Karthik Ramaswamy[1,*]
Tyler Lark[1,2]
Yanhua Xie[3]
Nazli Uludere Aragon[1]
[1]University of Wisconsin–Madison
[2]Michigan State University
[3]University of Oklahoma
*Correspondence: karthik.ramaswamy@wisc.edu

Reinforcement learning for **Sustainable Irrigation System Upgrades** in U.S. agriculture

AGU25
New Orleans, LA | 15–19 December 2025

Background

Why optimize irrigation?

- In the U.S., agricultural water uses about 80% of the nation's consumptive water use.
- In many western states, declining groundwater threatens long-term food production.
- Efficient irrigation systems (e.g., Pivot, Drip) offer a solution (Fig. 1), but where and when should upgrades occur?
- This study combines a meta-analysis (1965–2021) with reinforcement learning (RL) to recommend field-level irrigation upgrades.

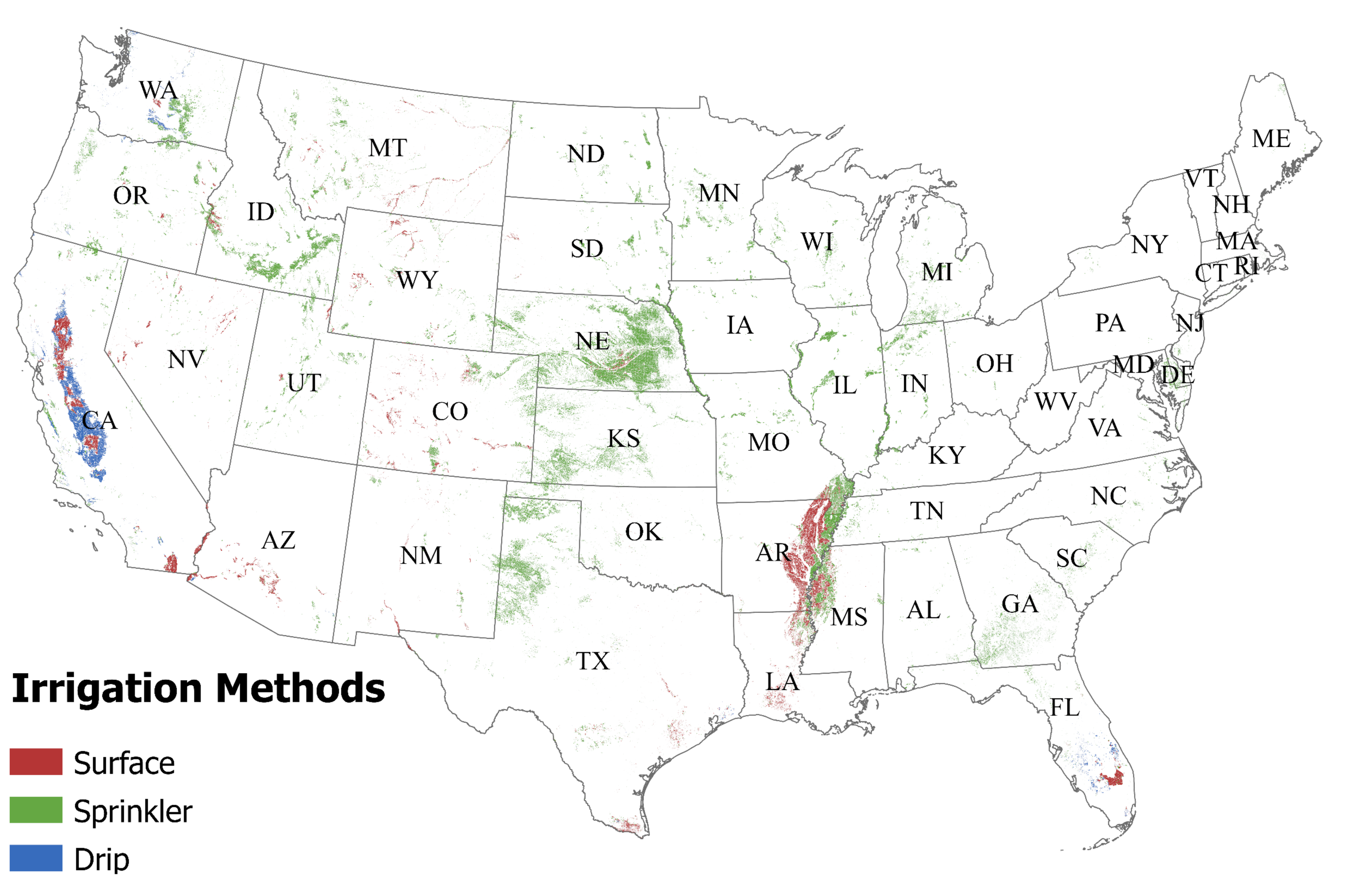

Figure 1. National map of irrigation technologies – surface, sprinkler, and drip.
Baseline Irrigation System Distribution Used for RL Model Training

Methods

Combining meta-analysis with machine learning (Fig. 2)

- Meta-analysis of 50+ studies covering CP, LEPA, and SDI systems.
- Extracted performance metrics: yield, water-use efficiency (WUE), economic returns.
- Developed a field-level decision model using Deep Q-Network (DQN) RL.
- RL model inputs: soil water capacity (AWC), slope, precipitation (PPT), Evapotranspiration (ET), and crop type.
- RL outputs: optimal system upgrade decision per field.

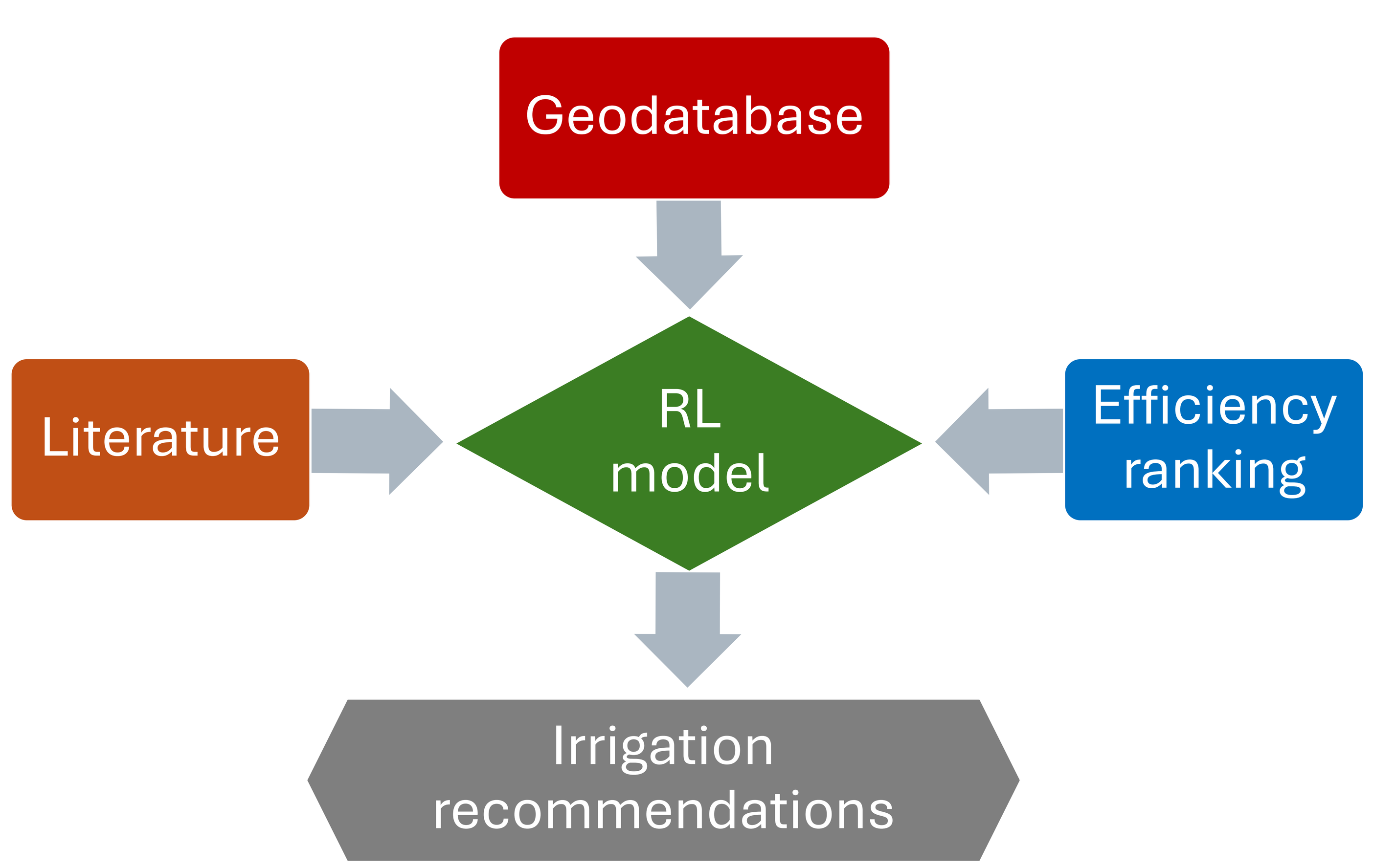

Figure 2. Reinforcement learning workflow integrating geospatial and meta-analytic inputs.

Inputs and Analysis

Field-level dataset & features

- Landsat-based Irrigation Dataset (LANID) enriched irrigated field dataset across the U.S.
- Each field characterized by:
  - Biophysical variables: ET, PPT, AWC, slope, and area
  - Crop type (e.g., hay, corn, berries). See Figure 3.
  - Current irrigation system: surface, sprinkler, or drip
- Total number of fields: 387,480
- Crop categories encoded as orthogonal encoding
- System status encoded as categorical (0 surface, 1 sprinkler, 2 drip)

Meta-analysis integration

- A literature-based meta-analysis informed application efficiencies:
  - Surface: 60%, sprinkler: 80%, drip: 90%
- These were used to simulate field-level irrigation performance and reliability under upgrades.

Reinforcement learning framework

Goal: Learn optimal irrigation system upgrades (surface → sprinkler → drip)
State values: Normalized features: AWC, slope, ET, precipitation, water deficit
Categorical: Crop type (multi-hot vector), current system (basis-vector), climate noise
Actions: 0 = stay or use surface | 1 = upgrade to sprinkler | 2 = upgrade to drip
Constraints: Drip allowed only for: AWC ≥ 60 mm, slope ≤ 8%. No downgrade allowed.

Reward design

$$\text{Reward} = \lambda_W \cdot \text{Water Saved (mm)} - \lambda_R \cdot \max(0, \alpha - \text{ET met ratio})$$

$\lambda_W = 1.0$ (reward for water saving), $\lambda_R = 10.0$ (penalty for ET short fall), and $\alpha = 0.90$ (ET threshold)

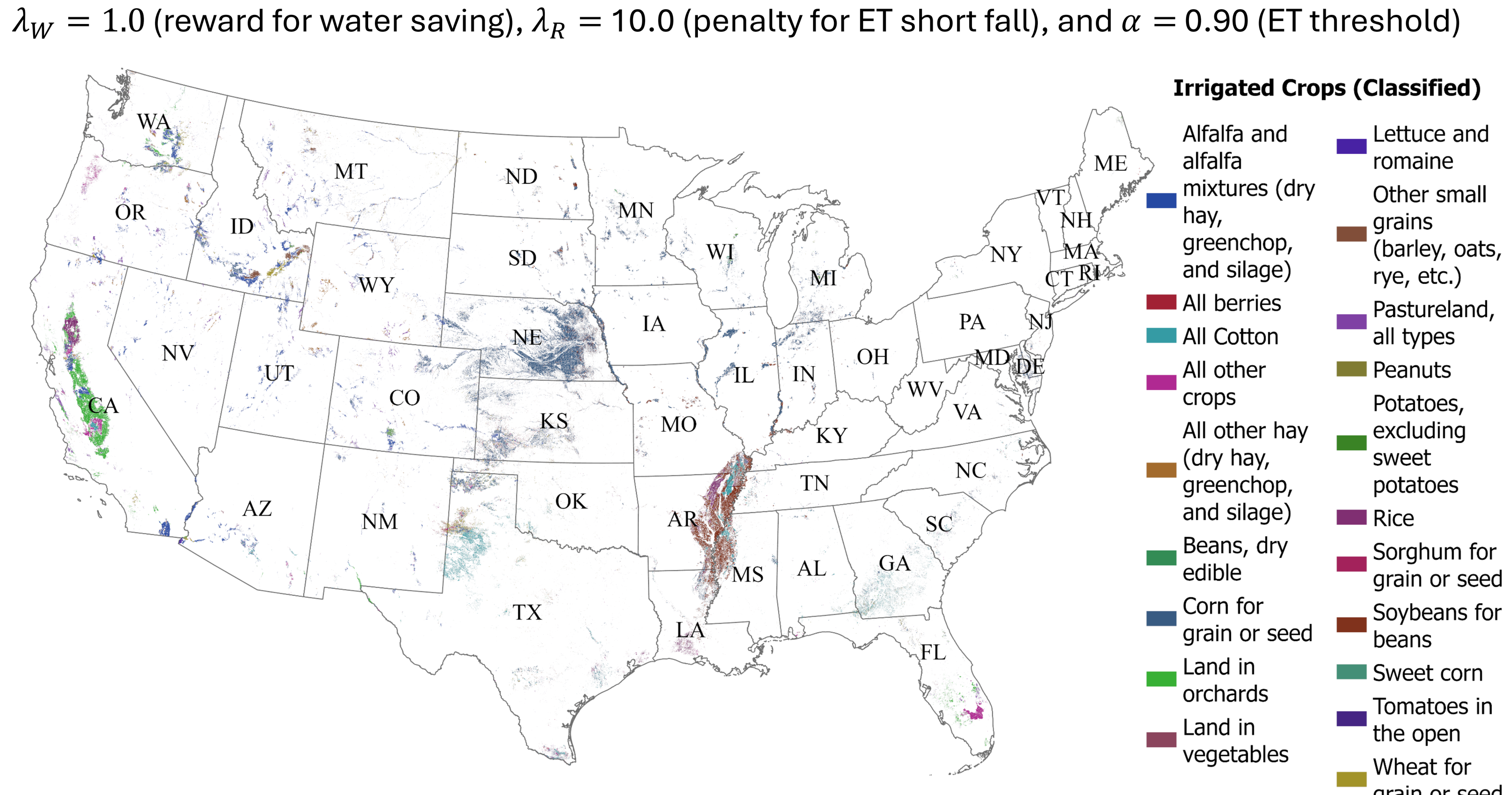

Figure 3. Geographic distribution of dominant irrigated crop types in the contiguous U.S., based on LANID-classified field data.

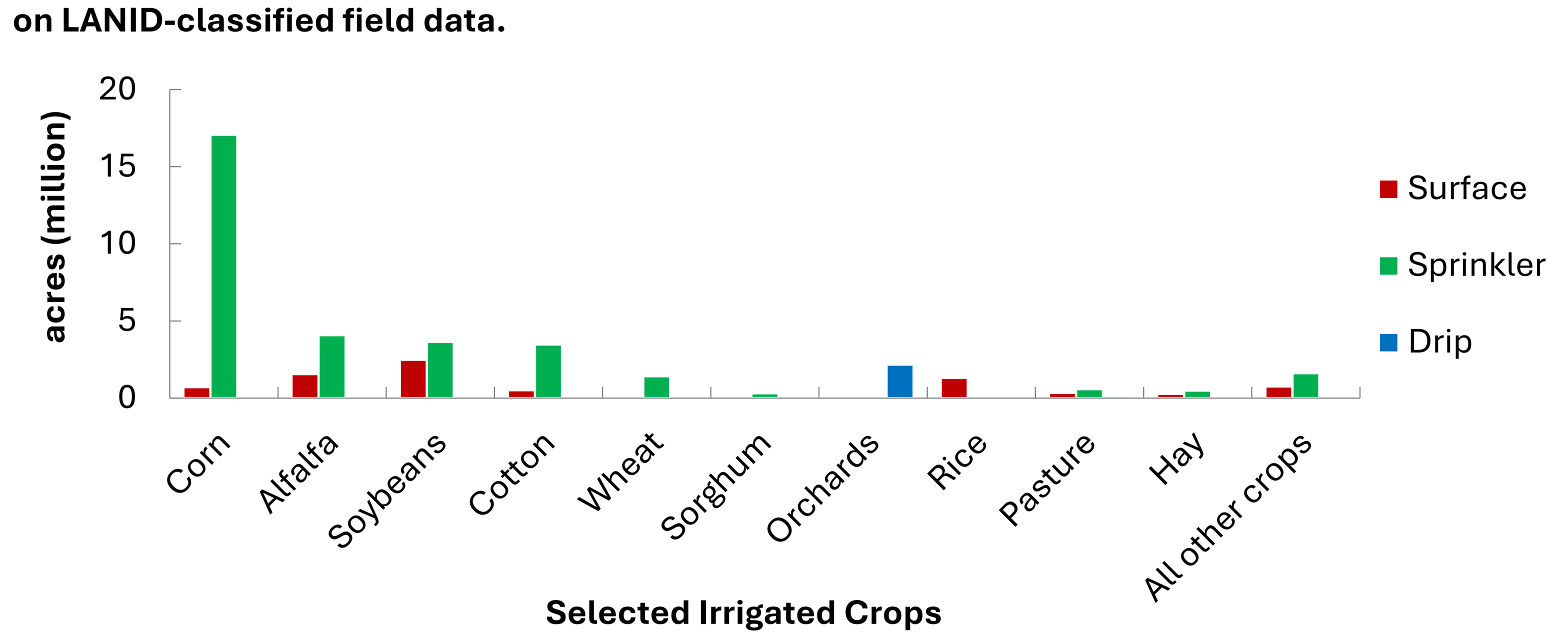

Figure 4. Distribution of irrigation methods (surface, sprinkler, drip) by crop type.
Bars represent the share of acreage per method for each crop category.

Results

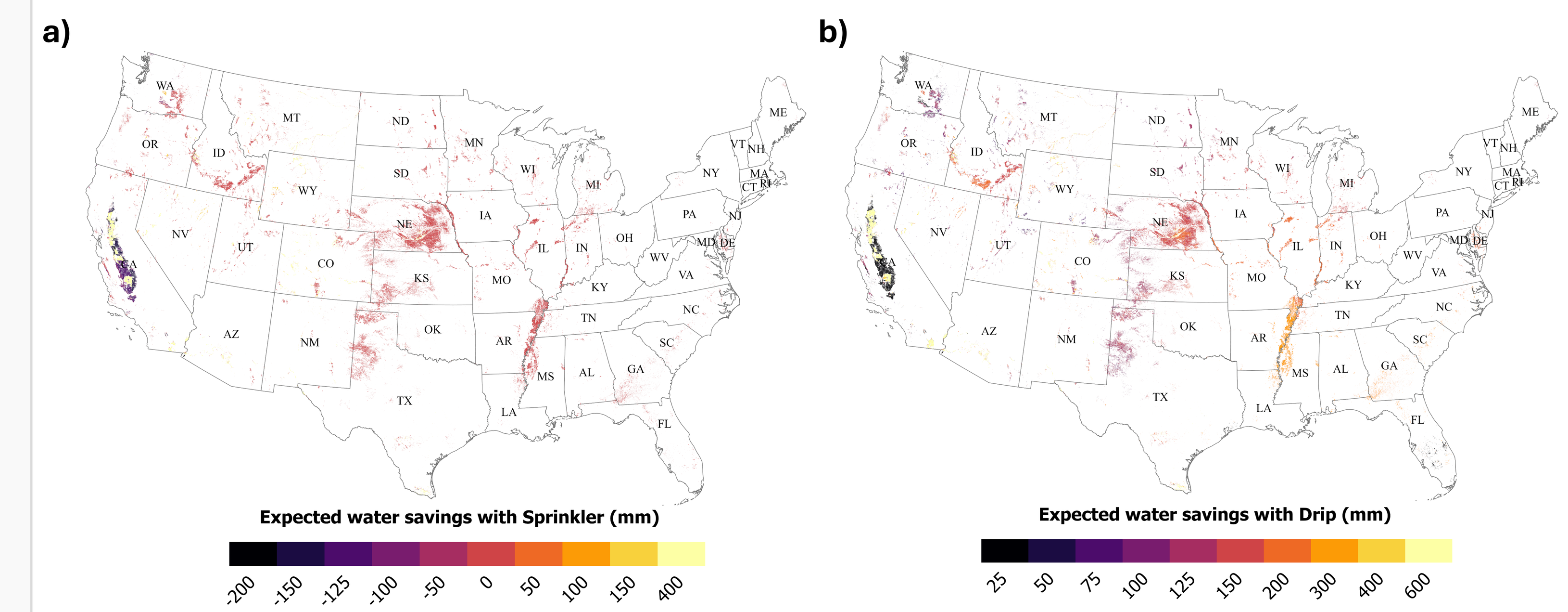

Figure 5. Expected water savings (mm) from hypothetical irrigation upgrades based on ET and efficiency. a) Baseline → Sprinkler b) Baseline → Drip

System Upgrade outcomes (CONUS irrigated fields, n = 387,480)

Surface: 73,546 fields, Sprinkler: 292,984 fields, Drip: 20,950 fields

Surface → Sprinkler

- Of 73,546 surface-irrigated fields, 5,972 fields (8.1%) are flagged for upgrade to sprinkler.
- These upgraded fields have an average gross irrigation savings about 267 mm/year.
- This corresponds to about 1.76×10^9 m^3/year of potential water savings (1.43 million ac-ft/year).

Sprinkler → Drip

- Of 292,984 sprinkler fields, 7,497 fields (2.6%) are recommended for upgrade to drip.
- These fields save on average 82 mm/year of gross irrigation.
- About 1.60×10^8 m^3/year (1.3×10^5 acre-feet/year) of potential water savings.

Drip systems

- All 20,950 drip fields (100%) remain drip – no downgrades are allowed.

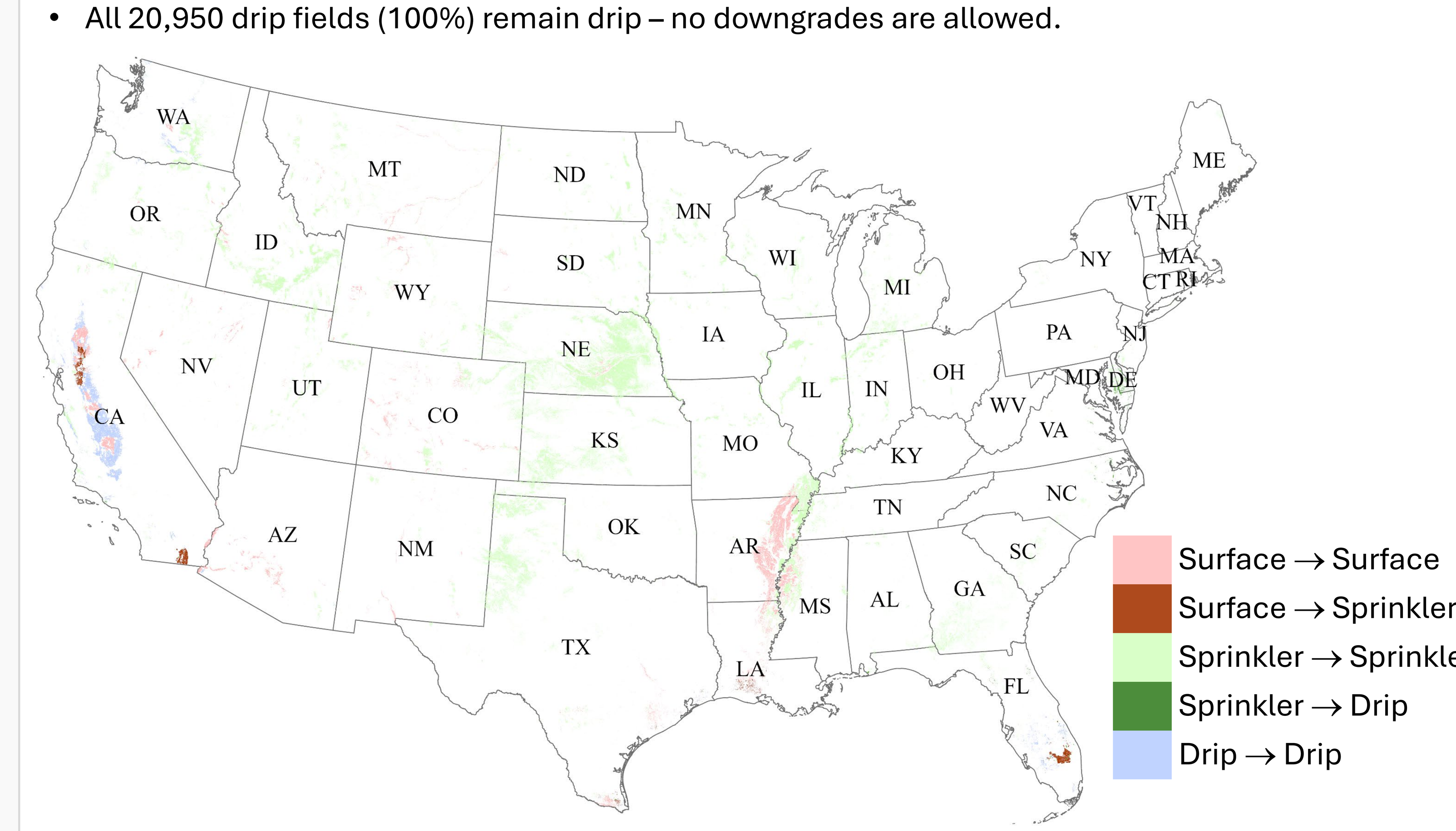

Figure 6. Optimal field-level recommendations for irrigation system transitions across the U.S.

Conclusion

- In total, about 3.5% of all irrigated fields (13,469 of 387,480) are economically and hydrologically feasible to upgrade (surface → sprinkler or sprinkler → drip).
- Combined, these upgrades yield an estimated 1.92 km^3 of gross irrigation water savings per year (1.56 million acre-feet/year), assuming average efficiencies and no indirect effects.
- Applying simple biophysical-based upgrade rules, we find that about 8% of surface-irrigated fields and 2.6% of sprinkler fields in the CONUS have strong potential for upgrading to more efficient systems.

Acknowledgments

The authors would like to thank members of the USGS Water Mission Area for sharing verified irrigation data, feedback and ideas for mapping, and insights regarding data use for water estimation. This research has been supported by the US Geological Survey (grant no. G19AC00080).