

Integrated Modeling of the Water–Food–Ecosystem Nexus in the Upper Main Catchment under Future Climate and Socioeconomic Scenarios

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MAPPING TEMPERATE VULNERABILITY

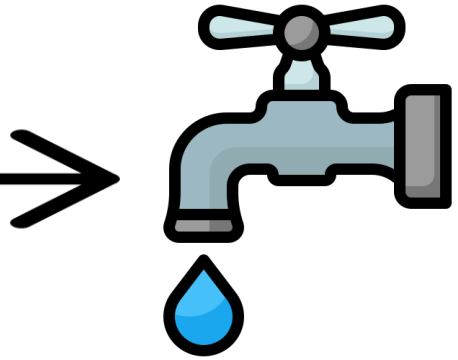


Climate Pressure in a Temperate & Rainfed Agricultural Region?

+1.7 to +4.8 °C Warming



Physical Hydrology
SWAT+



Human Allocation
WEAP

THE ANATOMY OF CLIMATE ADAPTATION



Intensifying ET Engine

Persistent summer droughts



"Drought Escape" Phenology

Accelerated crop maturation



The Adaptation Paradox

Yield Ceilings & Resource Stresses

This presentation participates in OSPP

EGU

Outstanding Student & PhD candidate Presentation contest

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Explore the Research

- Background
- Methodology
- Calibration
- Climate & Hydrology
- Agricultural Productivity
- Ecosystem Health
- Irrigation Intervention
- Nexus Synthesis

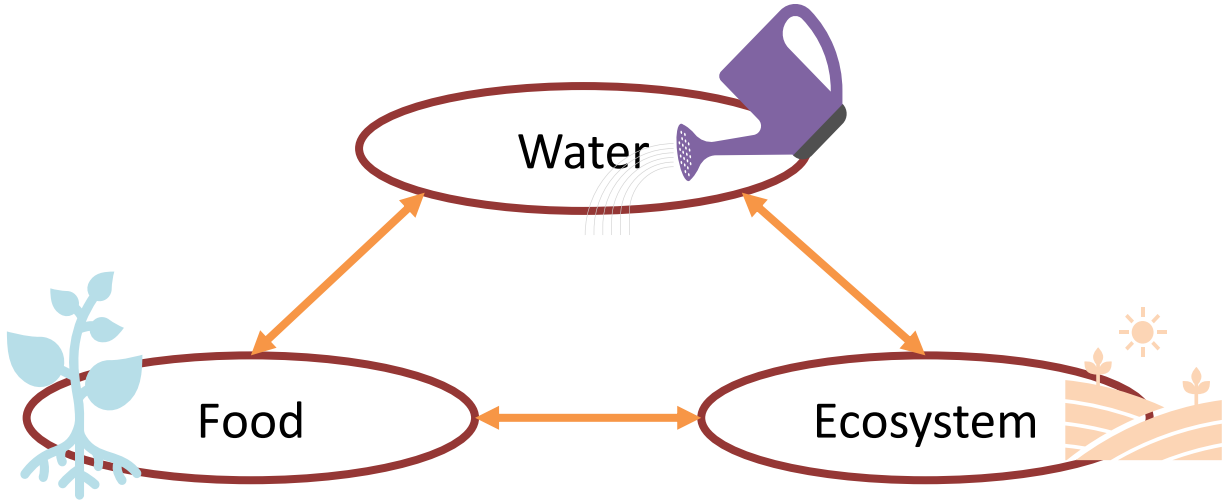
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MOTIVATION

INTRODUCTION



- Inextricably linked sectors
- Pressure exacerbated by population & climate change
- Research biased towards arid regions
- Isolated research ignores critical systemic feedback loops
- Need for integrated, forward-looking approaches

RESEARCH OBJECTIVES

INTRODUCTION

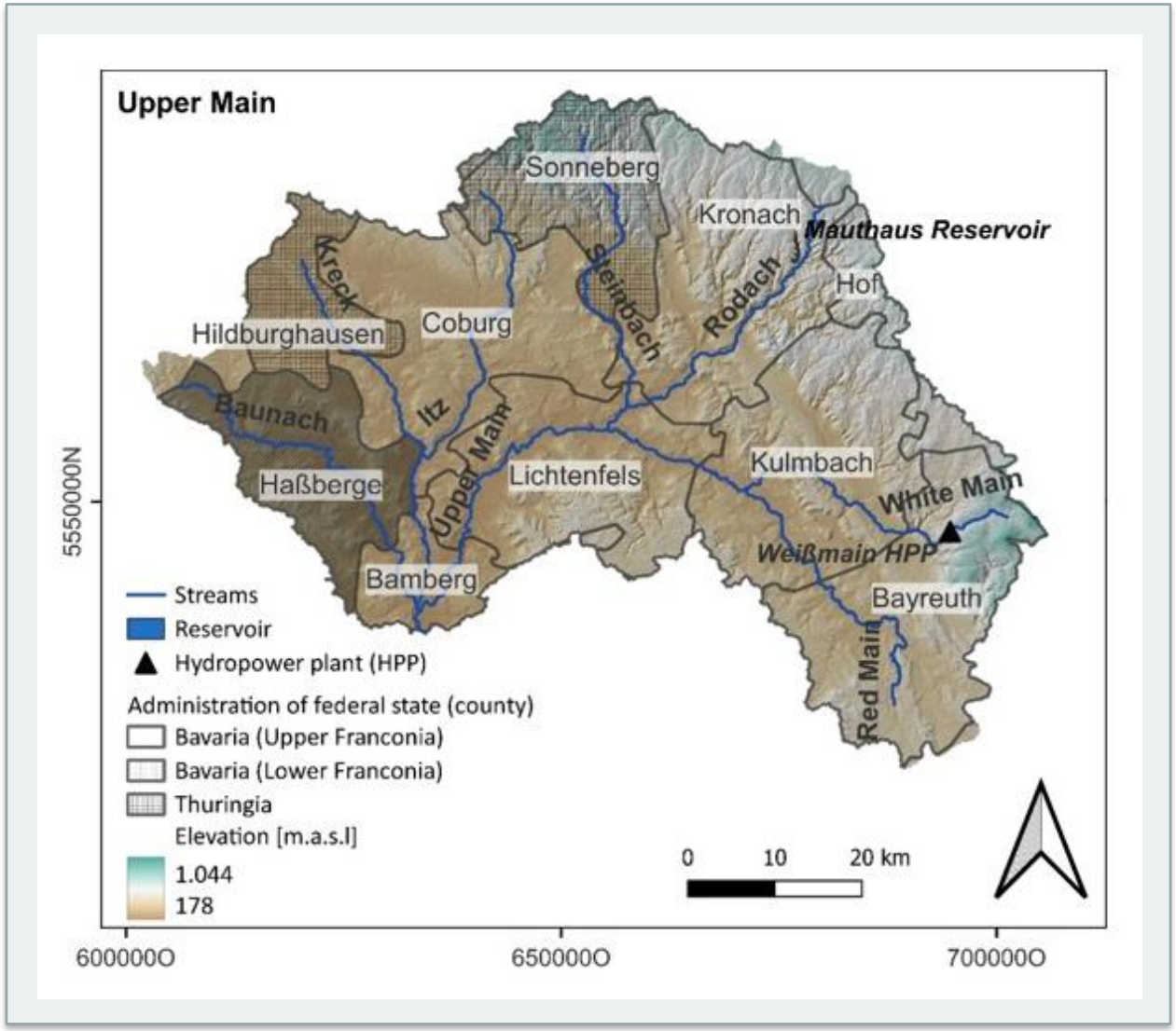
- **Hydrological** response to climate change
- Impacts on rainfed **agricultural** systems
- **Nitrate** dynamics and ecosystem response
- **Implications** for the WFE nexus
- **Irrigation** sensitivity analysis

STUDY AREA

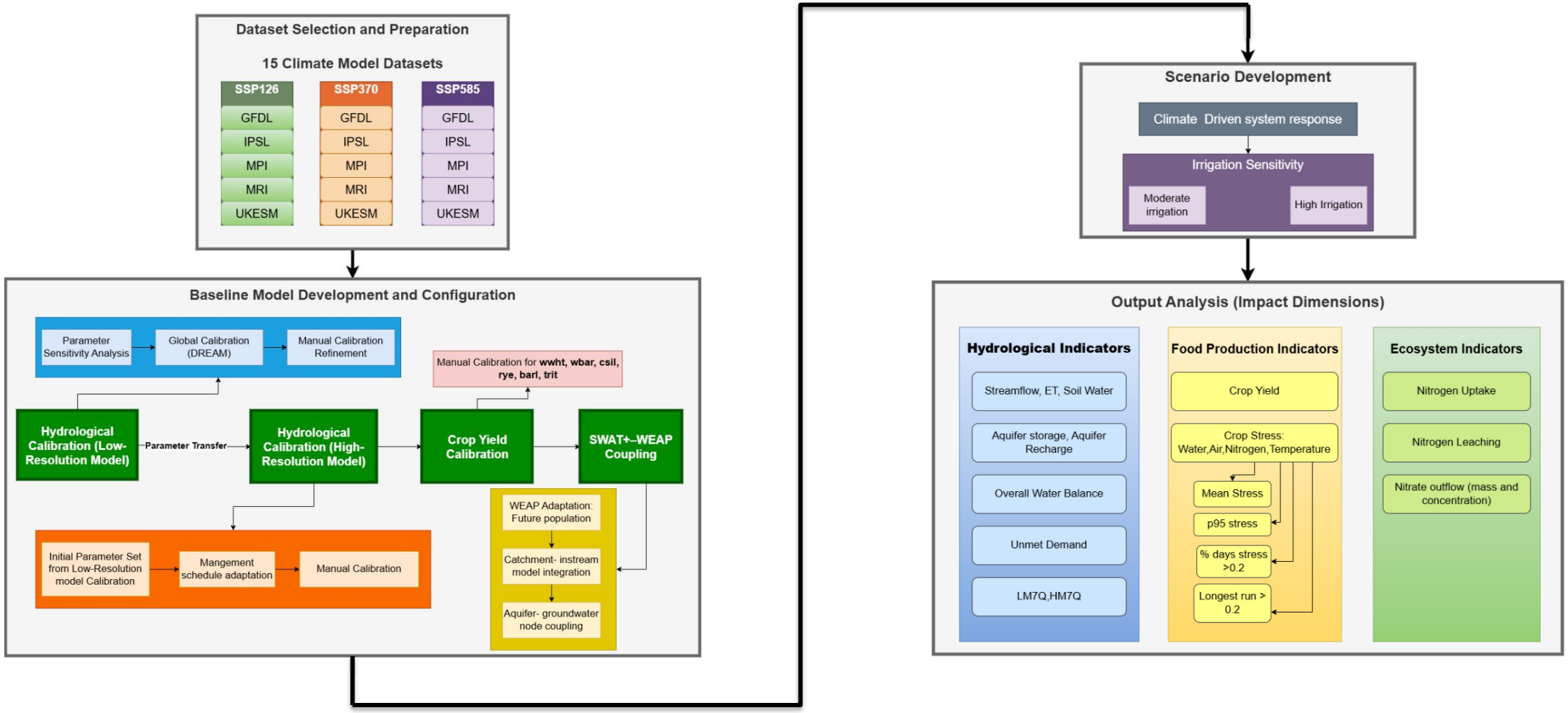
MATERIALS

Upper Main Catchment, Bavaria

- **Land Use:** Highly agricultural, driving regional food security.
- **Soils:** Luvisols & Cambisols, prone to waterlogging.
- **Hydrology:** Pluvial-nival regime with 700-1500 mm annual precipitation

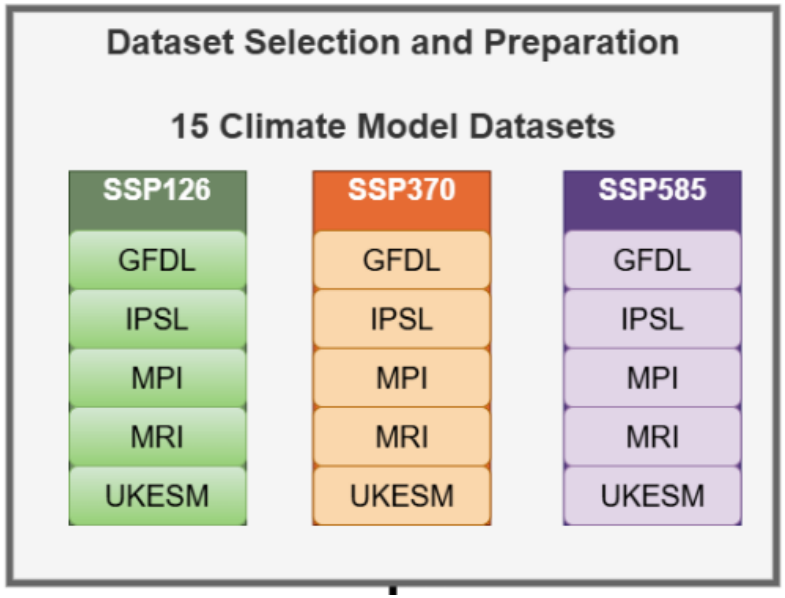


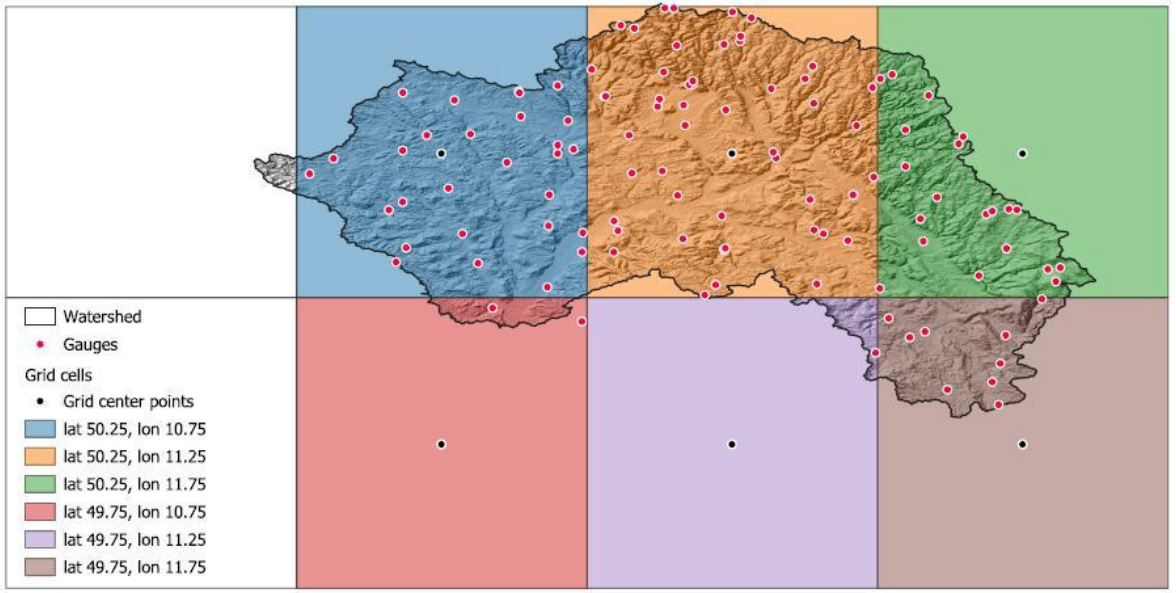
COMPOSITE MODELING FRAMEWORK



CLIMATE SCENARIOS AND MODEL FORCING

COMPOSITE MODELING FRAMEWORK





🌱 **SSP1–2.6:** Sustainability, low emissions

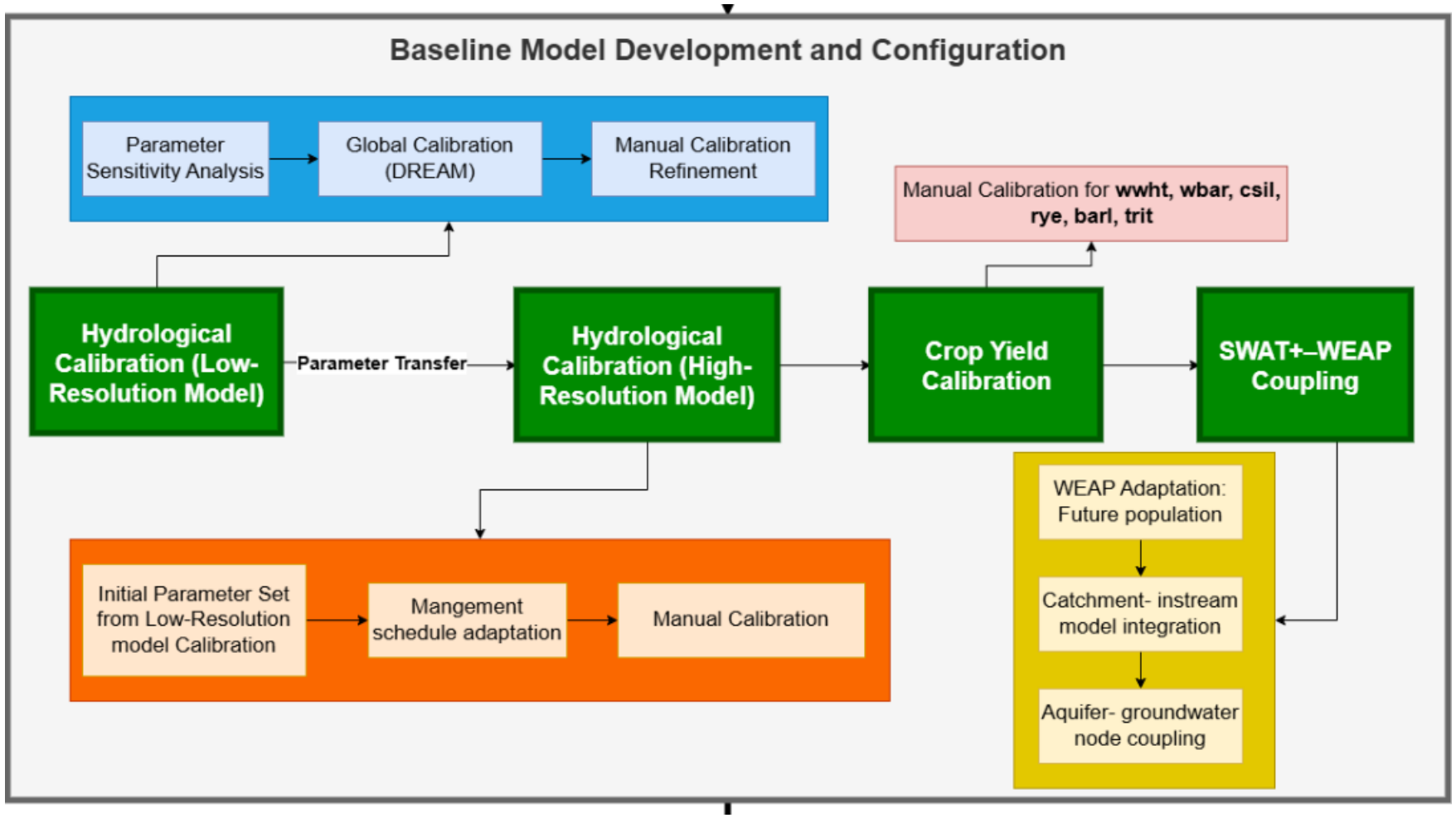
⚠️ **SSP3–7.0:** Regional rivalry, high challenges

🔥 **SSP5–8.5:** Fossil-fueled growth, very high emissions

Data Source: ISIMIP 3b bias-corrected GCM projections (0.5°×0.5°)

BASELINE MODEL DEVELOPMENT

COMPOSITE MODELING FRAMEWORK

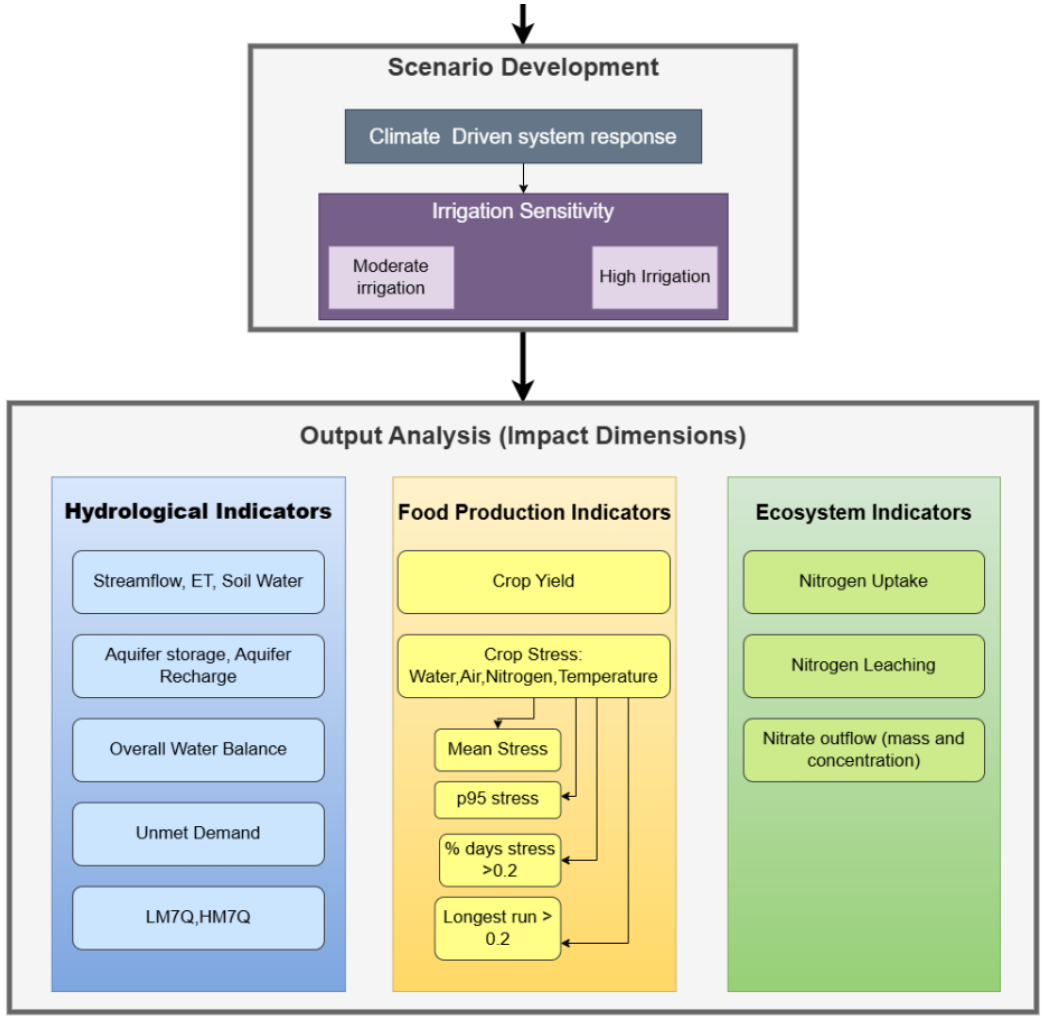


Major Crops:

- Winter wheat
- Winter barley
- Rye
- Triticale
- Spring barley
- Silage Maize

IMPACT ASSESSMENT FRAMEWORK

COMPOSITE MODELING FRAMEWORK

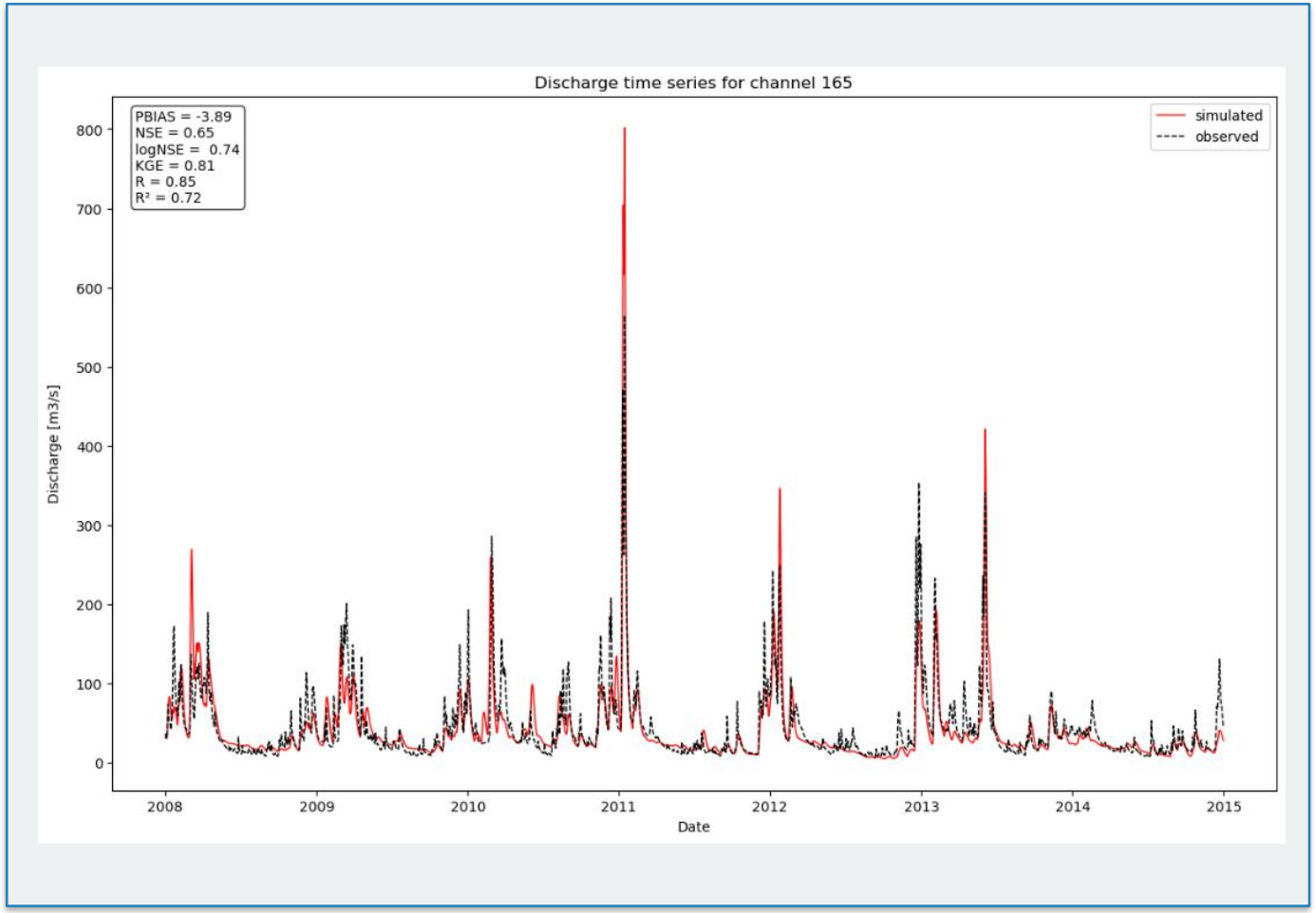


- Climate-driven simulations across SSP126, SSP370, SSP585
- Sprinkler irrigation as a controlled sensitivity scenario
- Multi-dimensional evaluation using hydrology, crop, and ecosystem indicators
- Stress-based metrics used to capture sub-seasonal crop responses

HYDROLOGICAL CALIBRATION: STREAMFLOW

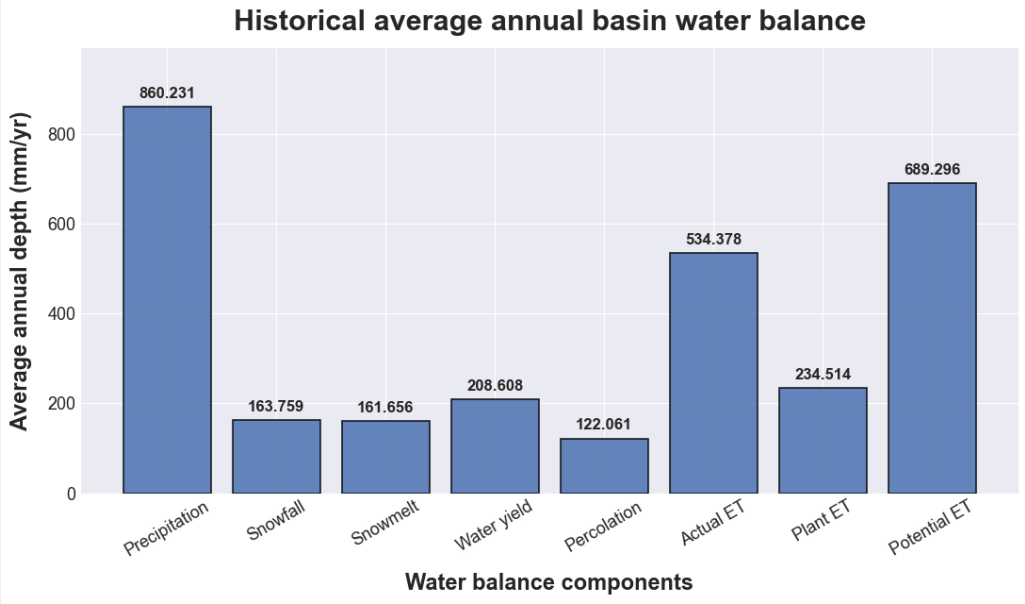
WATER

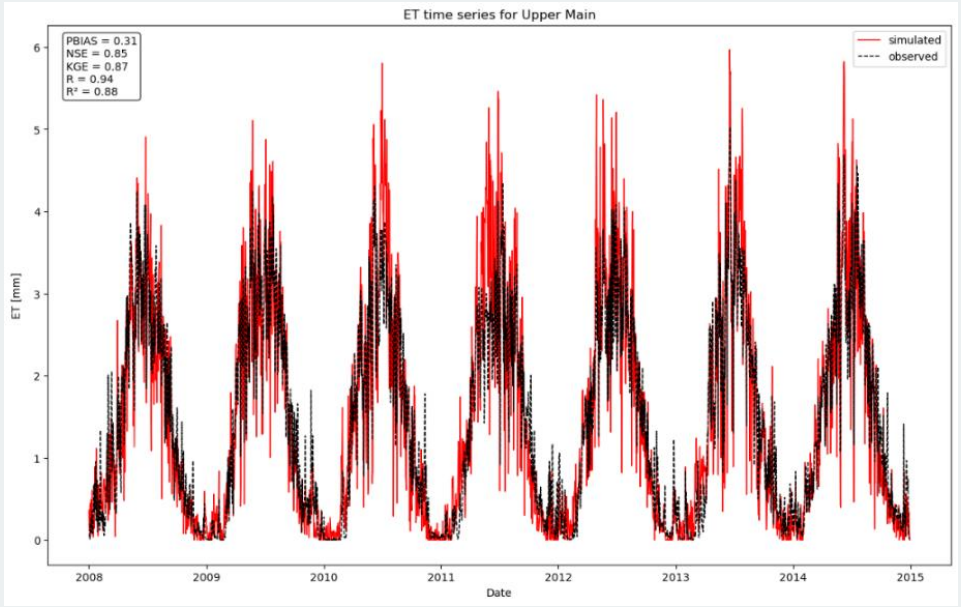
- **Objective:** Validate baseline physical hydrology (2008-2014).
- **Calibration:** 17 parameters (DREAM-based + manual refinement)
- **Performance:** NSE=0.65, logNSE=0.74



HYDROLOGICAL CALIBRATION: WATER BALANCE, ET

WATER

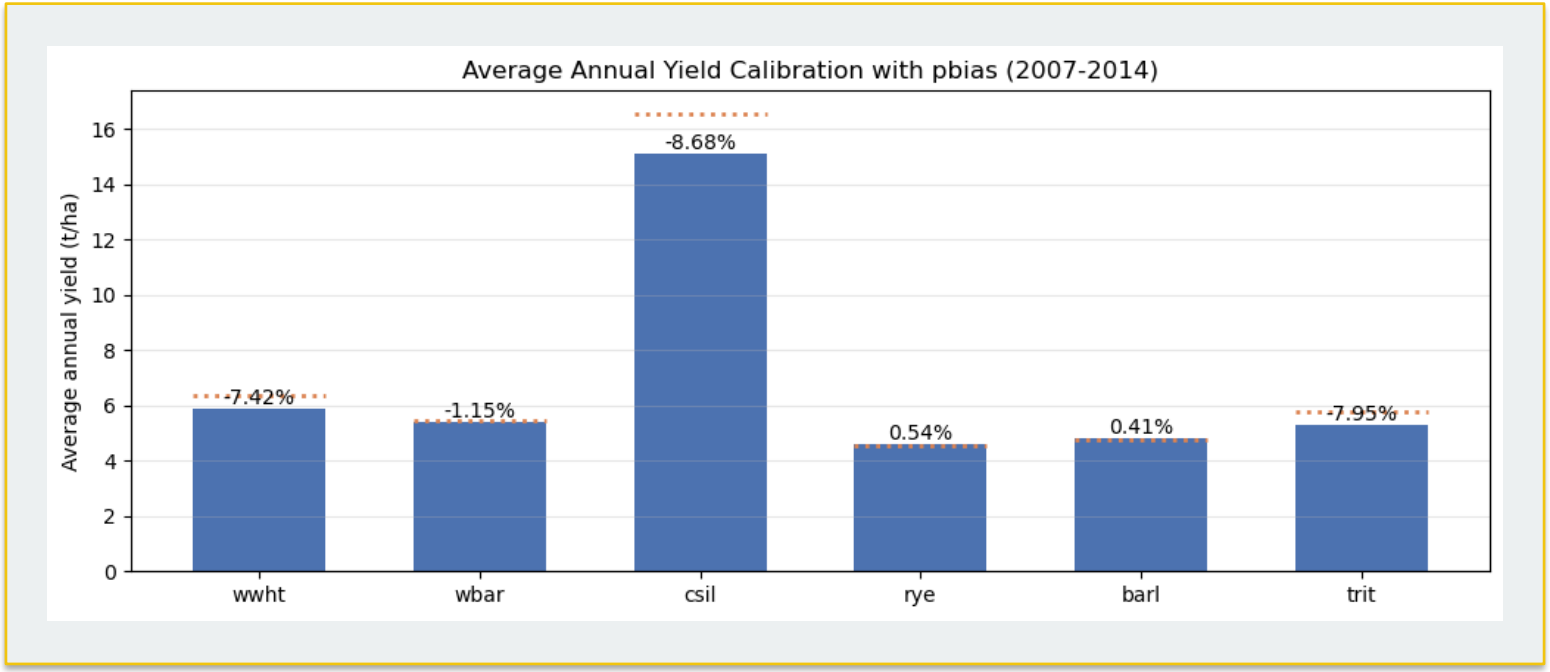




- **Objective:** Constrain basin water balance and ET processes
- **Validation:** Components within physically realistic ranges
- **Performance:** ET dynamics well captured (NSE ≈ 0.85)
- **Partitioning:** T/ET ≈ 44% (vs ~60% from GLEAM estimates)

CROP YIELD CALIBRATION

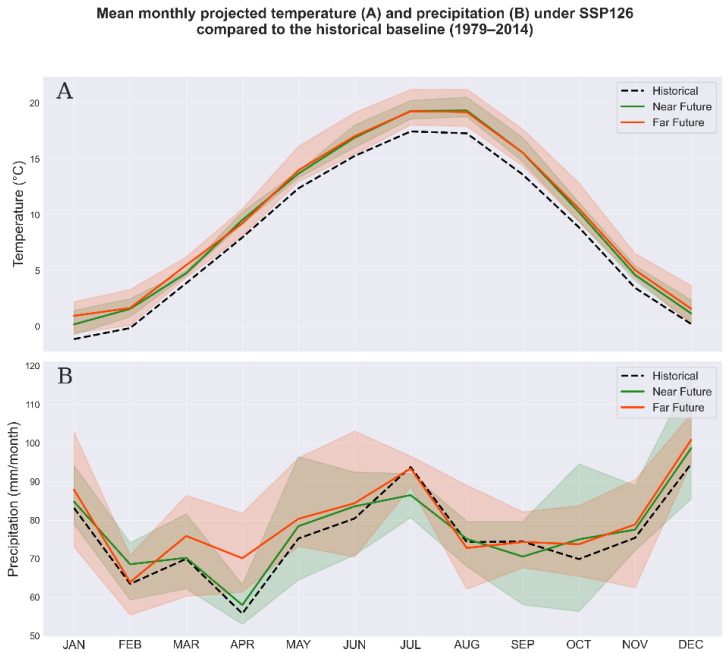
FOOD

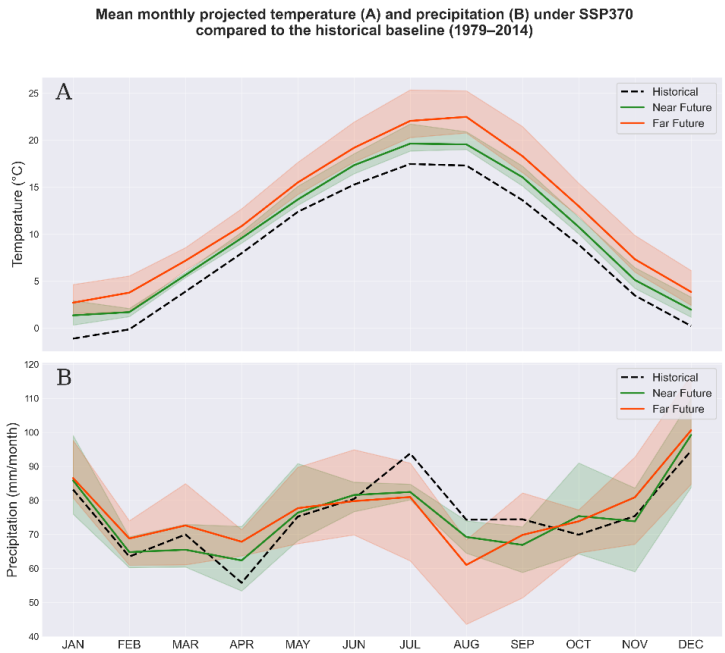


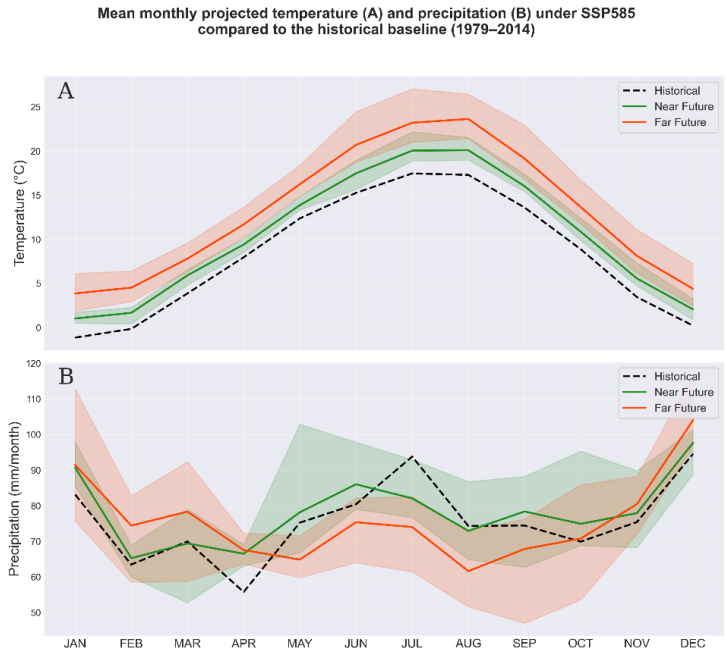
- Good agreement with observed yields
- Low bias (−8.7% to +0.5%)
- Slight underestimation (wwht, csil, trit)
- Parameter adjustment beyond defaults – csil, trit

PROJECTED CLIMATE CHANGES

NEXUS PERSPECTIVE



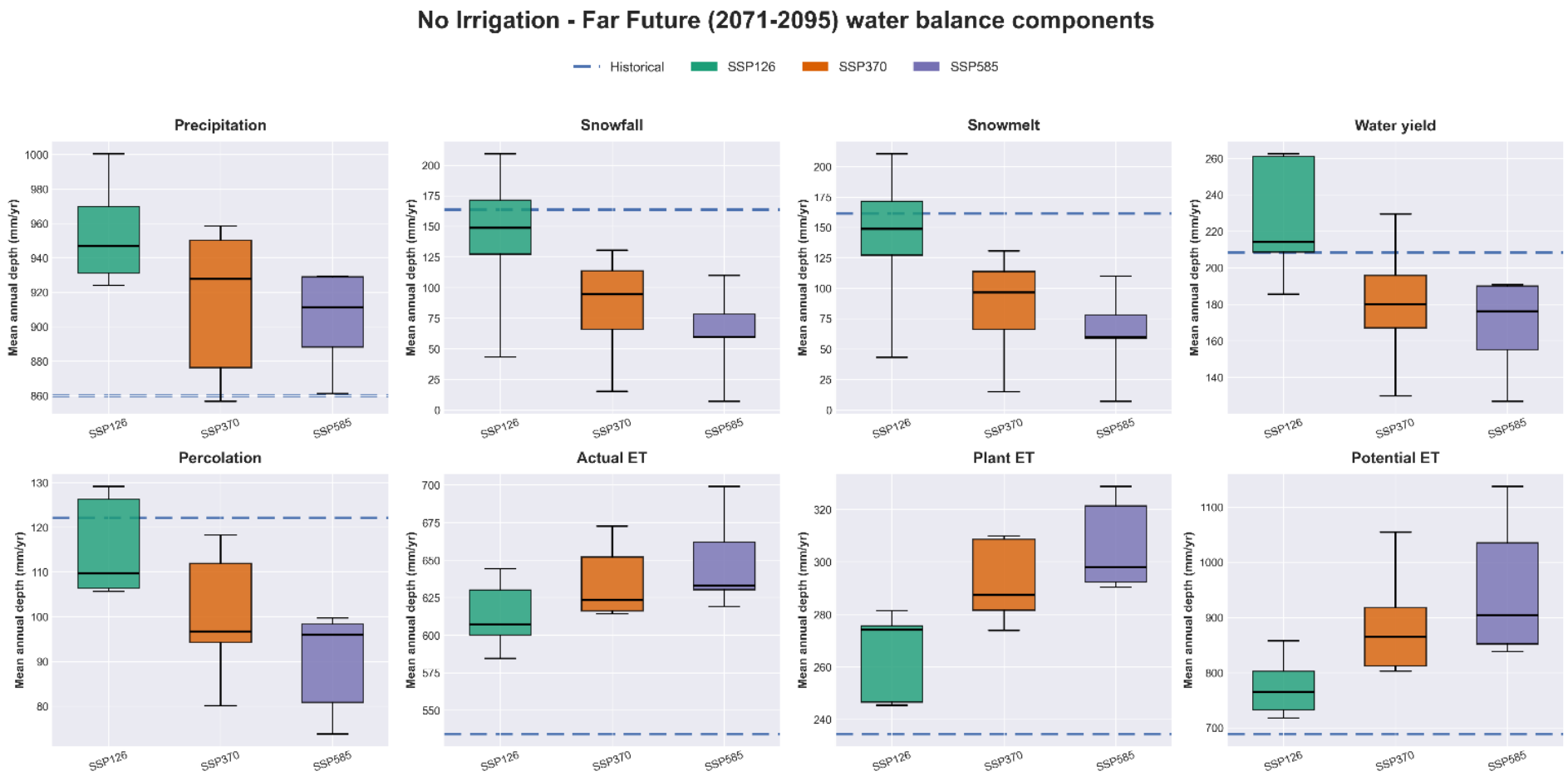




- Strong warming across scenarios (+1.7 to +4.8 °C by far future)
- Seasonal redistribution of precipitation (increasing intra-annual variability)

SHIFT IN WATER PARTITIONING

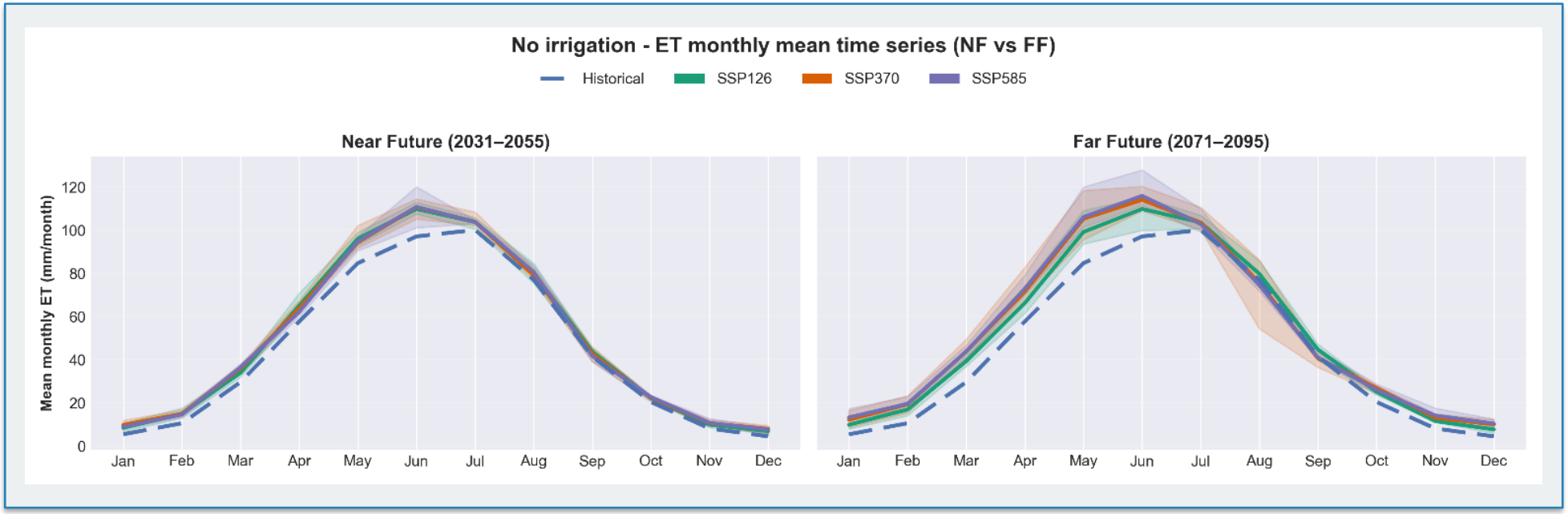
WATER



- Strong decline in snowfall & snowmelt
- Shift toward ET-dominated regime

SEASONAL ET SHIFT

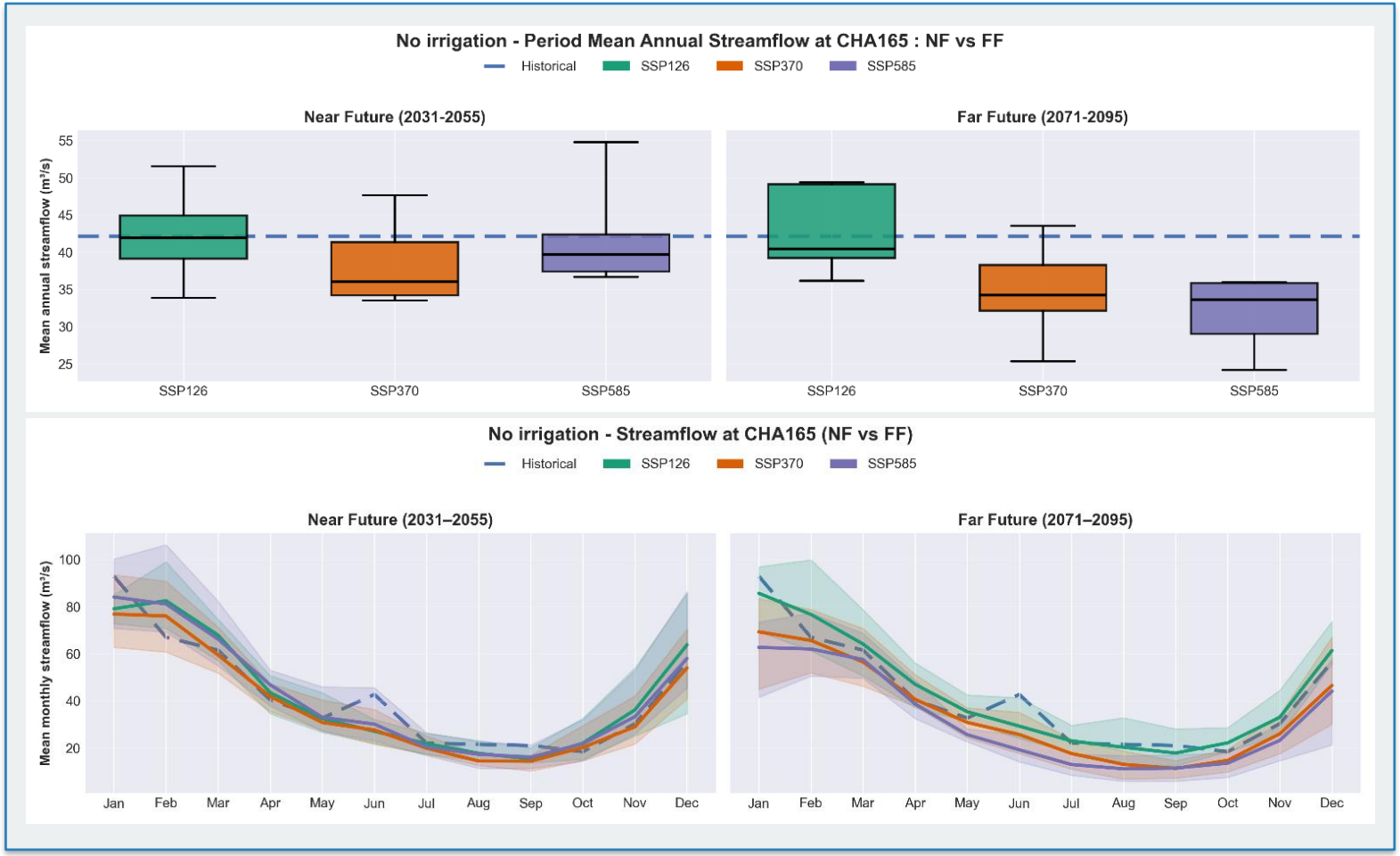
WATER



- Overall intensification of ET engine
- Peak shifts earlier (July → June)
- Divergence expands (growth period → full year)
- Indicative of a shift in crop growth and phenology

SEASONAL REDISTRIBUTION OF WATER AVAILABILITY

WATER

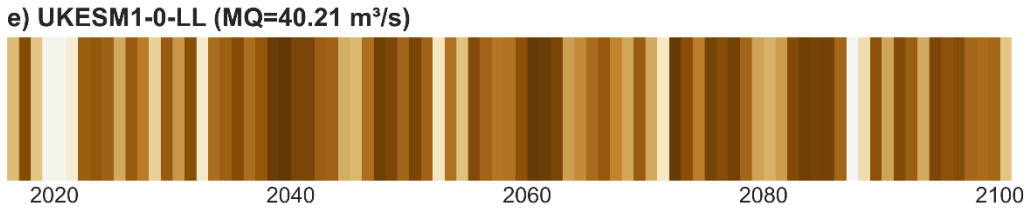


- Stable discharge under SSP126 (~40–42 m^3/s)
- Small reduction in SSP370 & SSP585 (~34–36 m^3/s)
- Increased winter flows (SSP126)
- Strong summer low-flow intensification (min ~11 m^3/s)
- Changes intensify in far-future

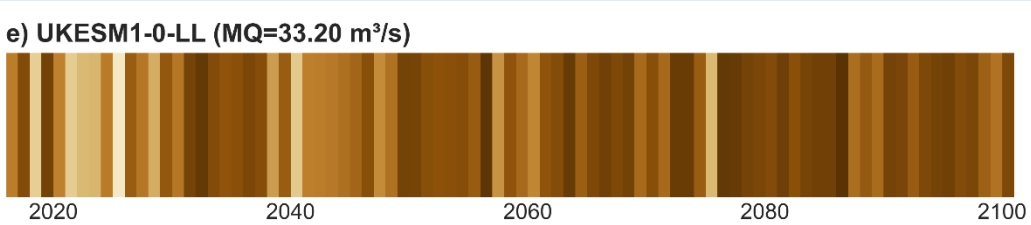
LOW-FLOW INTENSIFICATION

WATER

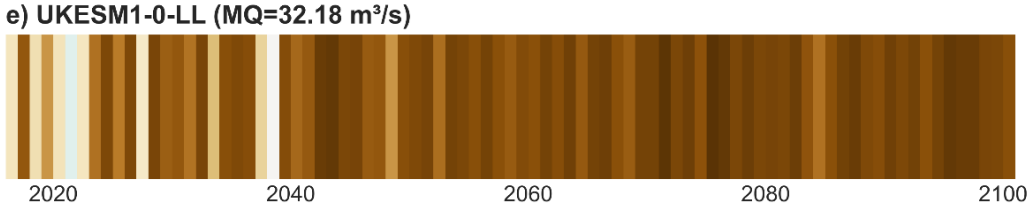
SSP126



SSP370



SSP585



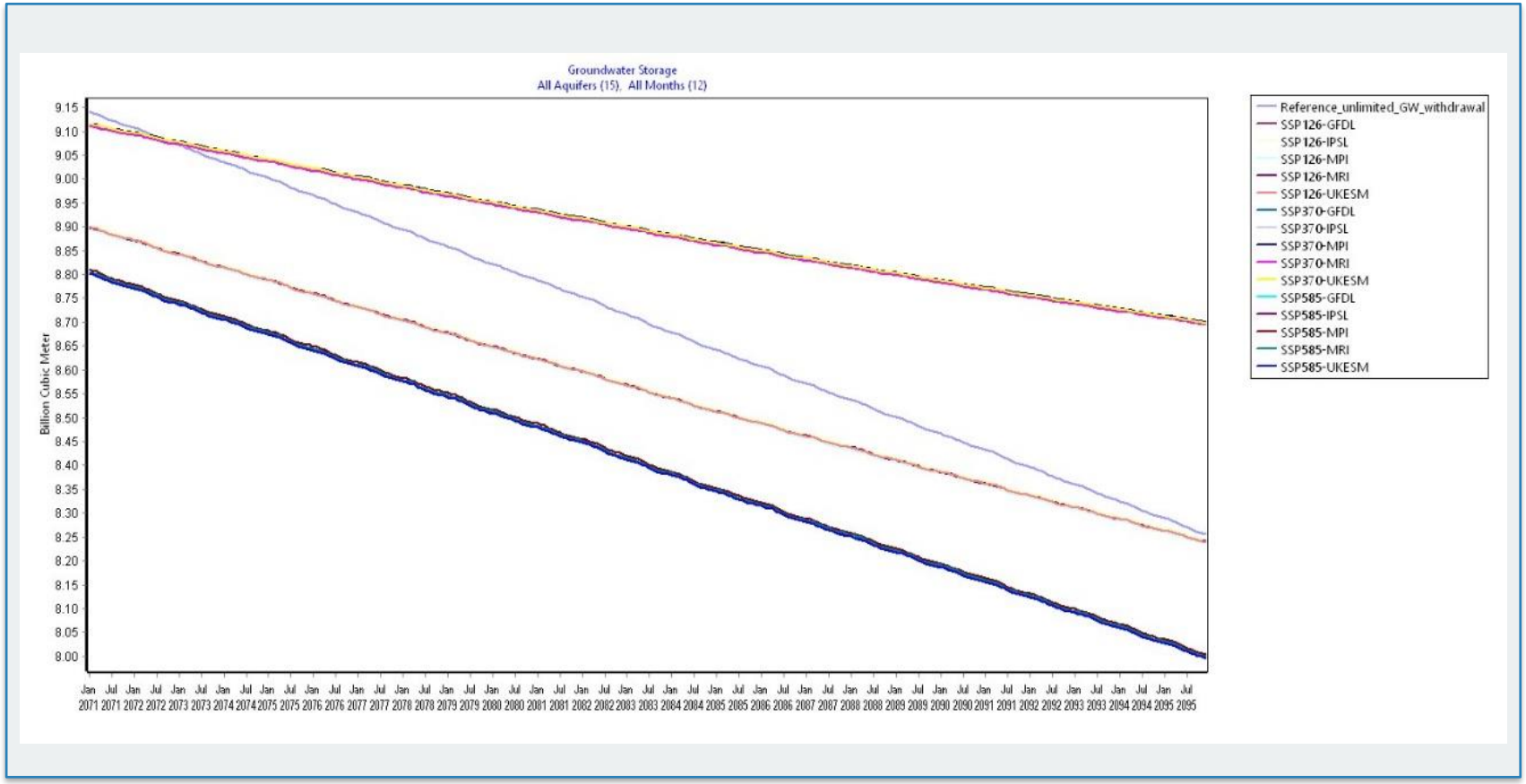
- High interannual variability in low flows
- SSP126: Variable but no persistent decline
- SSP370 & SSP585: Increasing persistence of low flows
- Strongest drought signal under SSP585 (far-future)



WATER ALLOCATION RESPONSE

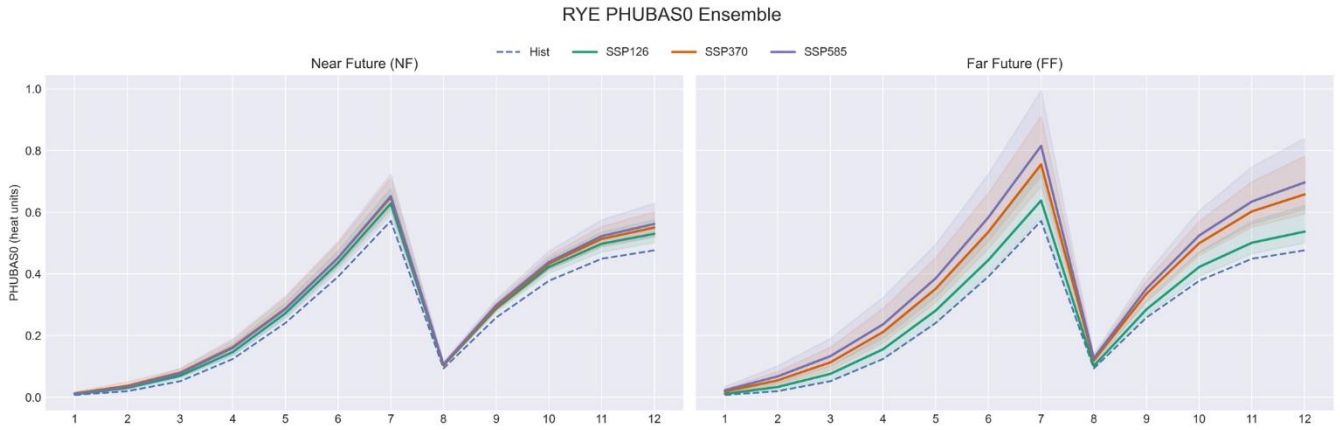
WATER

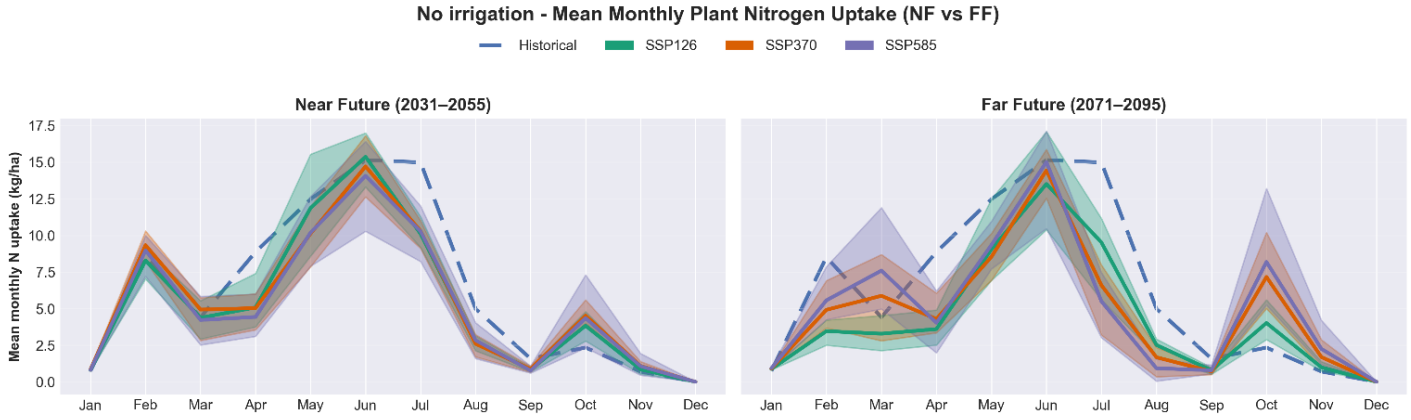
- No unmet demand
- Increasing reliance on groundwater
- Emerging vulnerability of groundwater nodes



PHENOLOGICAL ADAPTATION

FOOD

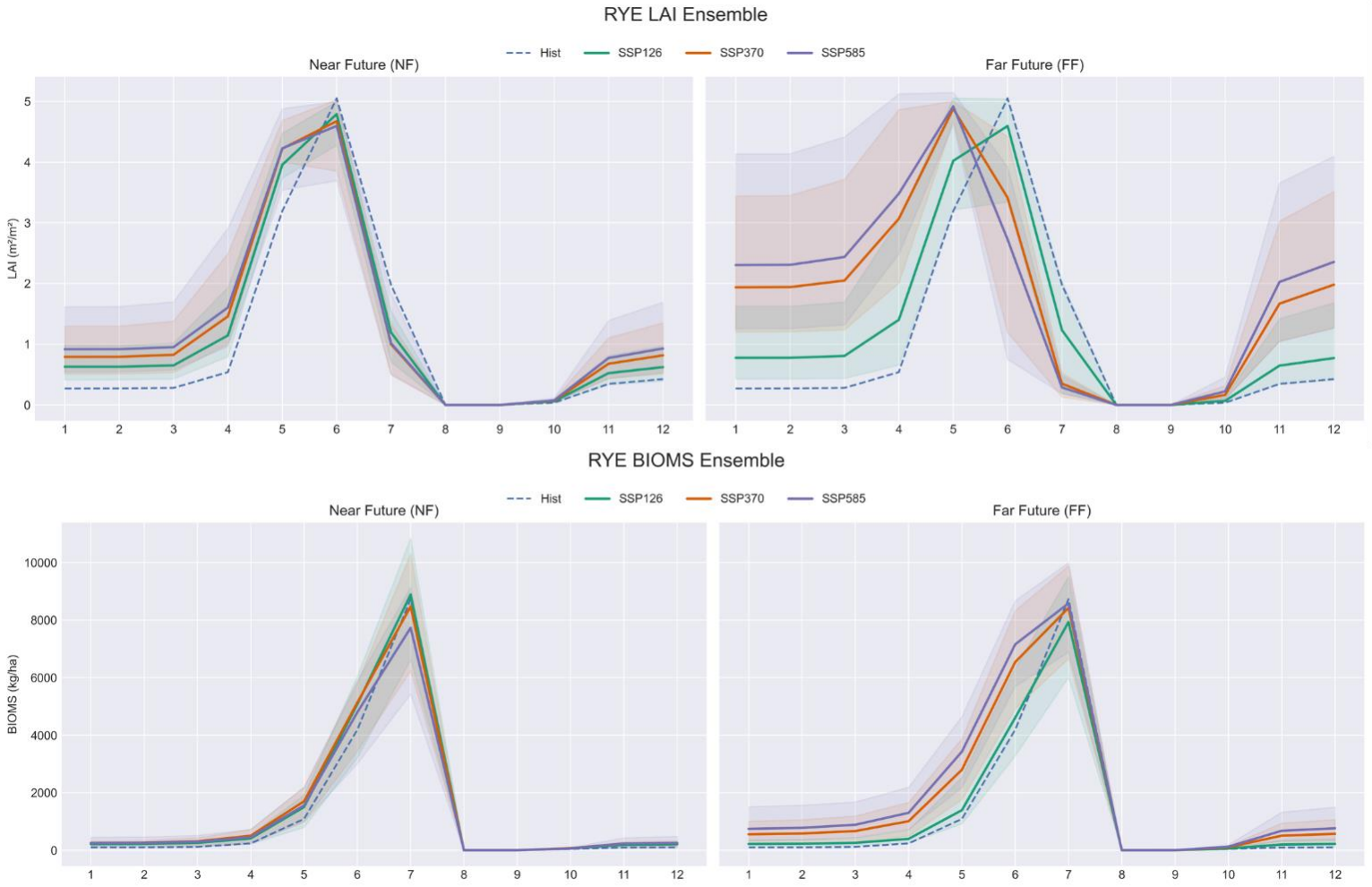




- Higher temperatures: Faster GDD accumulation
- Increased early-season resource capture: by 3x
- Forward shift in nitrogen uptake
- Summer drought escape via phenological acceleration

CROP YIELD RESPONSE

FOOD



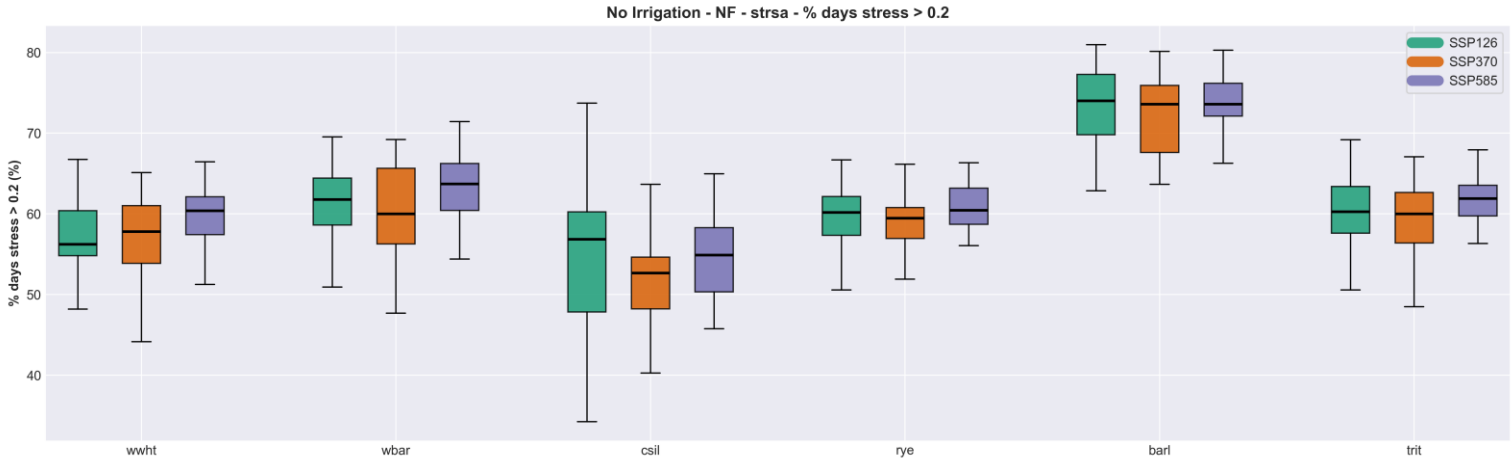
- Earlier onset and peak of canopy development
- Concave biomass accumulation
- No gain in productivity
- Earlier maturity enables drought escape but limits accumulation

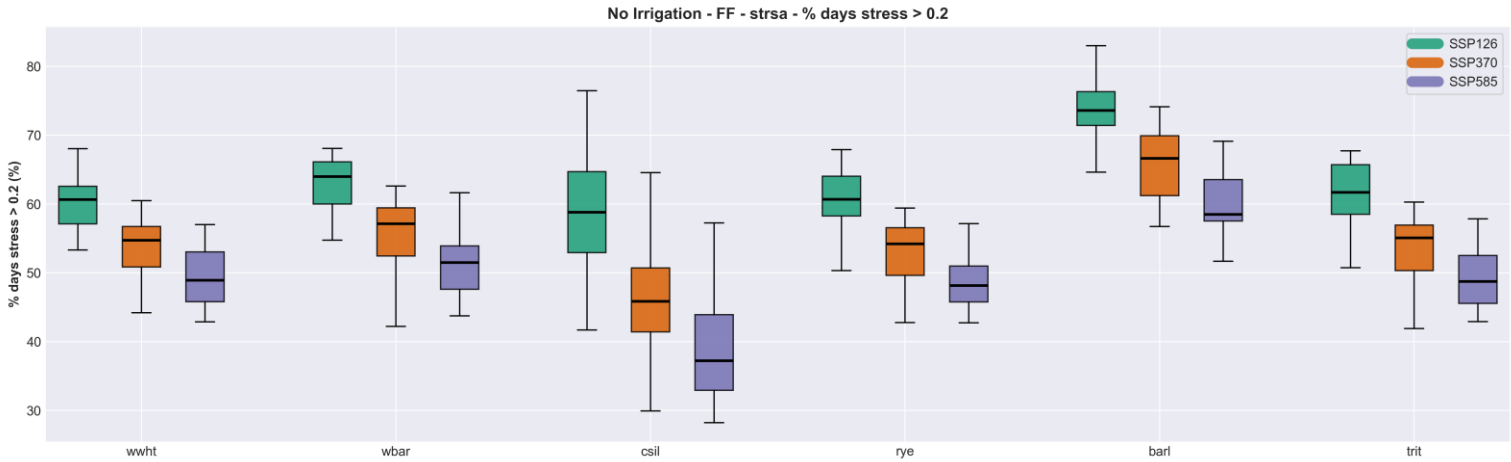
Phenological adaptation is compensatory, not beneficial

ENVIRONMENTAL STRESS: AERATION

FOOD

- Aeration stress during 50-60% of growing period
- Mean stress ranging between 40-60%
- Root hypoxia during peak spring growth season

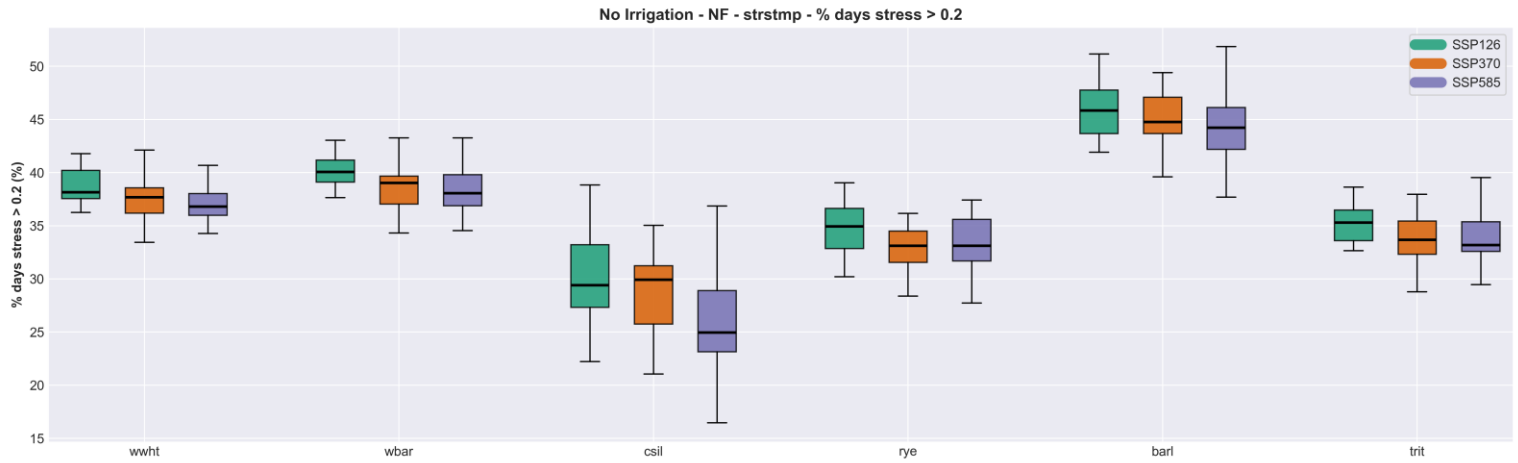


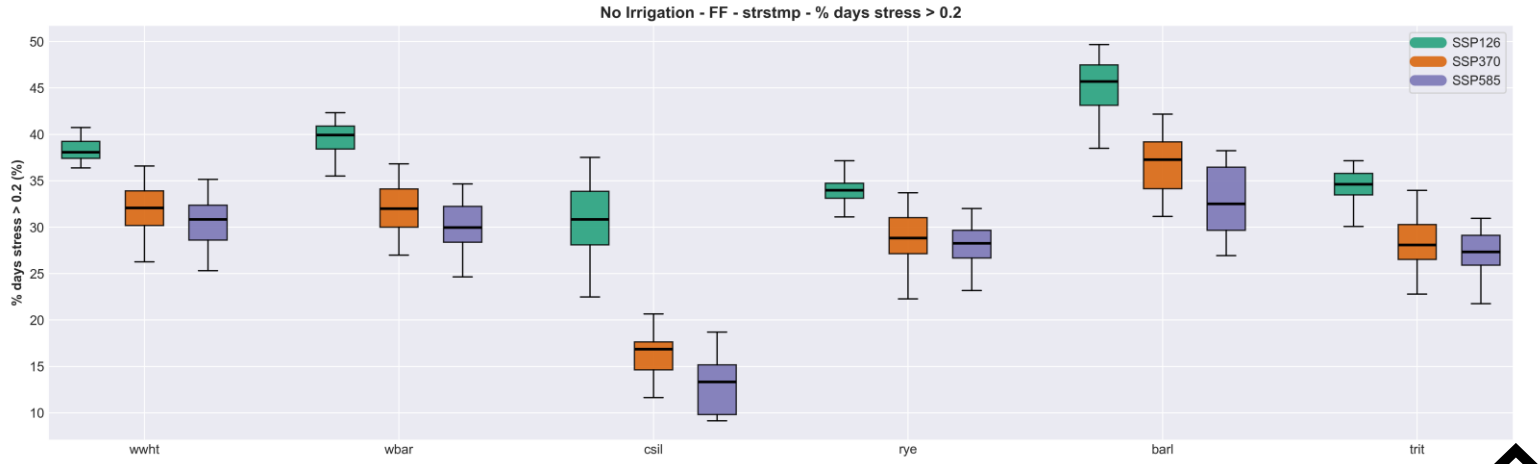


ENVIRONMENTAL STRESS: TEMPERATURE

FOOD

- Temperature stress during 30-40% of growing period
- Mean stress ranging between 20-25%
- Quick warming cuts off crop cycle at the end





DECOUPLING OF STRESS & CROP DEMAND: NF

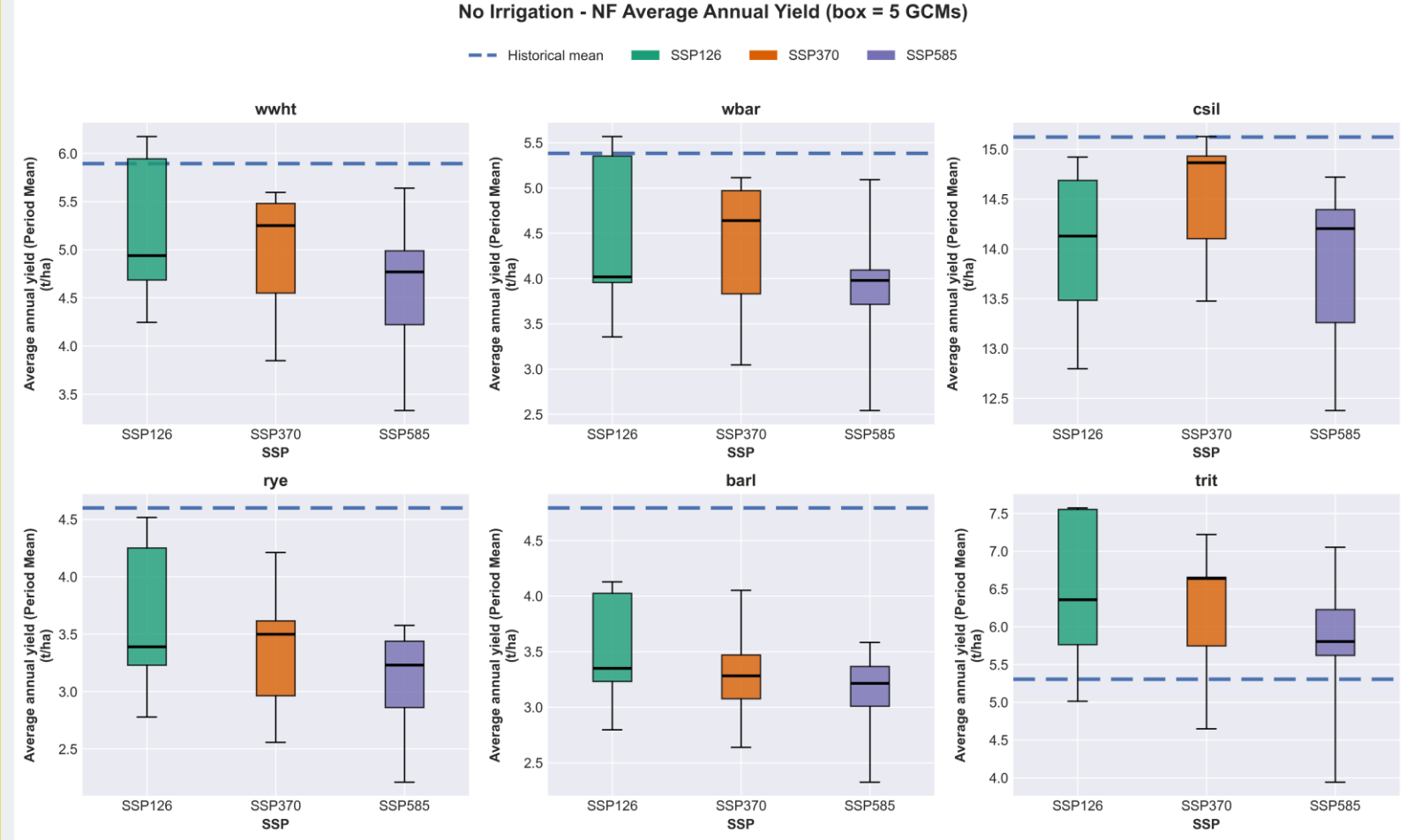
FOOD

Winter crops: Progressive intensification of temperature penalty

barl: Most sensitive to temperature

csil, trit: driven by calibrated growth parameters

Phenological shifts maintain moderate yield resilience



DECOUPLING OF STRESS & CROP DEMAND: FF

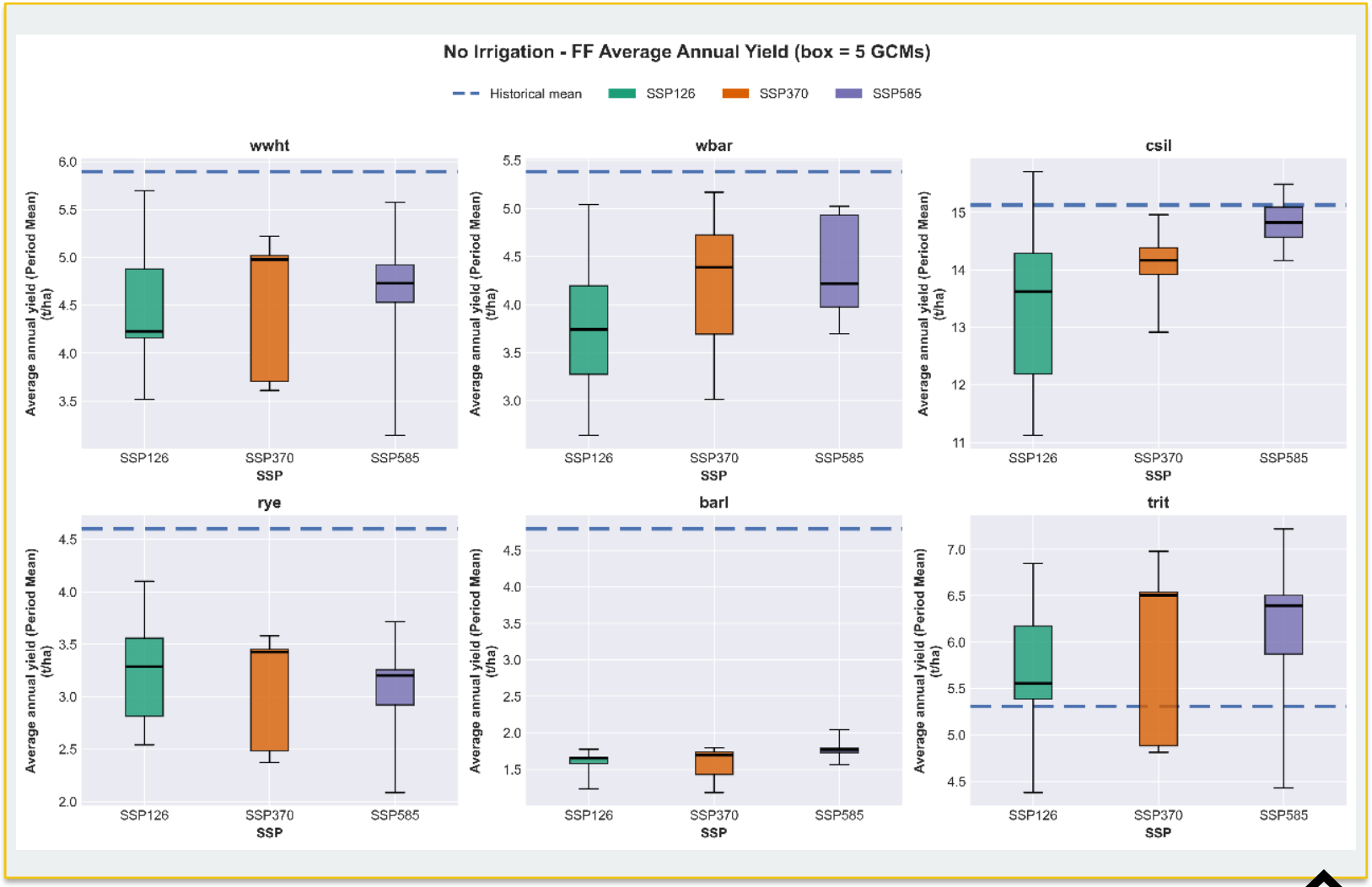
FOOD

Winter crops: Accelerated development truncates grain-filling period

barl: Elevated temperature stress

csil: operates closer to thermal optimum at higher SSP scenarios

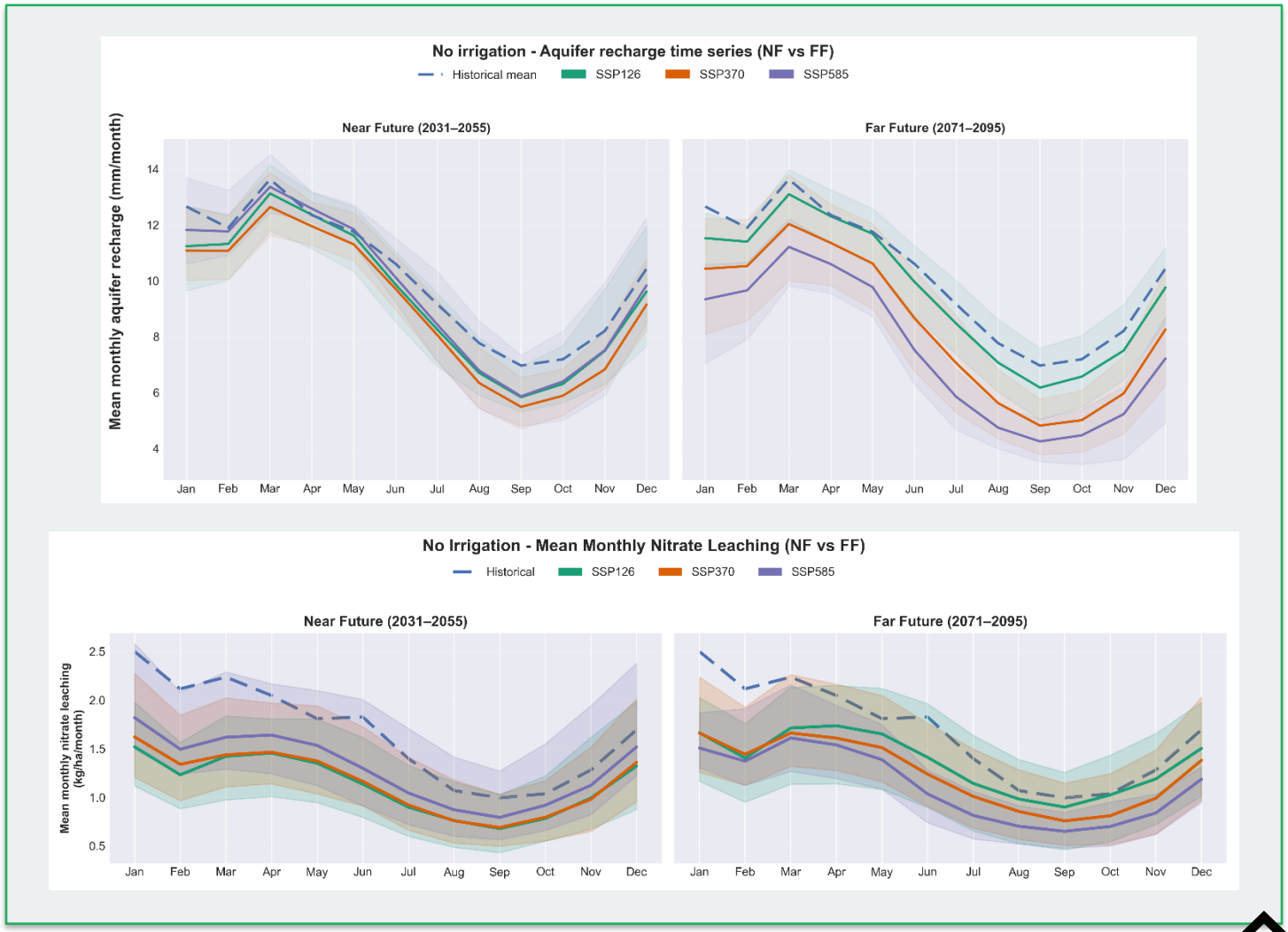
Warming reshapes crop suitability across the system



TRANSPORT LIMITATION OF NITRATE

ECOSYSTEM

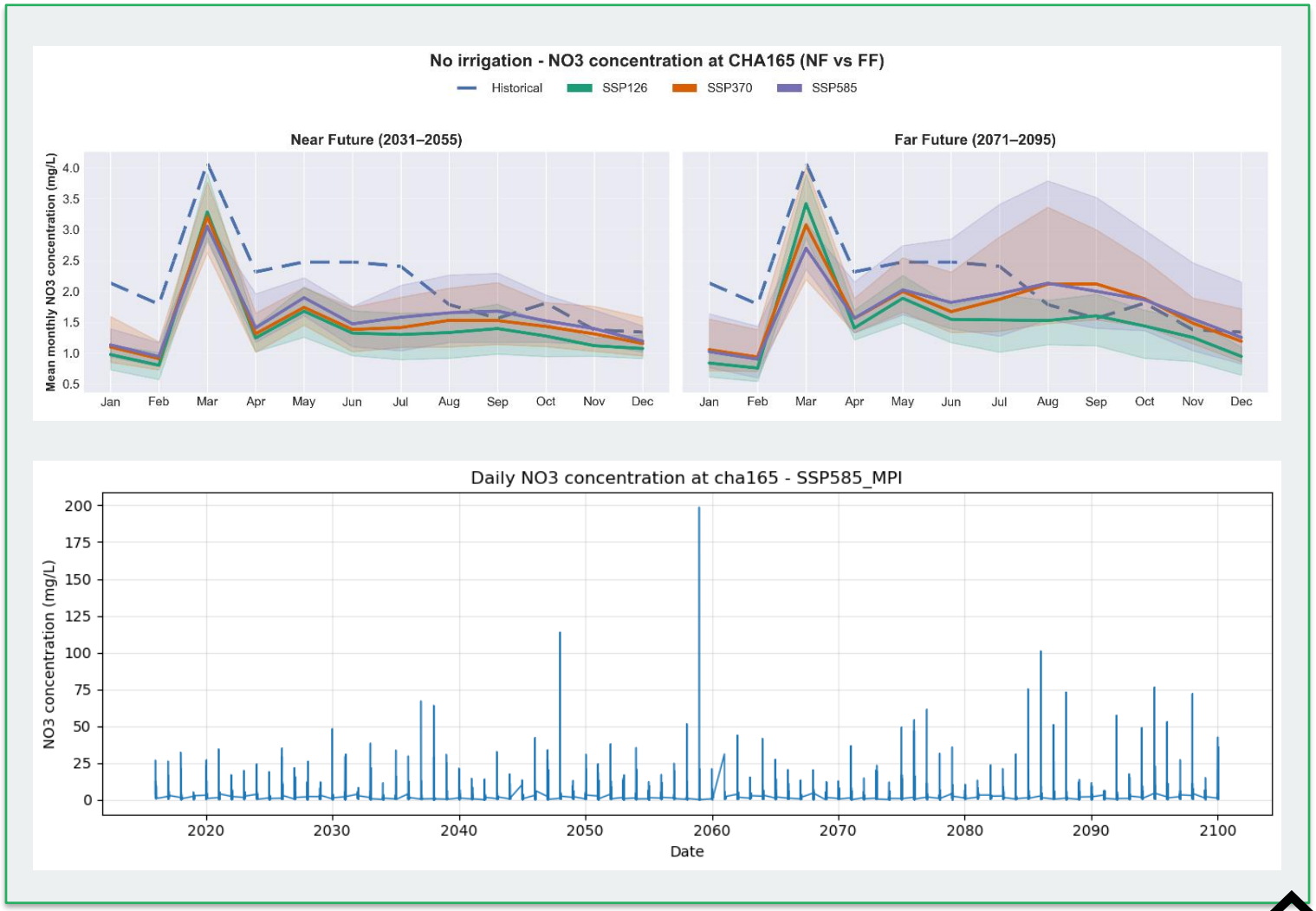
- Nitrate transport governed by water fluxes
- Increased ET reduces percolation and leaching
- Shift toward **transport-limited conditions**
- Tendency toward more episodic transport



FIRST-FLUSH EXPORT DYNAMICS

ECOSYSTEM

- Nitrate accumulation in soil profile
- Elevated summer low-flow concentrations
- Mobilized during events: transient first-flush spikes
- Extreme peaks highlight need for **nutrient balance calibration**



IRRIGATION INTERVENTION: YIELD RESPONSE

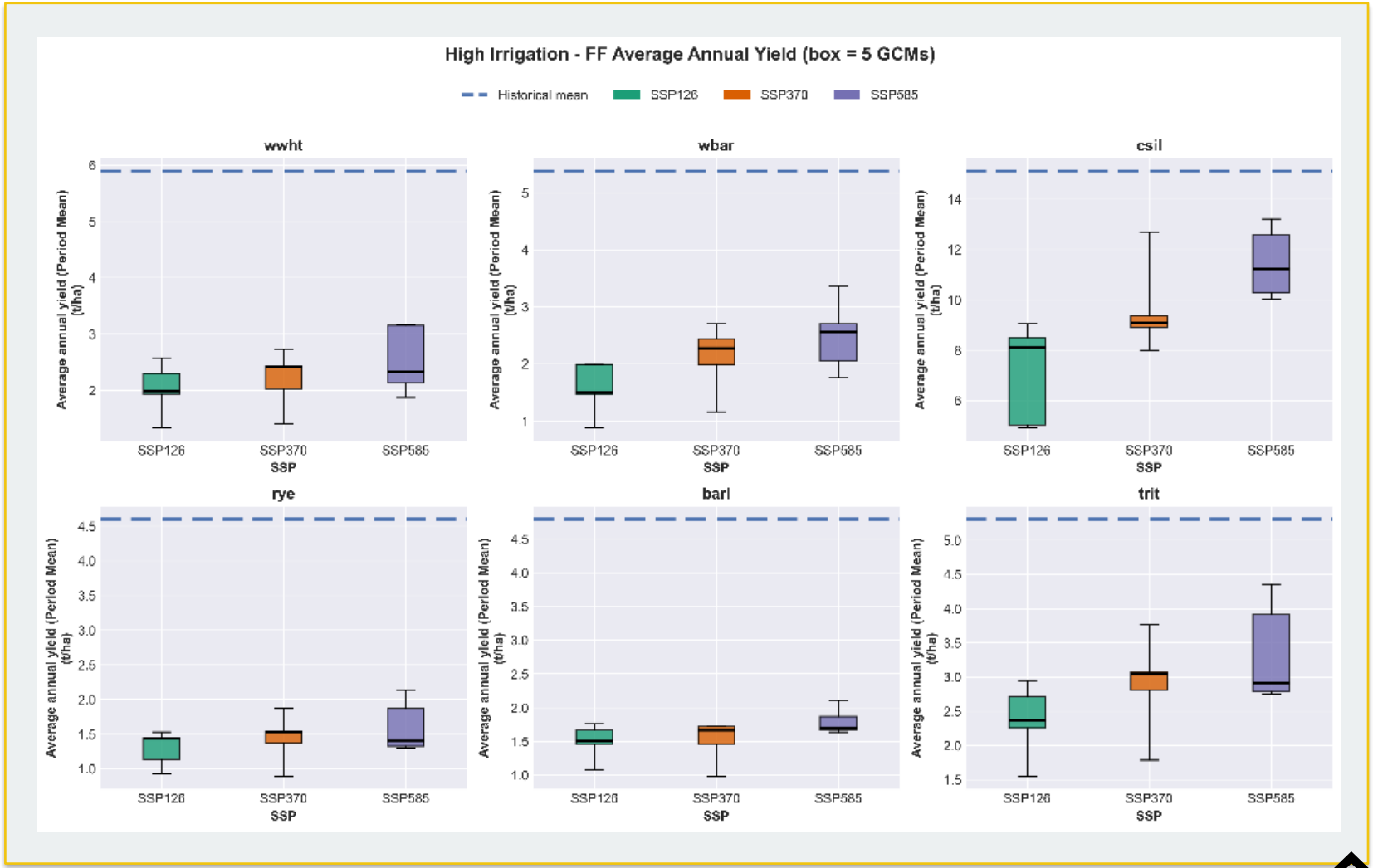
FOOD

Significant decline for all crops

Possibly significant root hypoxia

Added depletion of groundwater- dry-out by 2070

Irrigation becomes counterproductive



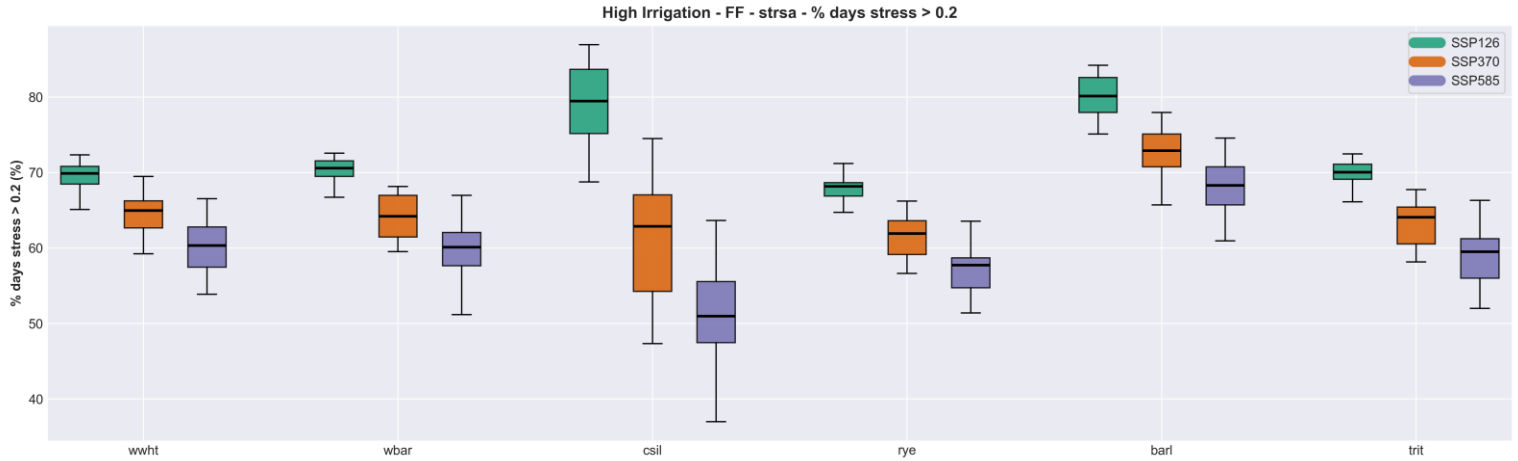
IRRIGATION INTERVENTION: AERATION STRESS

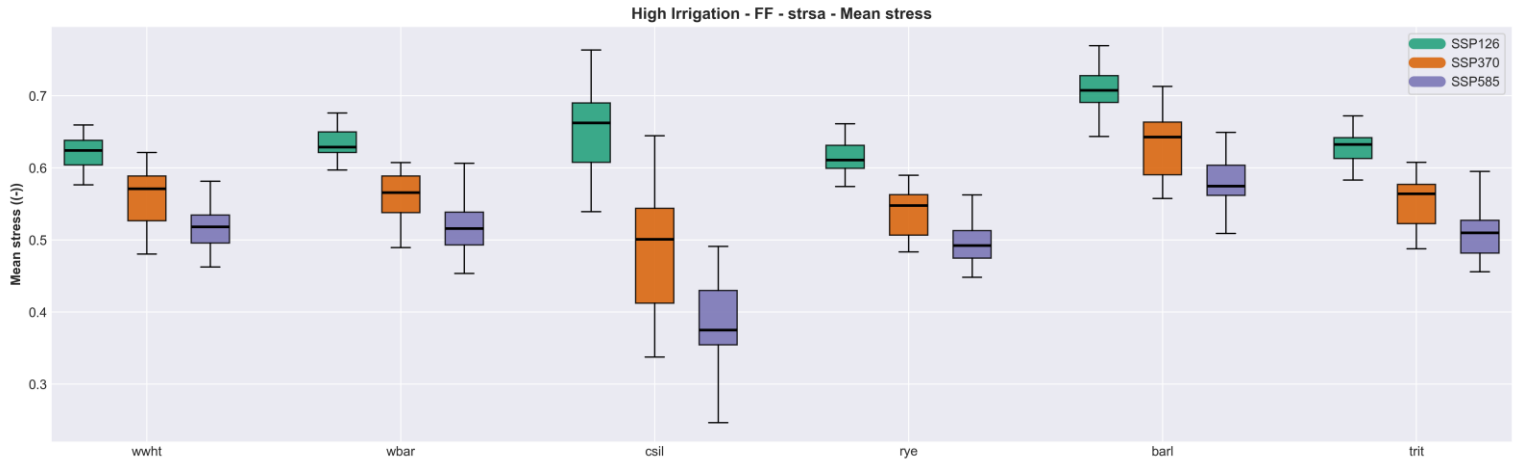
FOOD

Aeration stress exists for upto 80% of crop growth period

10% increase in mean aeration stress

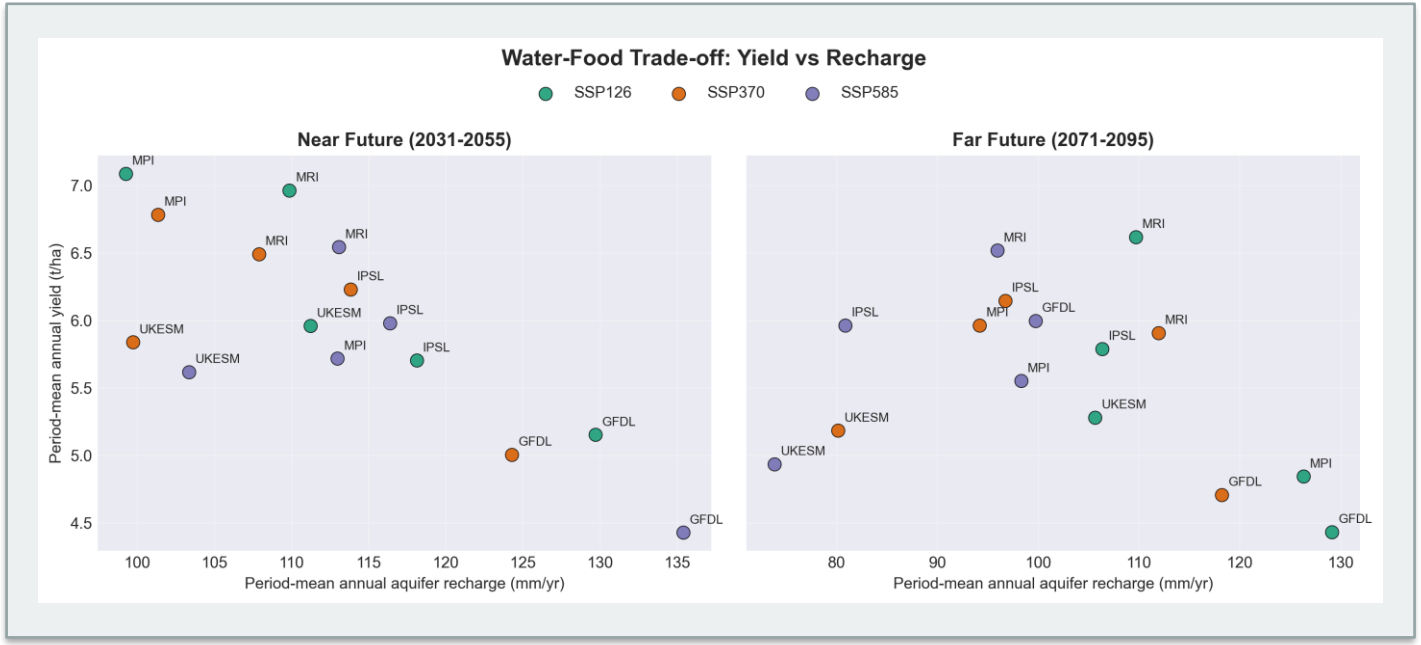
Plants attempting growth in submerged conditions





SYSTEM TRADE-OFFS: W-F

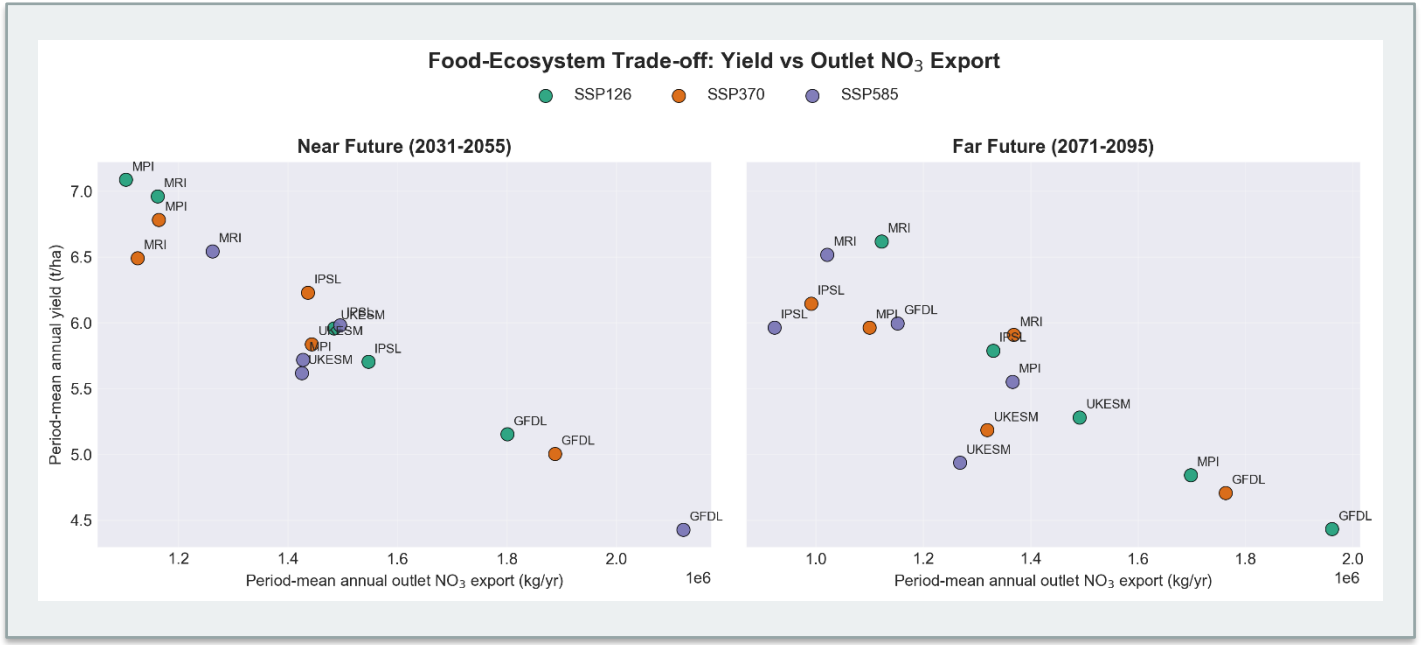
NEXUS PERSPECTIVE



- Agriculture weakly constrained by basin-scale water availability
- Yield relatively stable to range of simulated outlet streamflow or recharge

SYSTEM TRADE-OFFS: F-E

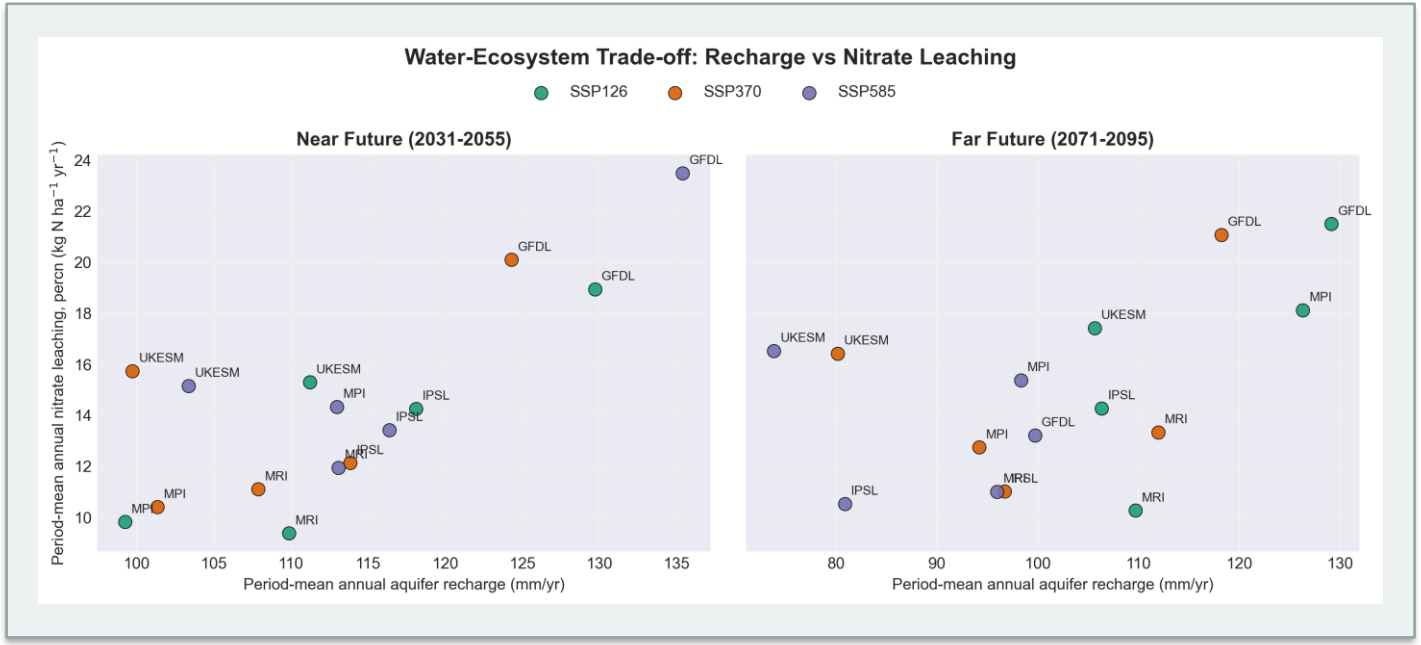
NEXUS PERSPECTIVE



- Consistent trade-offs between yield and nitrogen export
- Changes in soil nitrate retention complements crop yield and downstream water nitrate

SYSTEM TRADE-OFFS: W-E

NEXUS PERSPECTIVE



- Nitrogen losses are governed by hydrological transport
- Higher recharge also corresponds to elevated subsurface transport of nitrate downstream

MODEL LIMITATIONS AND FUTURE OUTLOOK

NEXUS PERSPECTIVE

Static land-use model

Absence of dynamic CO_2 coupling

Throughput reservoir behavior of groundwater in SWAT+

Adaptation of water-intensive crops in the catchment

Calibration of nitrate in-stream transport

Incorporation of Energy sector

IN CONCLUSION…

Structural transition to an ET-dominated regime

Agricultural resilience maintained via “Drought Escape” phenological adaptation

Transport-limited soil chemistry brings risks of high-concentration first-flush.

The irrigation paradox: an ineffective and potentially detrimental solution

Upper Main: A picture of resilience in vulnerability

Thank you!

Questions?