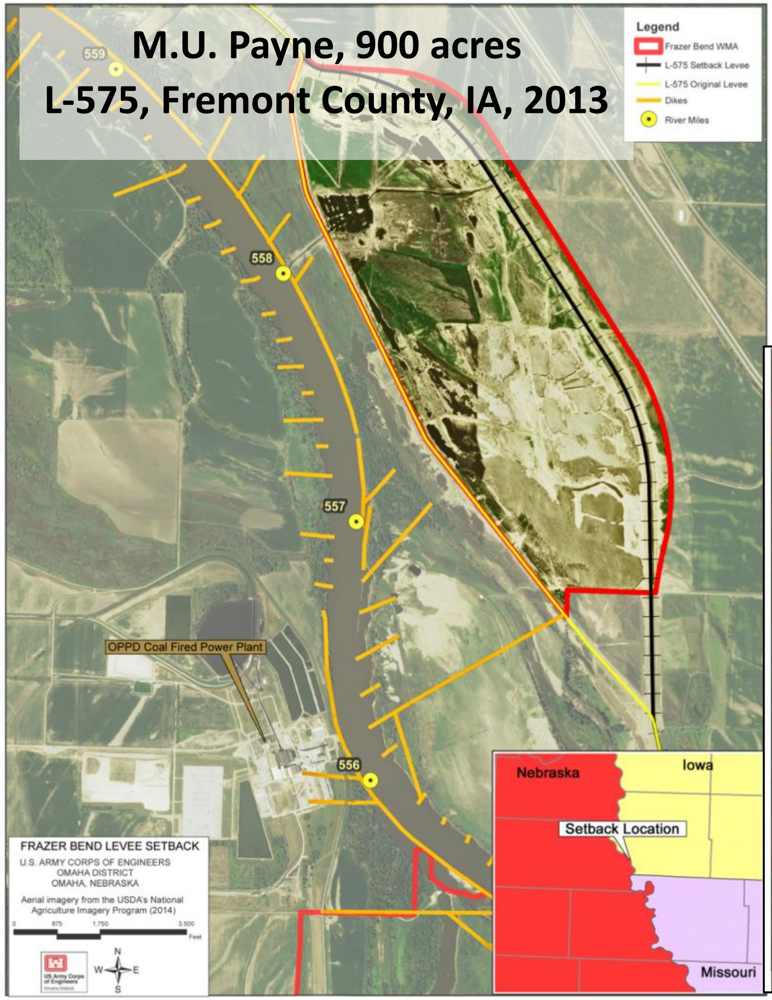
Missouri River Atchison County L-536 Levee Setback Project

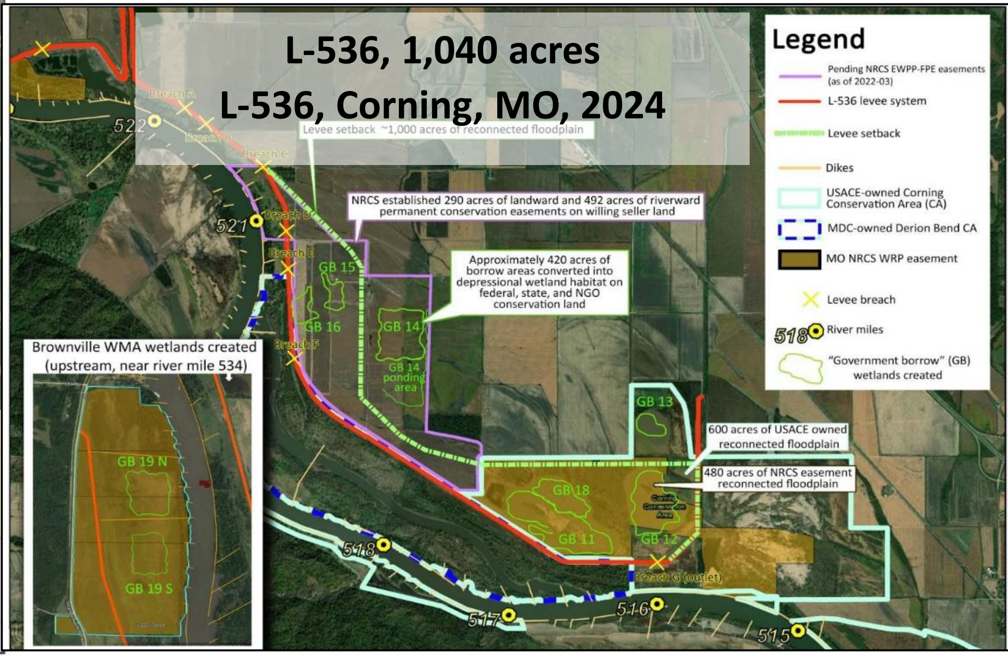
Missouri River "Levee Setbacks"

Completed or in design phase


Columbia Bottoms, ~2,400 acres
St. Louis, MO, in design


Copeland Bend, 760 acres
L-575, Fremont County, IA, 2013


M.U. Payne, 900 acres
L-575, Fremont County, IA, 2013


L-536, 1,040 acres
L-536, Corning, MO, 2024

Levee setback ~1,000 acres of reconnected floodplain

NRCS established 290 acres of landward and 492 acres of riverward permanent conservation easements on willing seller land

Approximately 420 acres of borrow areas converted into depressional wetland habitat on federal, state, and NGO conservation land

600 acres of USACE owned reconnected floodplain

480 acres of NRCS easement reconnected floodplain

Brownville WMA wetlands created (upstream, near river mile 534)

INCIDENTAL HYDRAULIC AND ENVIRONMENTAL BENEFITS

L-536 Hydraulic Benefits:

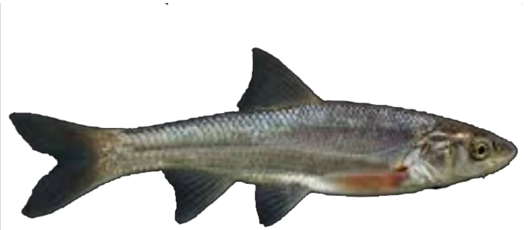
- Increased Conveyance:
  - Reduction in water surface elevation in excess of **0.8 feet for 100-yr flood stage.**
  - Reduction in velocities within the immediate vicinity of the levee.
- Overtopping protection: State-of-the-practice design for **landward levee slope of 5V:1H** reduces overtopping velocities and erosion damage.

L-536 Environmental Benefits:

- **1,040 acres of reconnected** floodplain.
- **420 acres of wetlands** from converted borrow pits.
- Expanded floodplain can be **“hot spots” for age-0 native fish.**
- **Rare, declining, and species of conservation concern** have been observed after past levee setback construction.

Wilson's Phalarope (lost prairie wetlands)

(Copeland Bend setback floodplain- Crane observation 2012, Murphy et al., 2014)



Flathead chub (state listed in MO)

(MU Payne WMA setback floodplain- Hass, et al., 2020)

Blanchard's Cricket Frog (declining across much of range)

(Copeland Bend and MU Payne WMA setback floodplain- Murphy et al., 2014)

Missouri River Levee Setbacks

- Two smaller (L-575 and L-536) levee setbacks have already been implemented (2013, 2022)
- USACE considering a larger (>6000 acre) levee setback at L-550
- But LS not chosen as preferred alternative. Why not?
- Need for better accounting of ecological co-benefits in Benefit-Cost Accounting

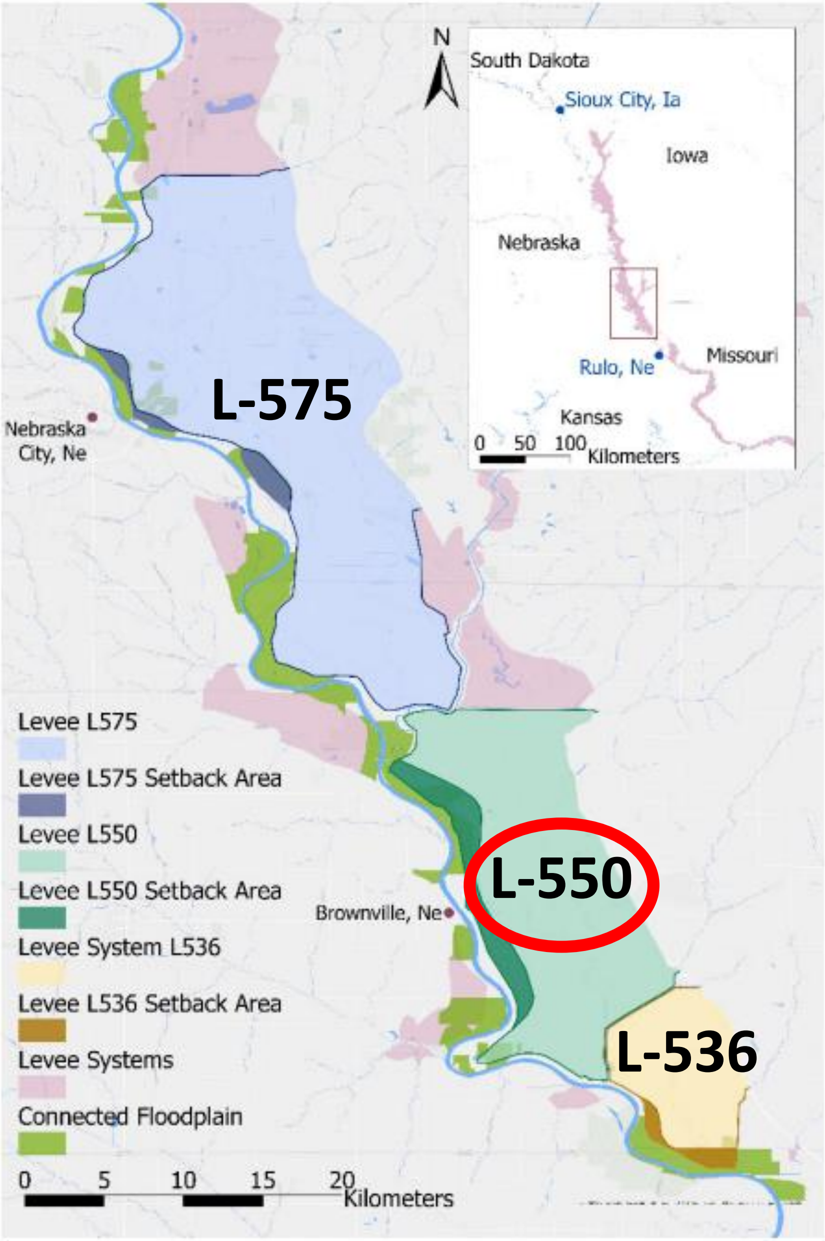
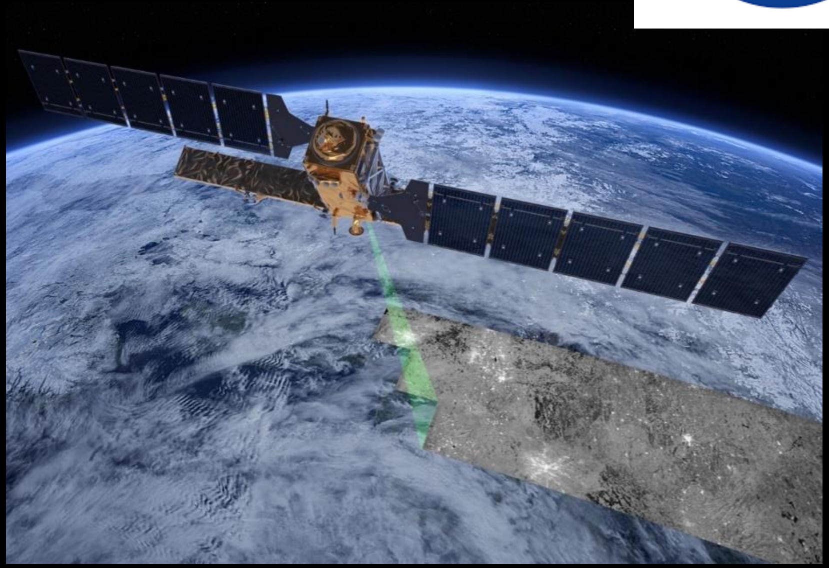
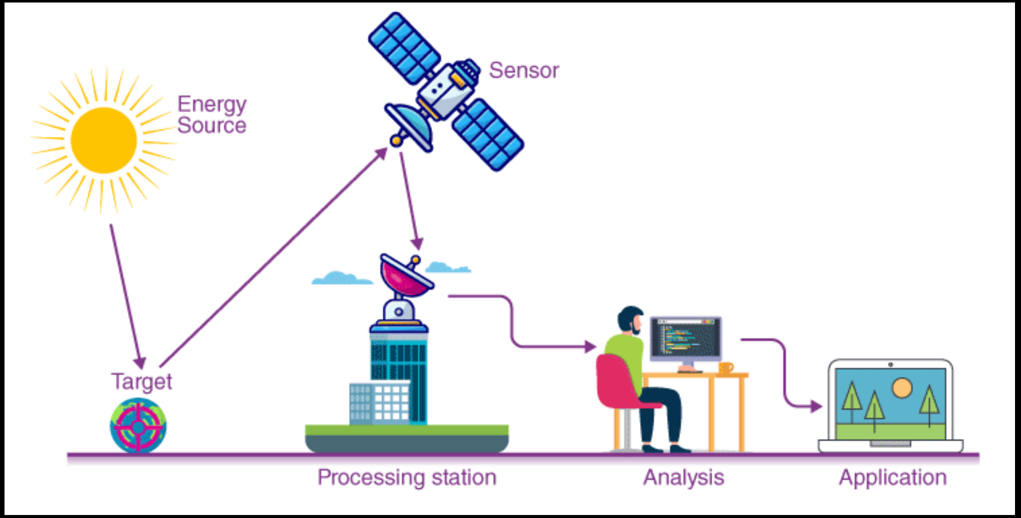


Fig. 1: Study area for the proposed work, including completed levee setbacks at L-575 and L-536, existing floodplain protected areas, and the proposed site for a setback at L-550.

Research: NASA ROSES Grant

- Applied ecological research combining field data collection and use of NASA remote sensing products
- Specific interest in providing decision-making tools for action agencies
  - Here to include ecosystem services as co-benefits of levee setbacks for USACE decision-making
  - Test case is L-550 on Missouri River
  - Use approach in future applications?





EO Habitat / Vegetation data

Canopy height[1,2] & biomass[1]
Phenology[3]
Land Cover[4]
NDVI[3,4]

EO Surface Water data

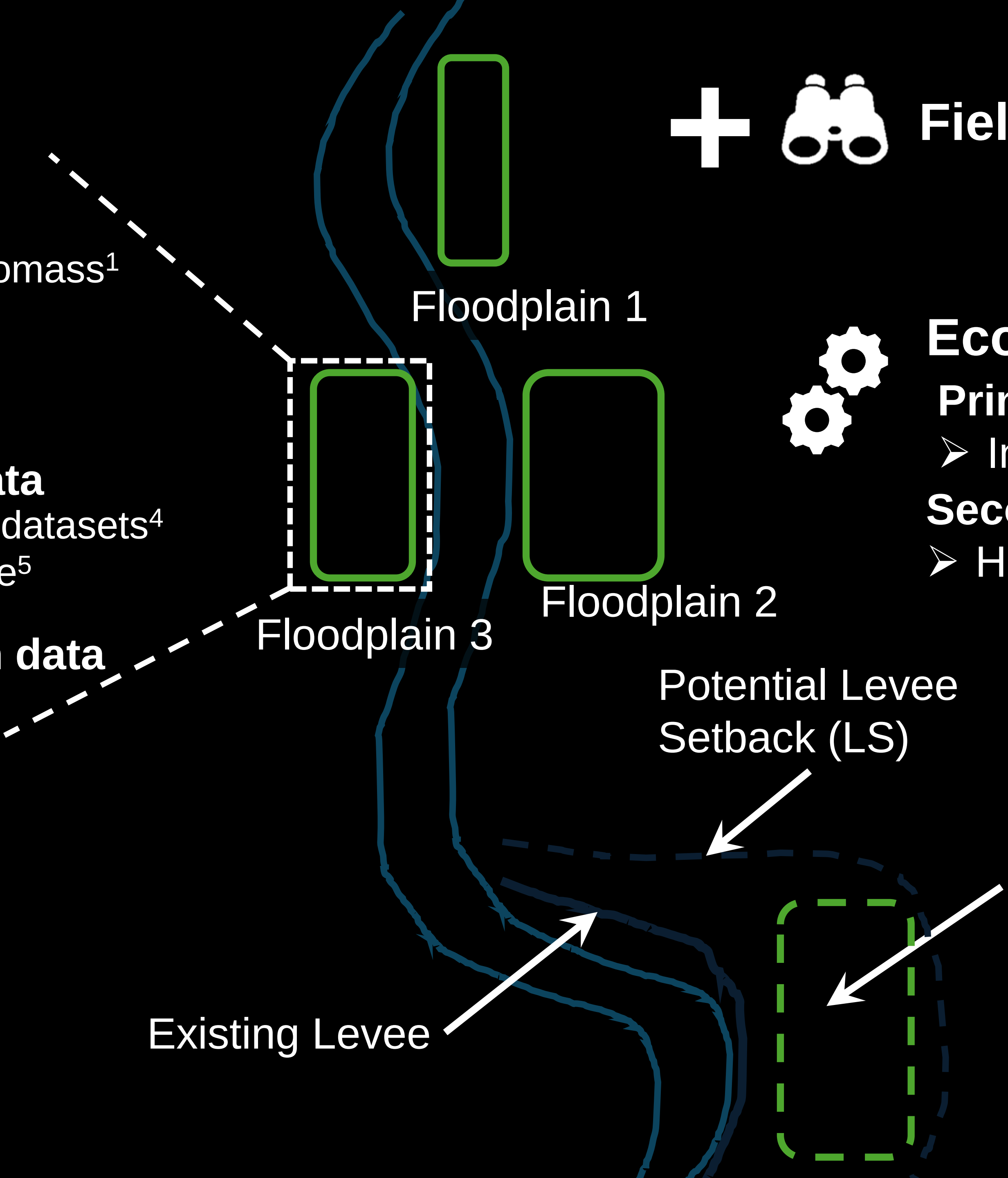
Global Surface Water datasets[4]
Global Flood Database[5]

Backcast Inundation data

2D HEC-RAS model

NASA Sensors Used

[1]GEDI
[2]IceSat-2
[3] VIIRS
[4]Landsat
[5]MODIS



Floodplain 1

Floodplain 2

Floodplain 3

Potential Levee Setback (LS)

Modeled Floodplain Habitat

Existing Levee

\+ **Field Data**

↓

Ecological Models

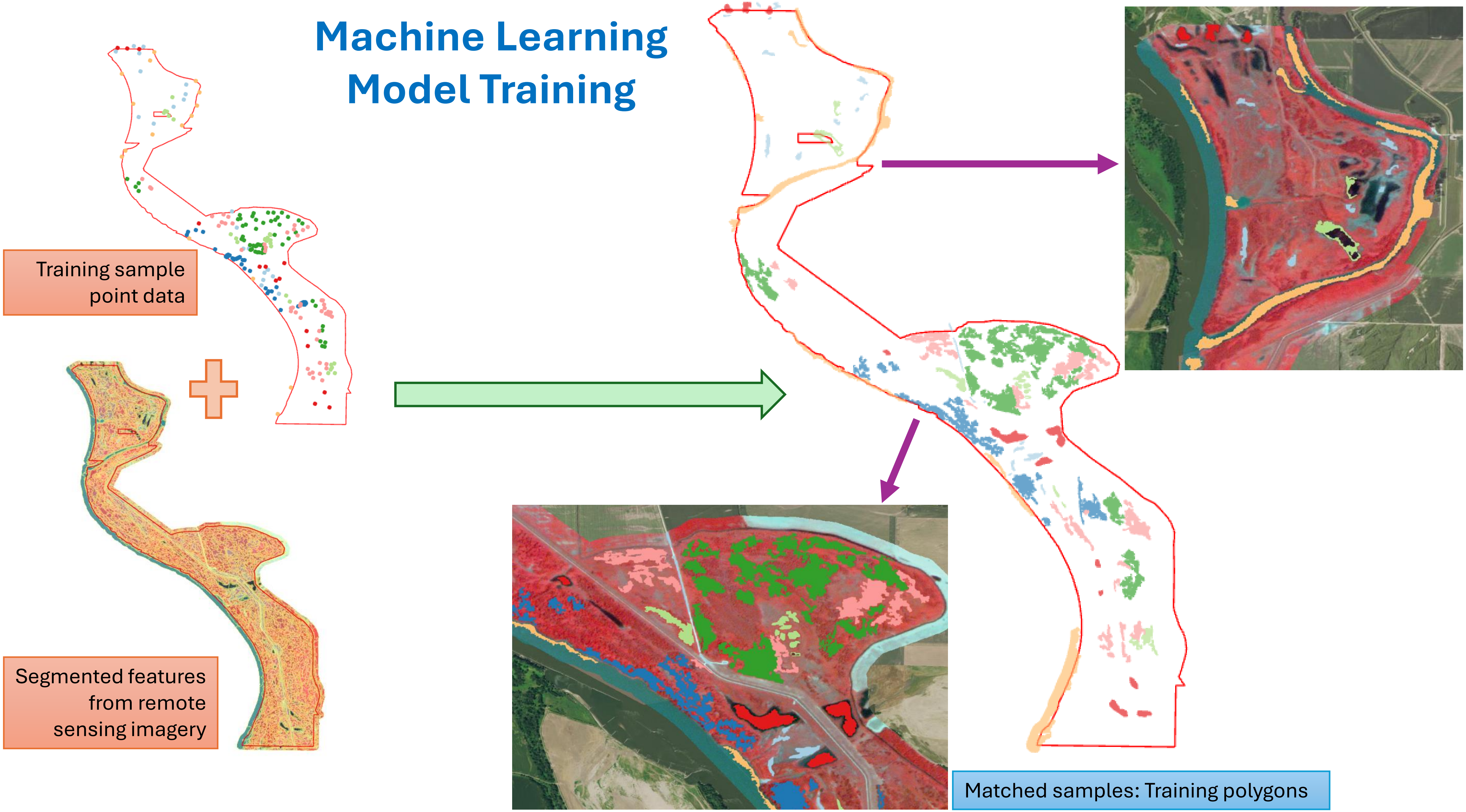
Primary

- ➢ Inundation → Habitat/Veg

Secondary

- ➢ Habitat/Veg → Vertebrates

Machine Learning Model Training



Training sample point data

Segmented features from remote sensing imagery

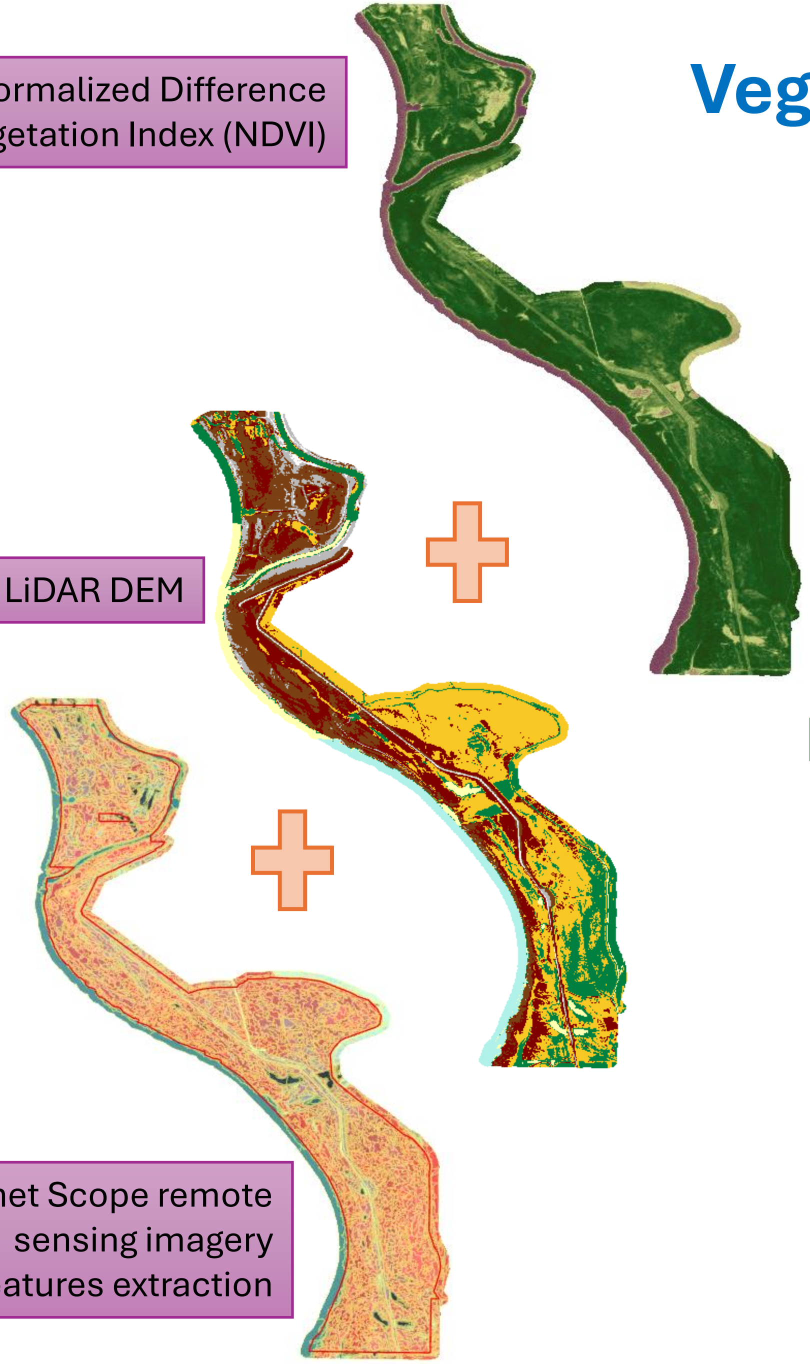
Matched samples: Training polygons

Vegetation Land Cover Classification

Normalized Difference Vegetation Index (NDVI)

LiDAR DEM

Planet Scope remote sensing imagery features extraction



Machine Learning Algorithms

Preliminary vegetation land cover map of Nishnabotna Conservation Area

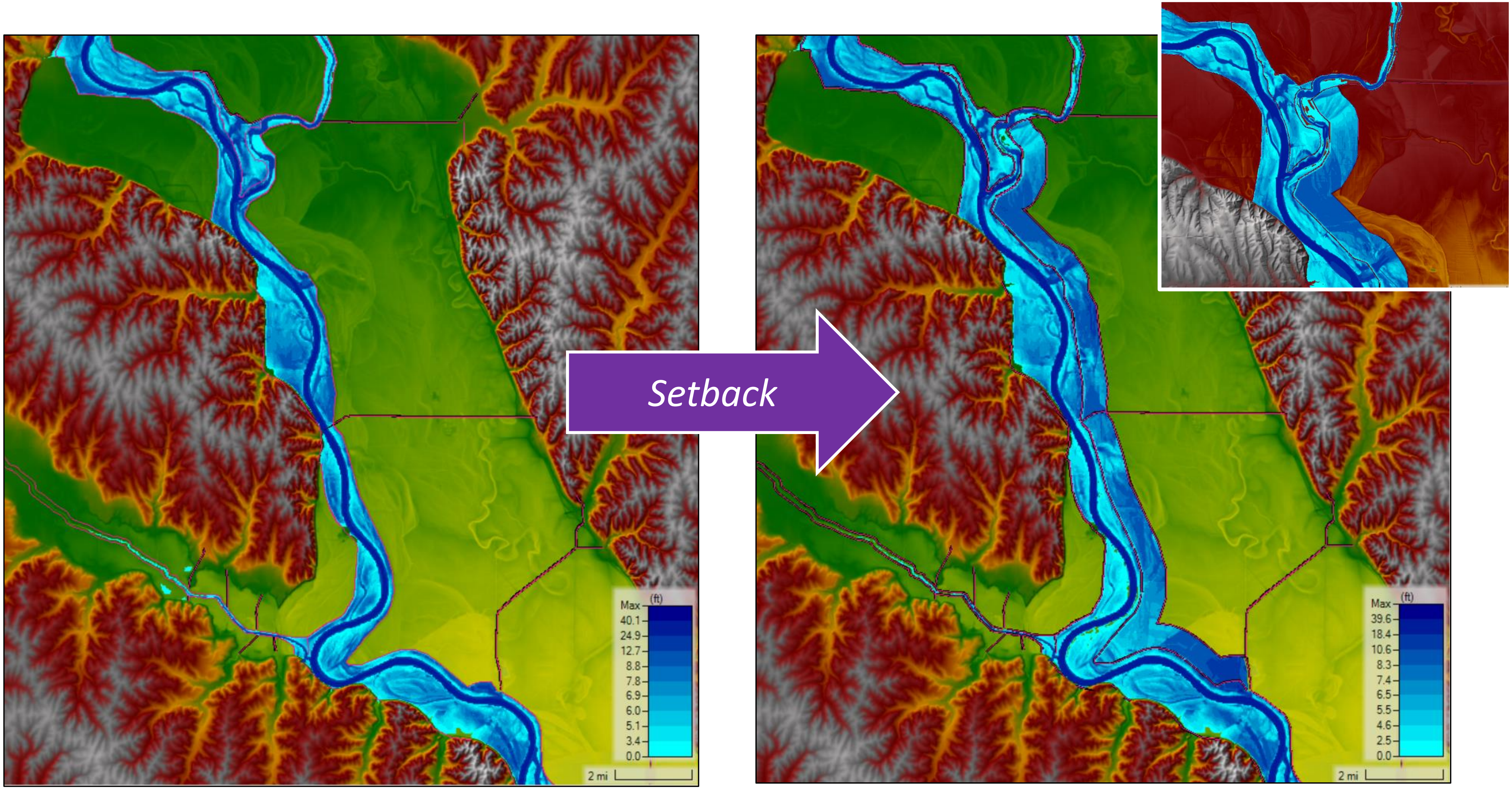
Field Data

- Survey existing floodplains & levee setbacks for multiple taxonomic groups
    - (Insectivorous) bats
    - Neotropical migrant songbirds
    - Anurans (frogs & toads)
    - Vegetation composition/structure
- Automated recording units
- In-person surveys
- Starting Summer 2024
- 2+ M.S. Student(s) – UGA, USD

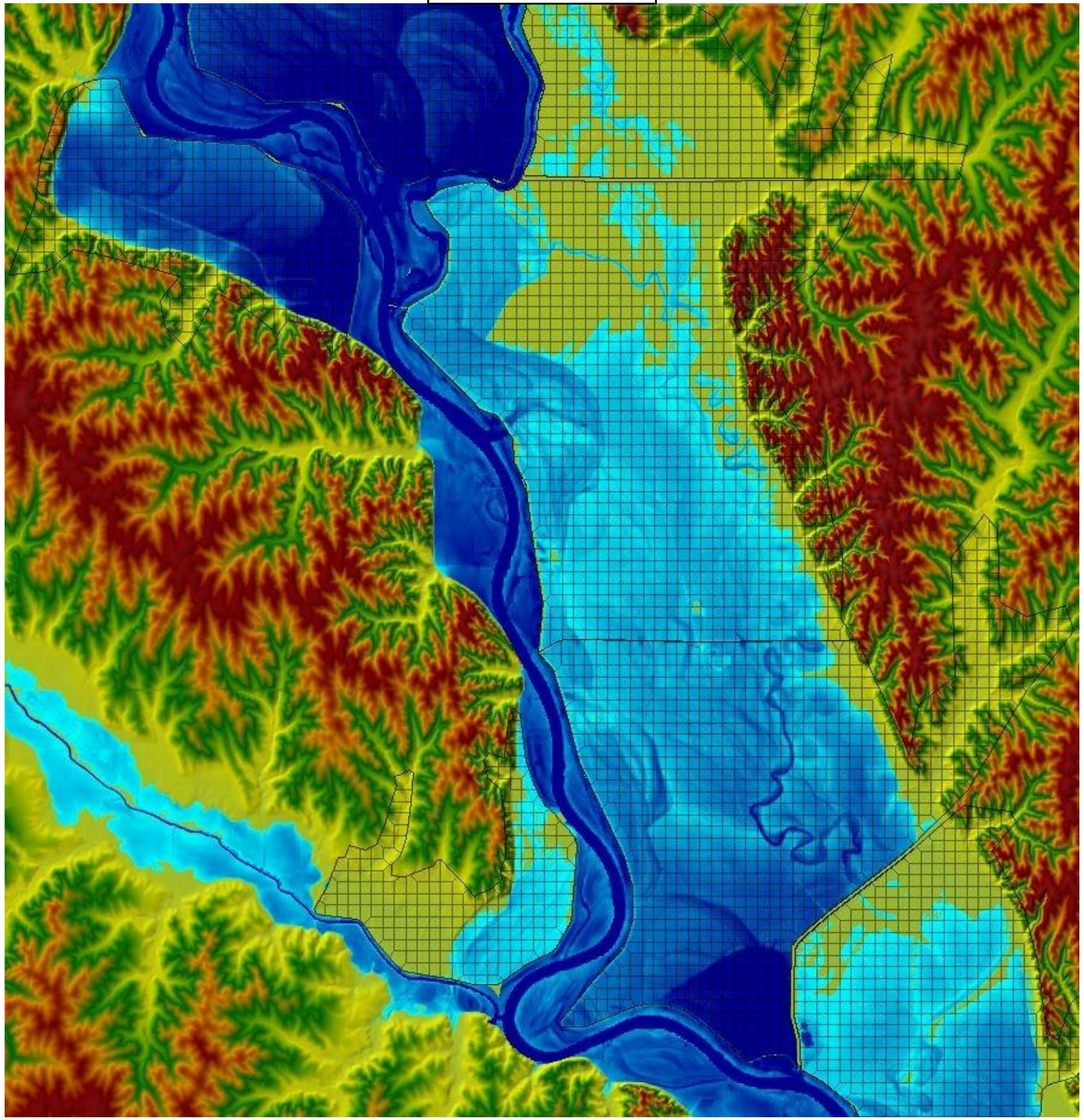
Hydrological Models

- Developed by USACE
- Modified by Matt Chambers (UGA) & Rod Lammers (CMU)
- “Back-casts” to generate predictor variables
  - Peak velocity / scour
  - Inundation depth
  - Inundation frequency

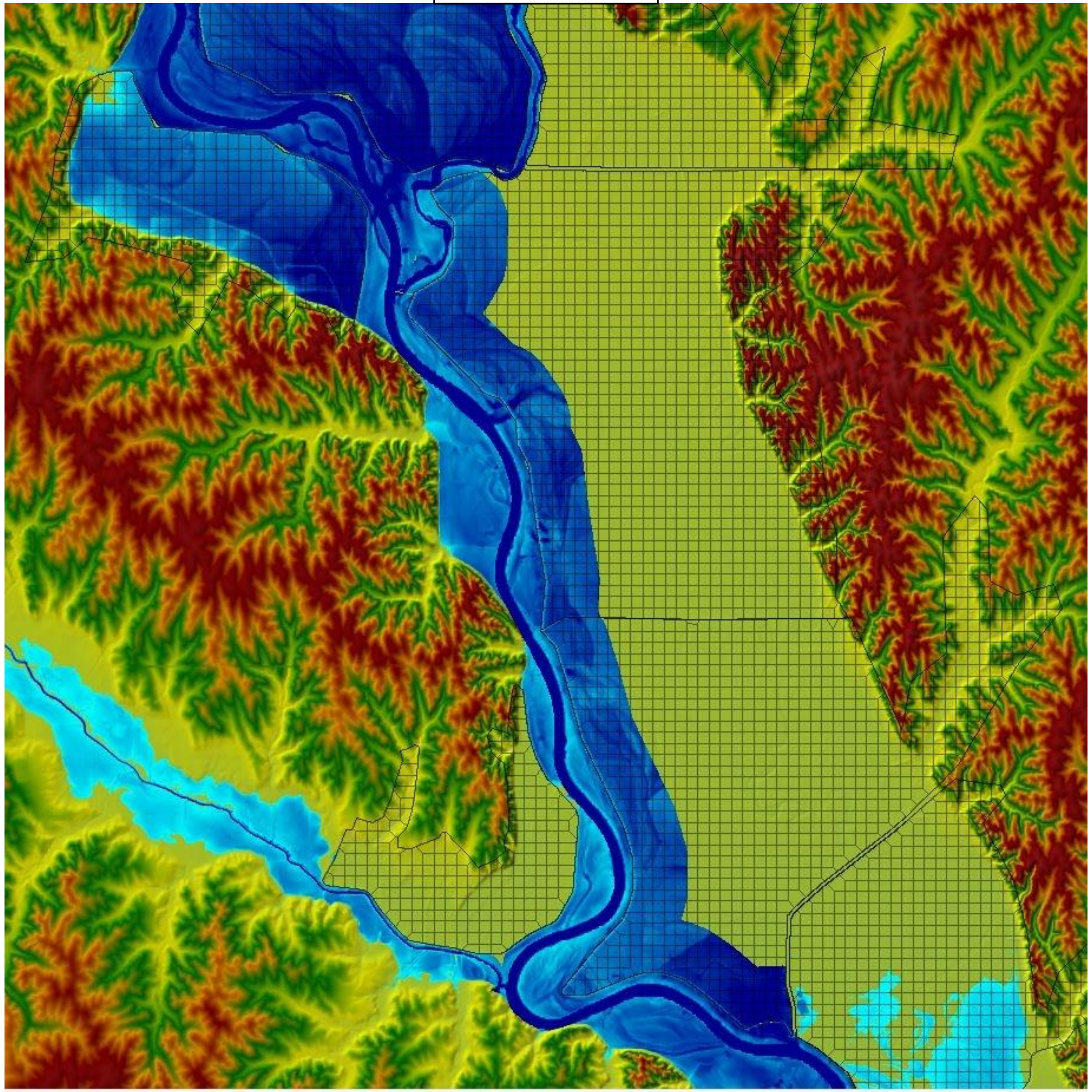
Flood Inundation Modeling



Existing



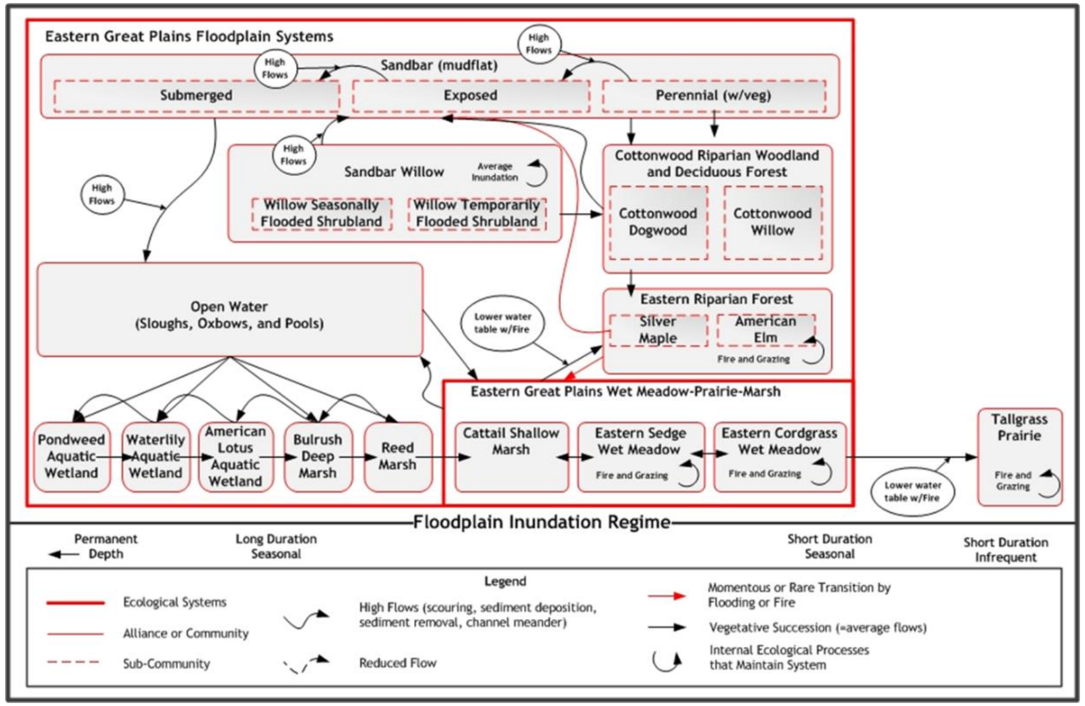
Setback



Ecological Questions

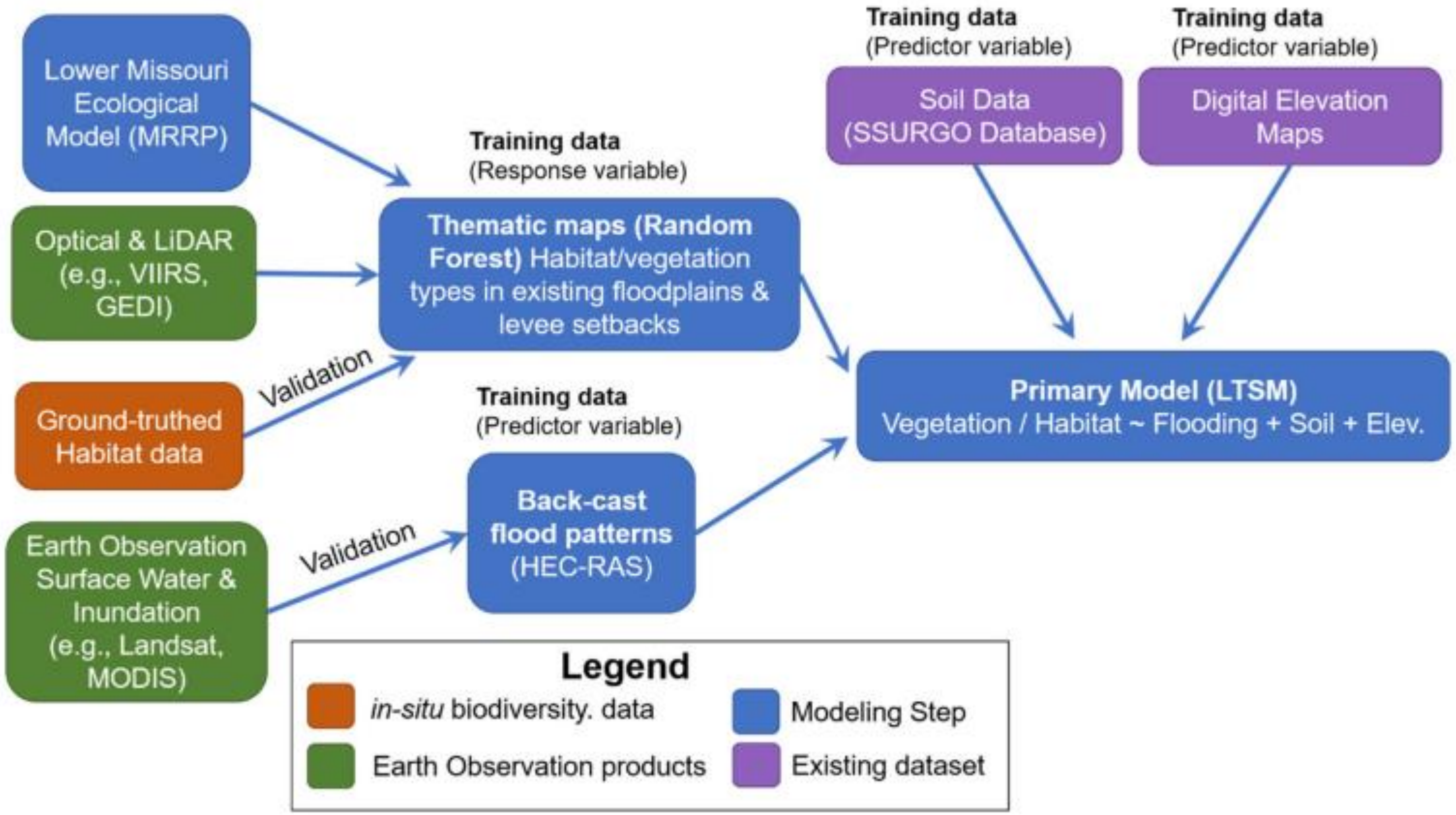
- When floodplains are reconnected, what vegetation types will establish & how will they change through time?
    - Natural succession, floods, soils, management

- How will the mix of vegetation types influence:
    - Wildlife (e.g., birds, amphibians, bats)
    - Flood dynamics (e.g., flood stage, deposition/erosion)
    - Other ecosystem services (e.g., nutrient retention)



NASA ROSES Proposal – Primary Models

- Veg. community ~ Flooding + soil + …



Lower Missouri Ecological Model (MRRP)

Optical & LiDAR (e.g., VIIRS, GEDI)

Ground-truthed Habitat data

Earth Observation Surface Water & Inundation (e.g., Landsat, MODIS)

Validation

Validation

Training data
(Response variable)

Thematic maps (Random Forest) Habitat/vegetation types in existing floodplains & levee setbacks

Training data
(Predictor variable)

Back-cast flood patterns (HEC-RAS)

Training data
(Predictor variable)

Soil Data (SSURGO Database)

Training data
(Predictor variable)

Digital Elevation Maps

Primary Model (LTSM)
Vegetation / Habitat ~ Flooding + Soil + Elev.

Legend

🟧 *in-situ* biodiversity. data

🟩 Earth Observation products

🟦 Modeling Step

🟪 Existing dataset

Fig. 2: Our primary ecological model combines earth observation-derived thematic maps of existing floodplains with back-cast flood patterns (validated with additional earth observation products) to predict vegetation structure and habitat types in restored floodplains from proposed levee setbacks.

NASA ROSES Proposal – Secondary Models

- Biodiversity, Ecosystem Services (denitrification, sedimentation, flood risk)
- e.g., Bat occupancy ~ veg community + canopy height, channel width…

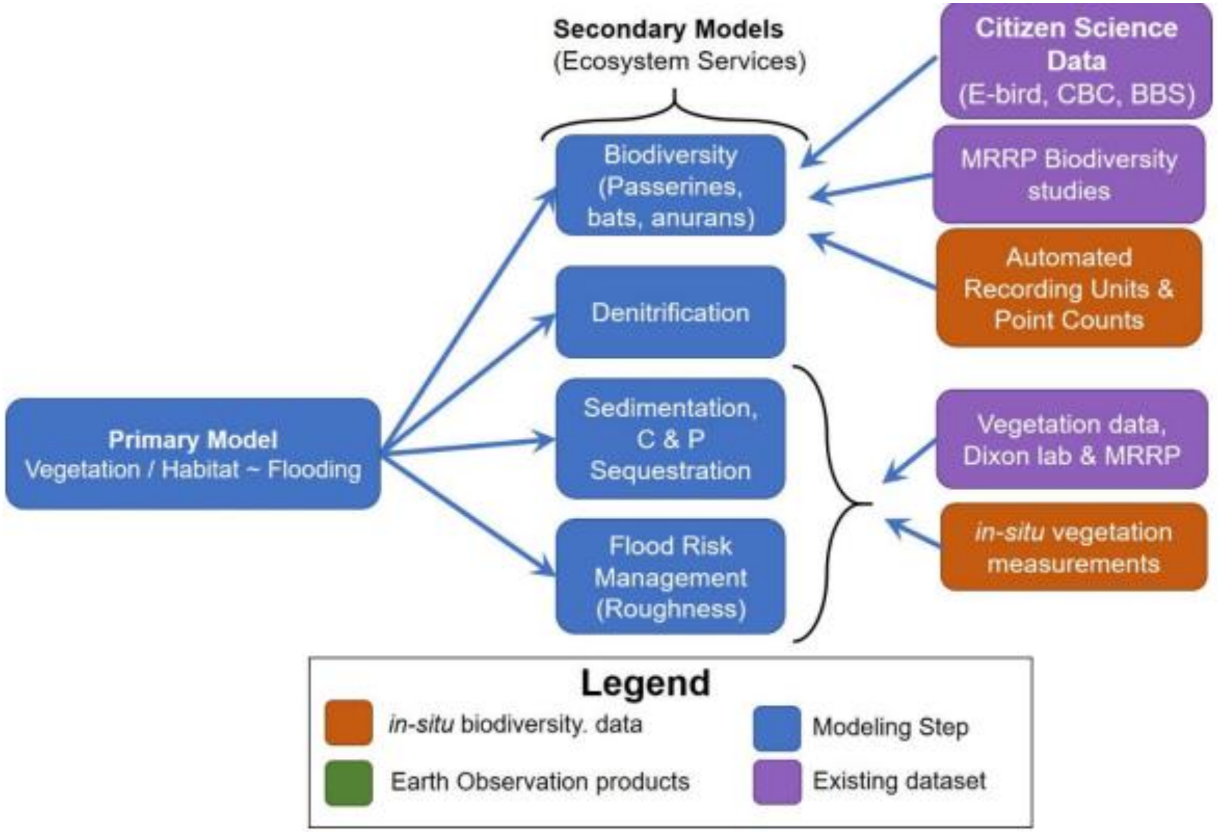
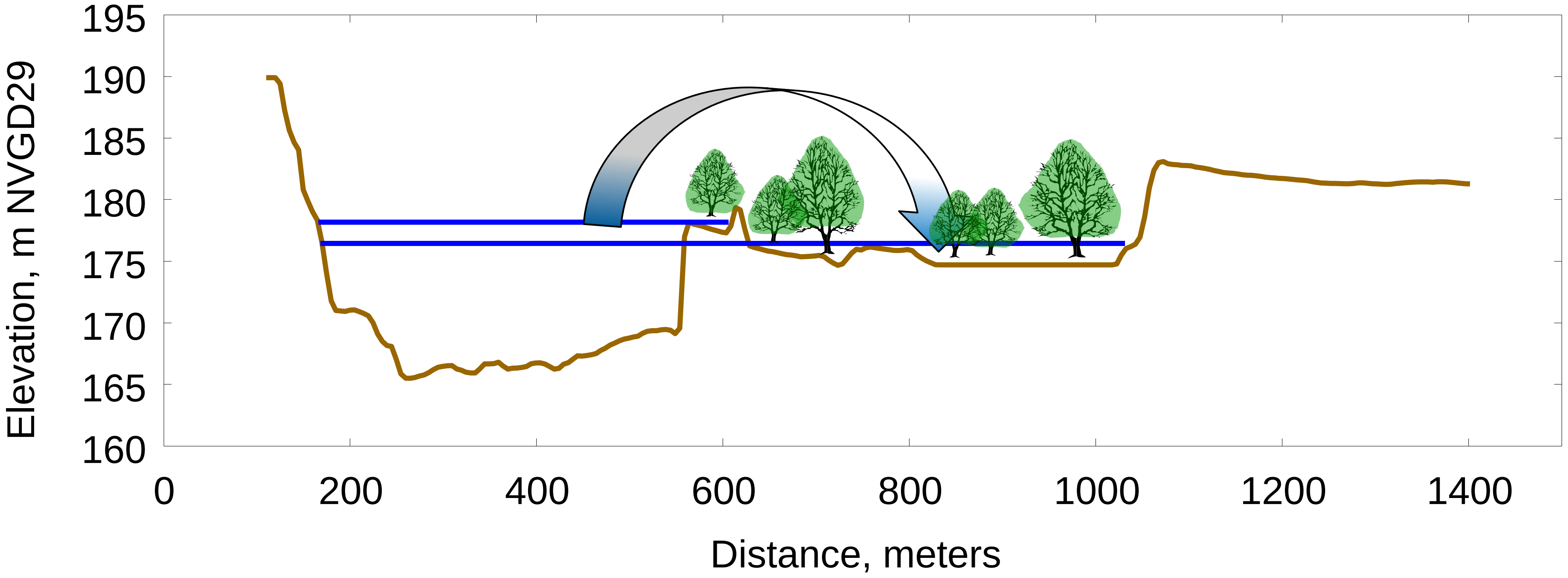


Fig. 3: Outputs of the primary model will feed into a suite of secondary ecosystem service models that assess delivery and tradeoffs between multiple services of the restored floodplain.

Theoretical local stage effects of setbacks



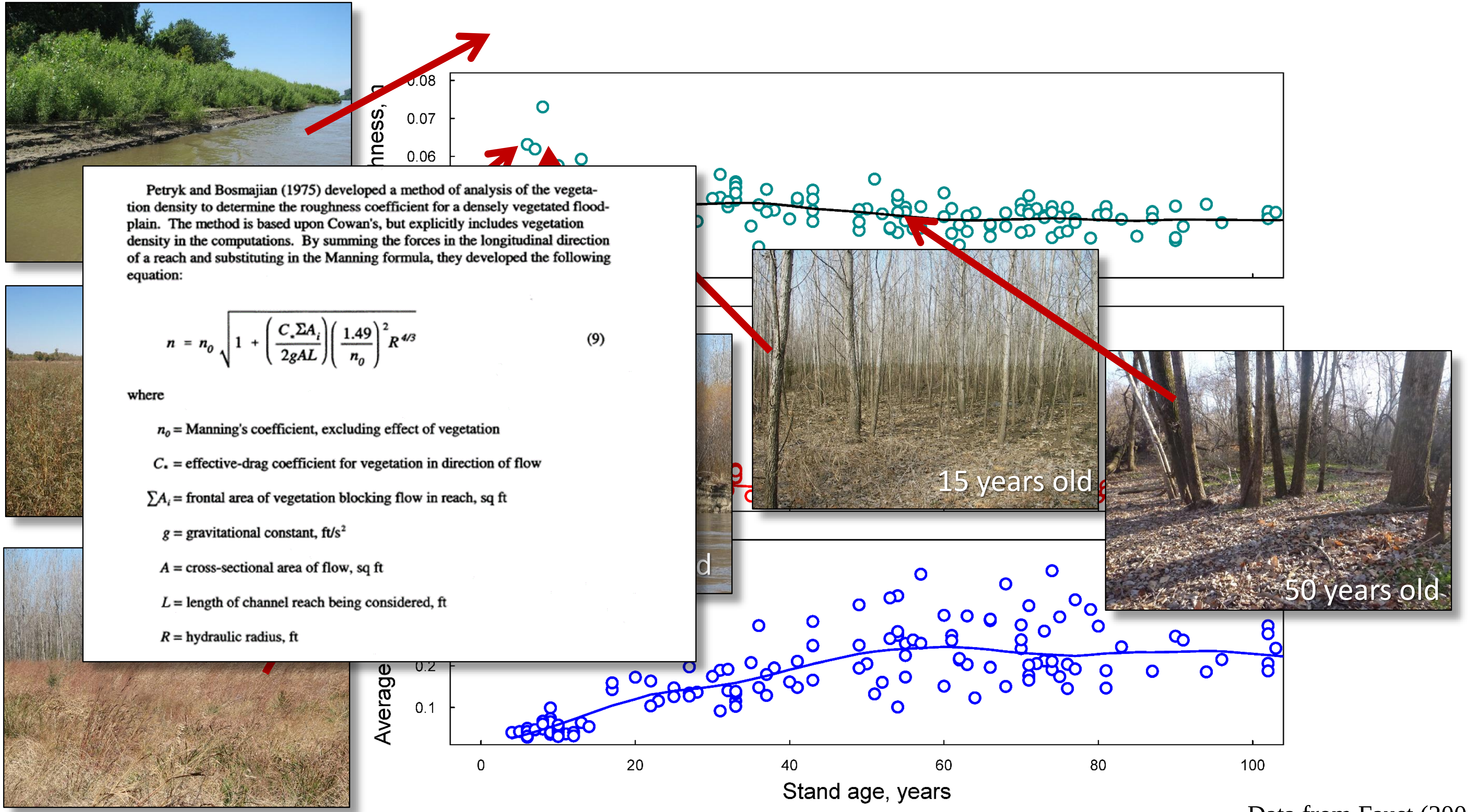
Conservation of Mass:

$$Q_1 = A_1 * V_1 = Q_2 = A_2 * V_2$$

$$A = D * W$$

$$V = \frac{k}{\boxed{n}} D^{2/3} S^{1/2}$$

Hydraulic roughness – vegetation interaction



Petryk and Bosmajian (1975) developed a method of analysis of the vegetation density to determine the roughness coefficient for a densely vegetated floodplain. The method is based upon Cowan's, but explicitly includes vegetation density in the computations. By summing the forces in the longitudinal direction of a reach and substituting in the Manning formula, they developed the following equation:

$$n = n_0 \sqrt{1 + \left(\frac{C_* \Sigma A_i}{2gAL}\right)\left(\frac{1.49}{n_0}\right)^2 R^{4/3}} \qquad (9)$$

where

n_0 = Manning's coefficient, excluding effect of vegetation

C_* = effective-drag coefficient for vegetation in direction of flow

ΣA_i = frontal area of vegetation blocking flow in reach, sq ft

g = gravitational constant, ft/s^2

A = cross-sectional area of flow, sq ft

L = length of channel reach being considered, ft

R = hydraulic radius, ft

Data from Faust (2006)

Floodplain sedimentation – Wilkinson Island, Mississippi River

Remo and others (2018)

Vegetation Interactions

- Age, type, structure, density & location of vegetation influences hydraulic roughness
  - Influence sedimentation, flood conveyance, stage
  - Grasslands, older forests have lower roughness than dense young forests
- Manage successional trajectories & spatial patterns of vegetation to optimize flood risk reduction benefits of setbacks
  - Possible ecosystem service tradeoffs


5 years old


15 years old


50 years old

Water Quality

- Downstream WQ benefits
  - Potential to reduce nutrient loading?
  - Large rivers with high nutrient loading?
  - Spatial scale of one setback?
  - Material impact on BCR?
- Parallel approach
  - Engineer borrow pit treatment wetlands
  - Re-plumb agriculture drainage to retain excess nutrients
  - Affordable? Practical? Effective?

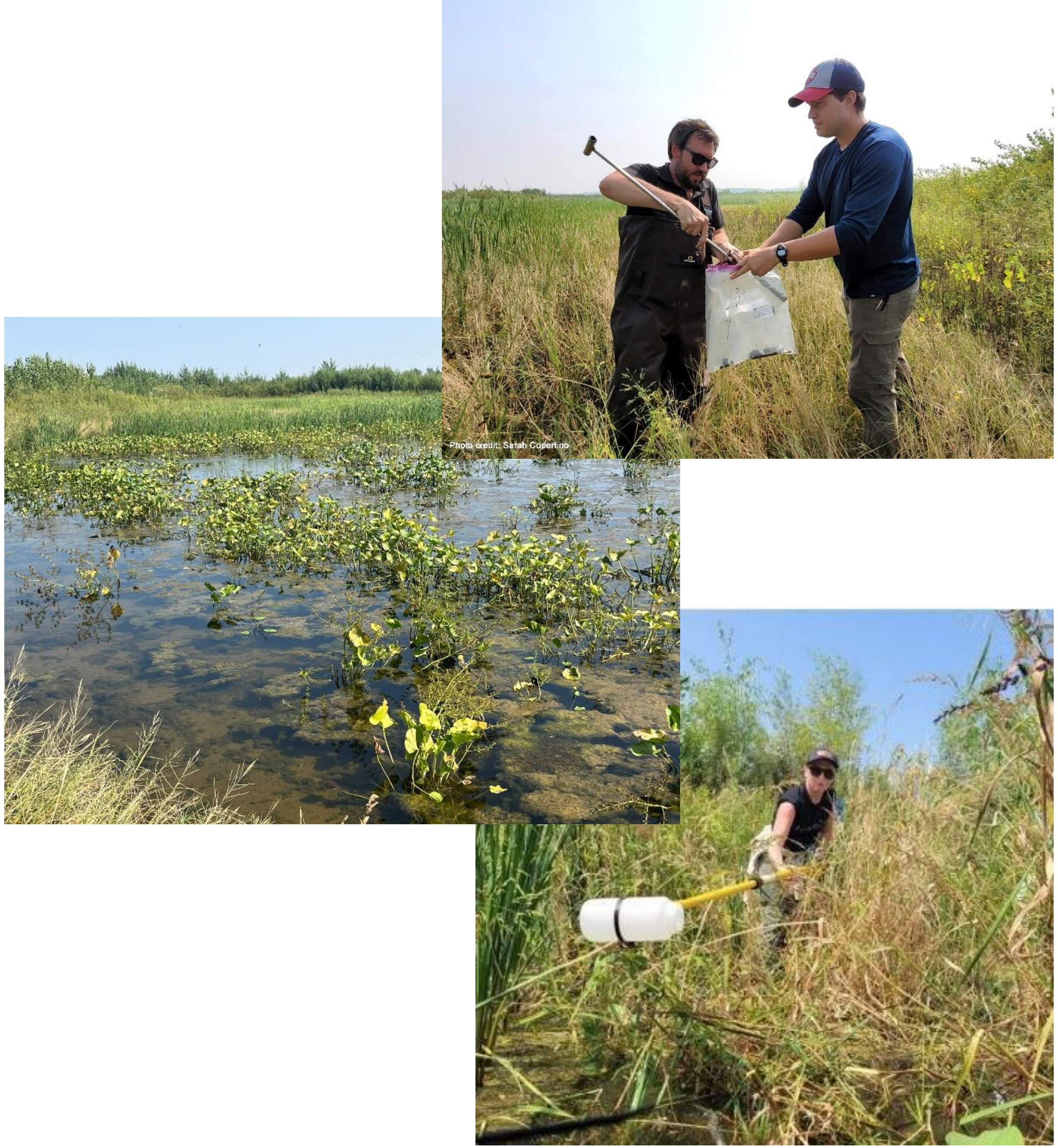
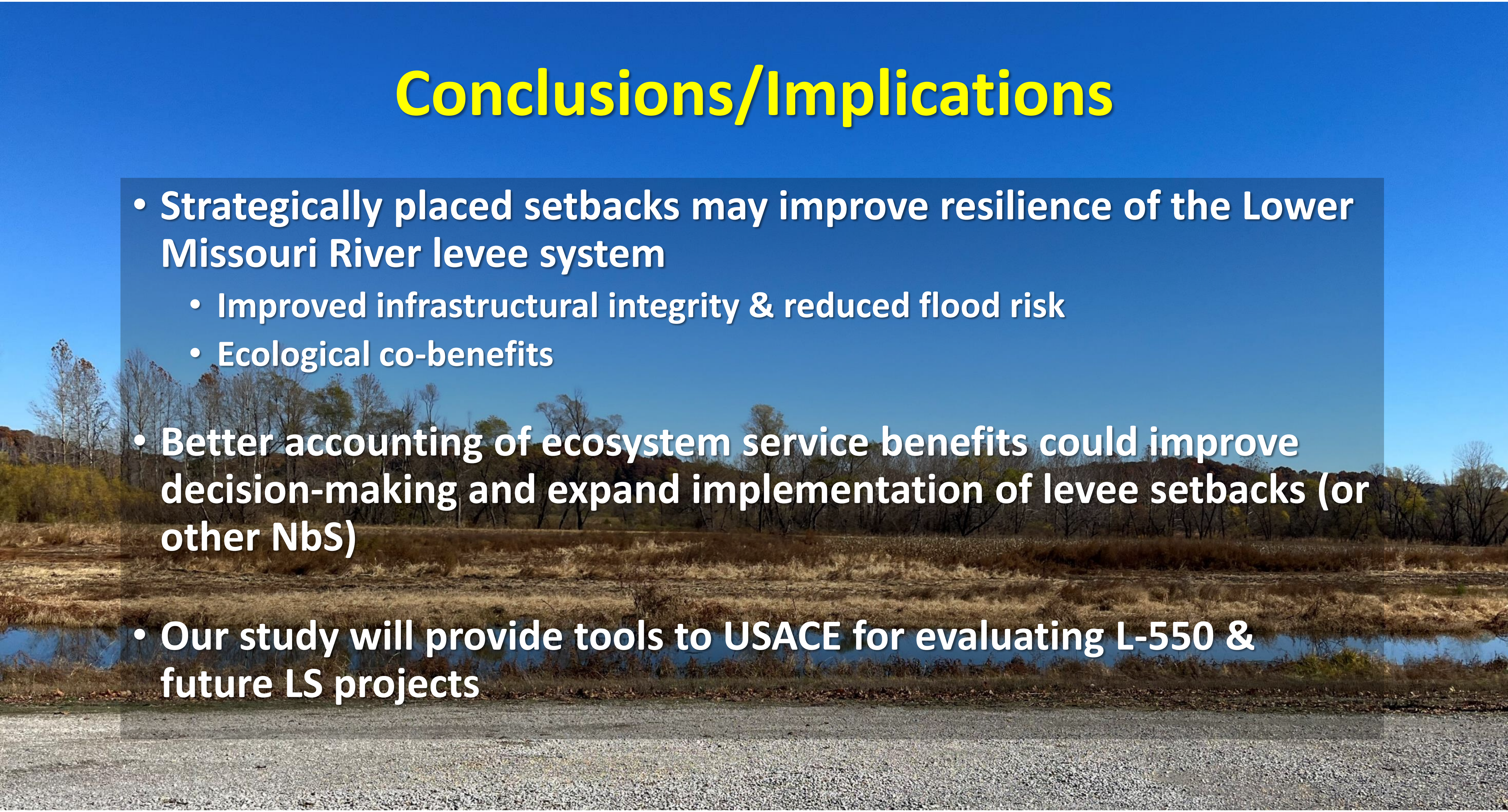


Photo credit: Sarah Copertino

Conclusions/Implications



- Strategically placed setbacks may improve resilience of the Lower Missouri River levee system
  - Improved infrastructural integrity & reduced flood risk
  - Ecological co-benefits

- Better accounting of ecosystem service benefits could improve decision-making and expand implementation of levee setbacks (or other NbS)

- Our study will provide tools to USACE for evaluating L-550 & future LS projects

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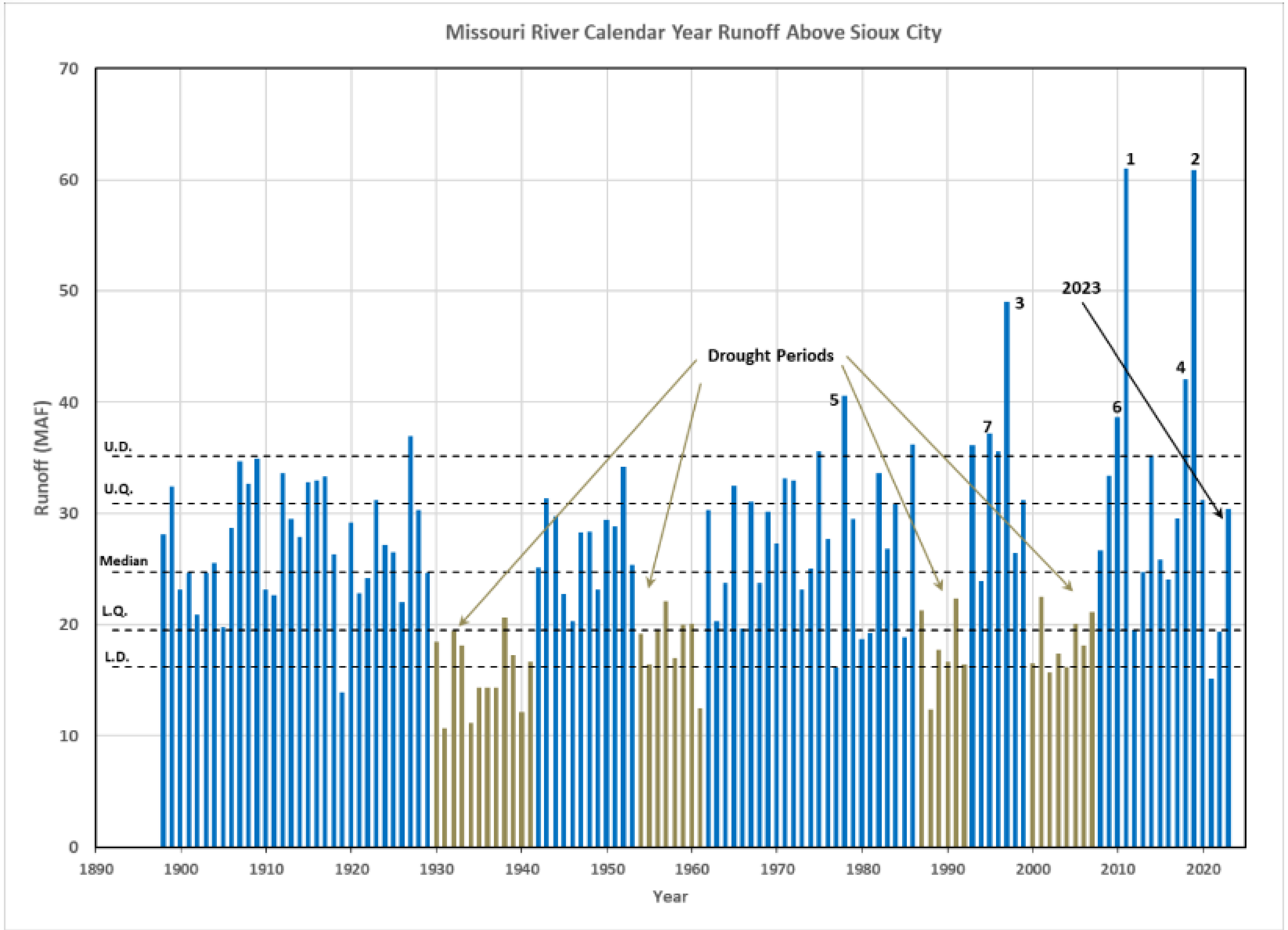

Calendar-year runoff from 1898 to 2023 above Sioux City, IA, showing the drought periods and median, quartile, and upper/lower deciles. The top seven runoff years in the POR are numbered.

Theoretical flow-attenuation effects of setbacks