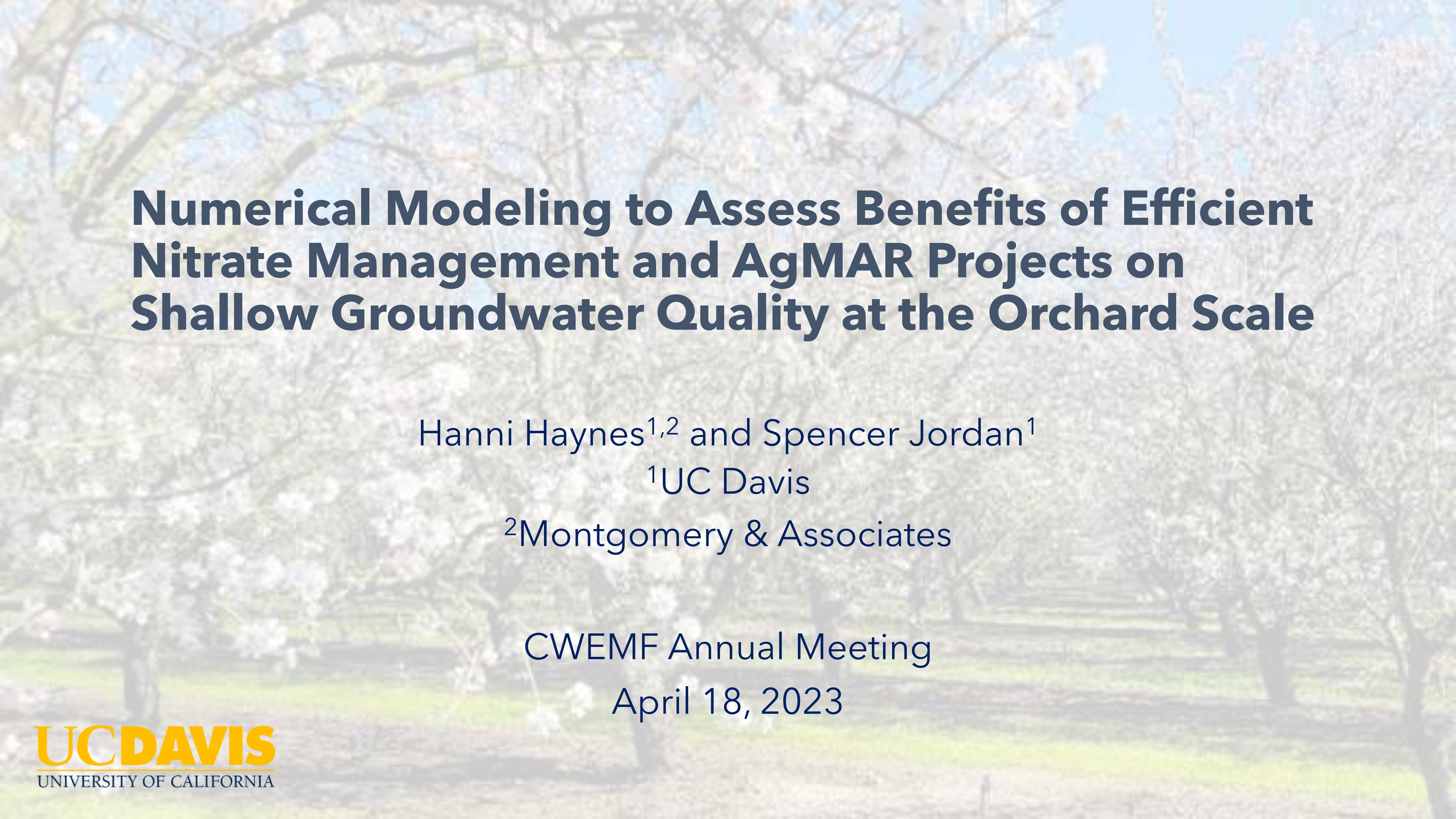


Numerical Modeling to Assess Benefits of Efficient Nitrate Management and AgMAR Projects on Shallow Groundwater Quality at the Orchard Scale

Hanni Haynes[1,2] and Spencer Jordan[1]
[1]UC Davis
[2]Montgomery & Associates

CWEMF Annual Meeting
April 18, 2023

UCDAVIS
UNIVERSITY OF CALIFORNIA

Field-Scale Study of Nitrate Leaching from Agriculture

Problem: Nitrate (NO_3^-) from fertilizer leaching into groundwater

This Project:

Field-scale (small)

Orchard study site in Modesto, CA

- Experimental fertilization method
- AgMAR field experiment
- Field data collection
- Vadose zone and groundwater models

Result:

- Model long-term groundwater quality underlying the almond orchard
- Future scenario assessment
- Model uncertainty with stochastic approach (Monte Carlo simulation)

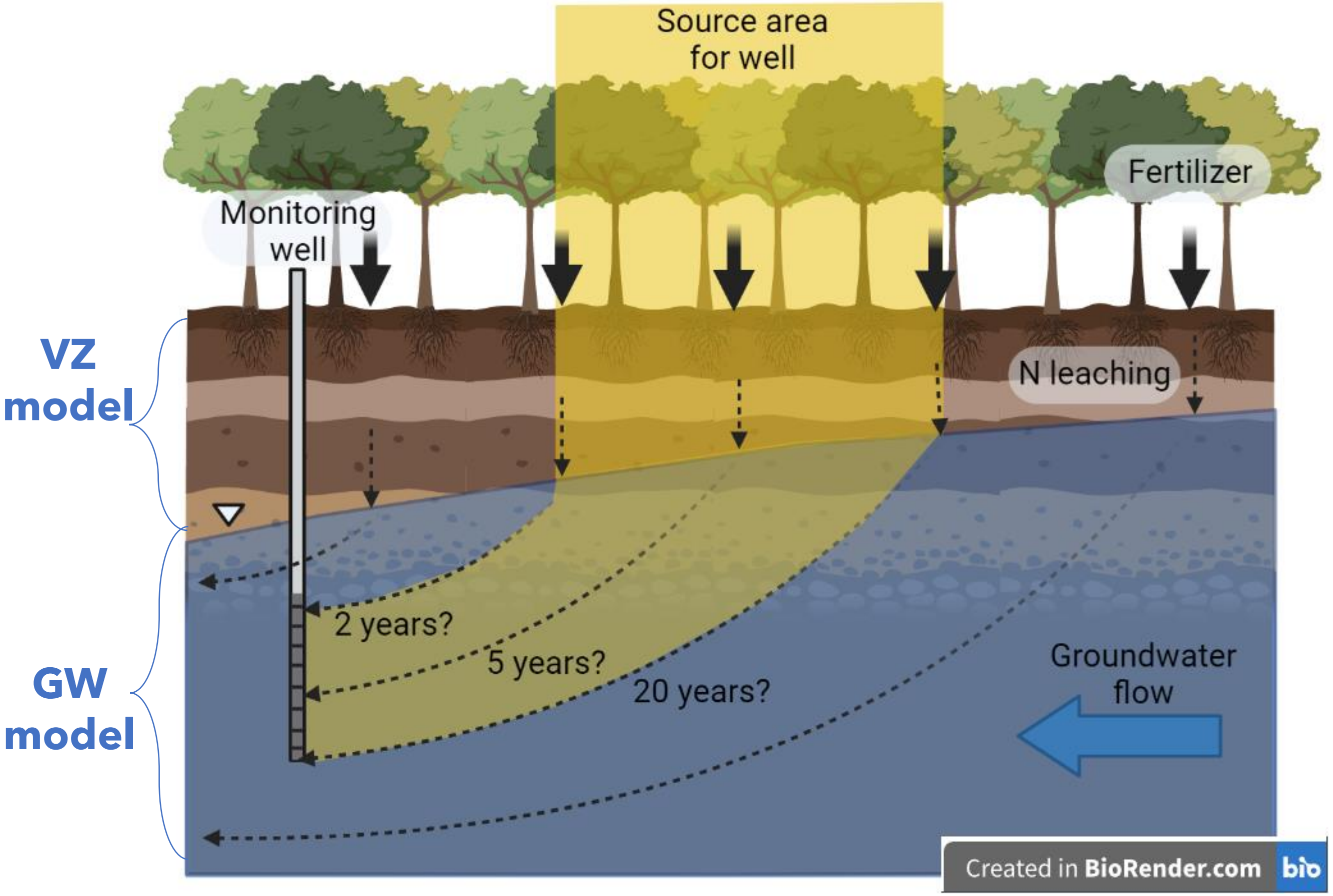
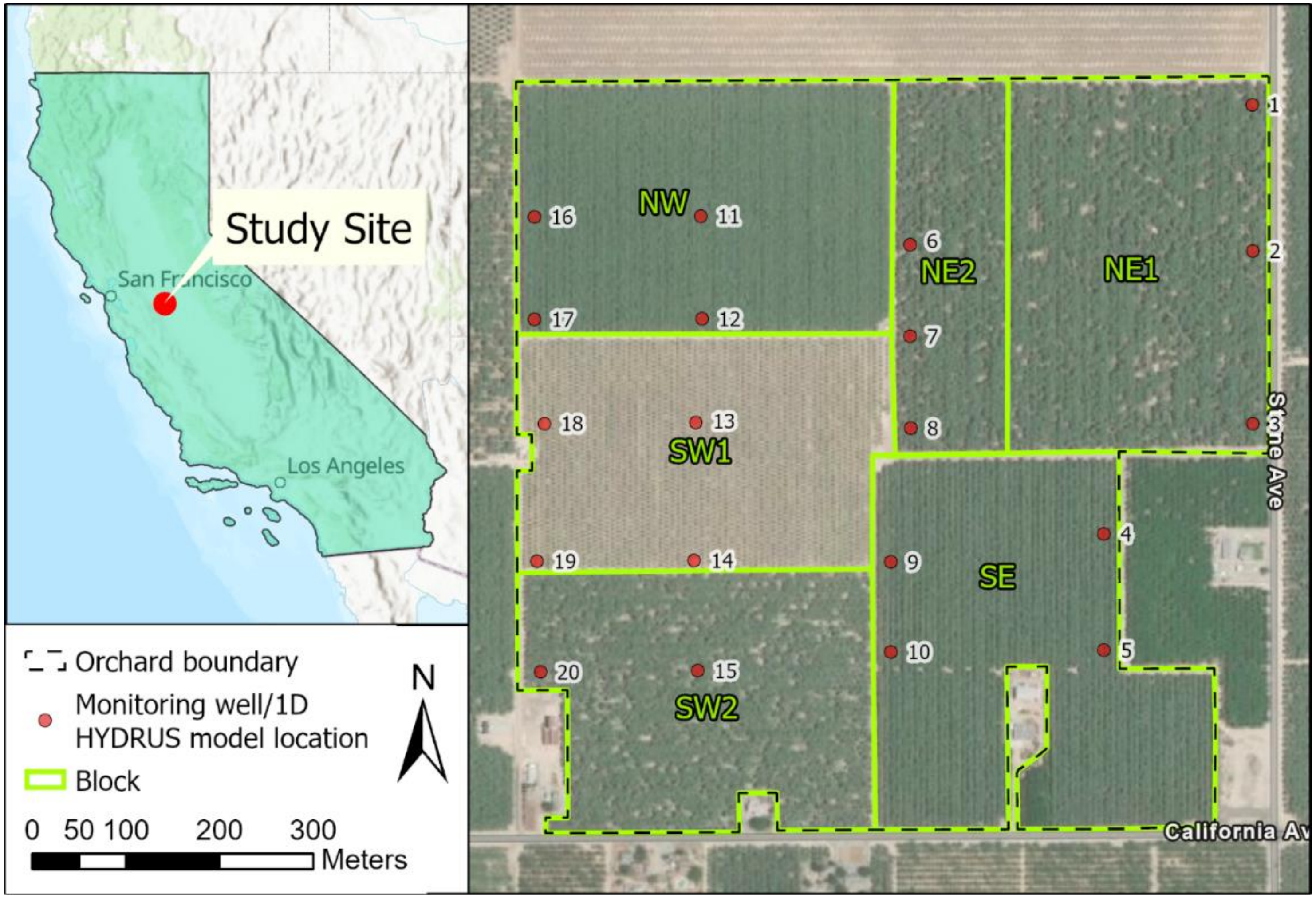


Figure: Transport of nitrate from fertilizer to groundwater wells

Project Takeaways

1. Experimental fertilization was more efficient = less nitrate leaching
2. Water quality concerns remain due to nitrate concentration leaching to groundwater still > MCL (10 mg/L NO3-N)
3. Nutrient management ↔ groundwater quality ↔ AgMAR?

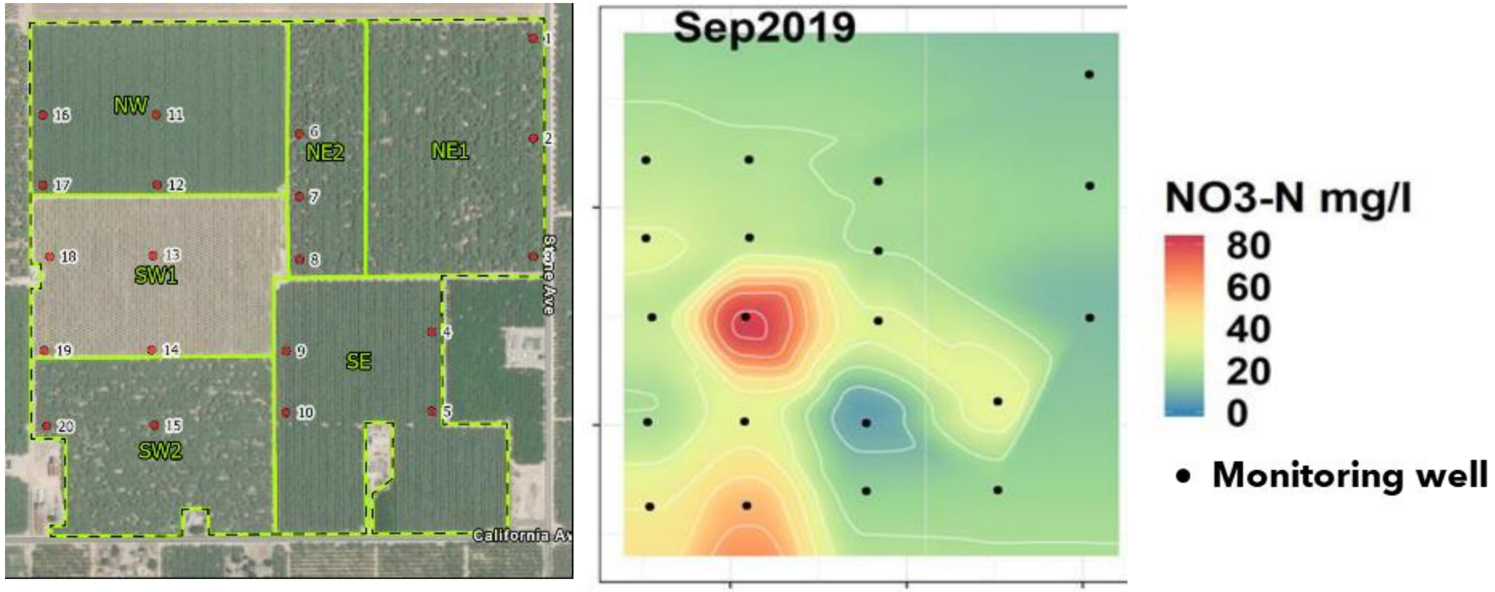
Orchard Study Site



- Multi-year study since 2017
  - High frequency low concentration (HFLC) fertigation since 2018
  - 20 water table groundwater monitoring wells (20-40 ft bgs)
  - Vadose-zone monitoring stations
- AgMAR (field flooding) experiment 2022

Measured Groundwater Nitrate Concentrations

- Median >10 mg/L NO3-N (MCL)
- Average has not decreased in 6 years since switch to HFLC
- Spatial variability: 4-113 mg/L



Site map (left); interpolated nitrate concentrations in monitoring wells (right)

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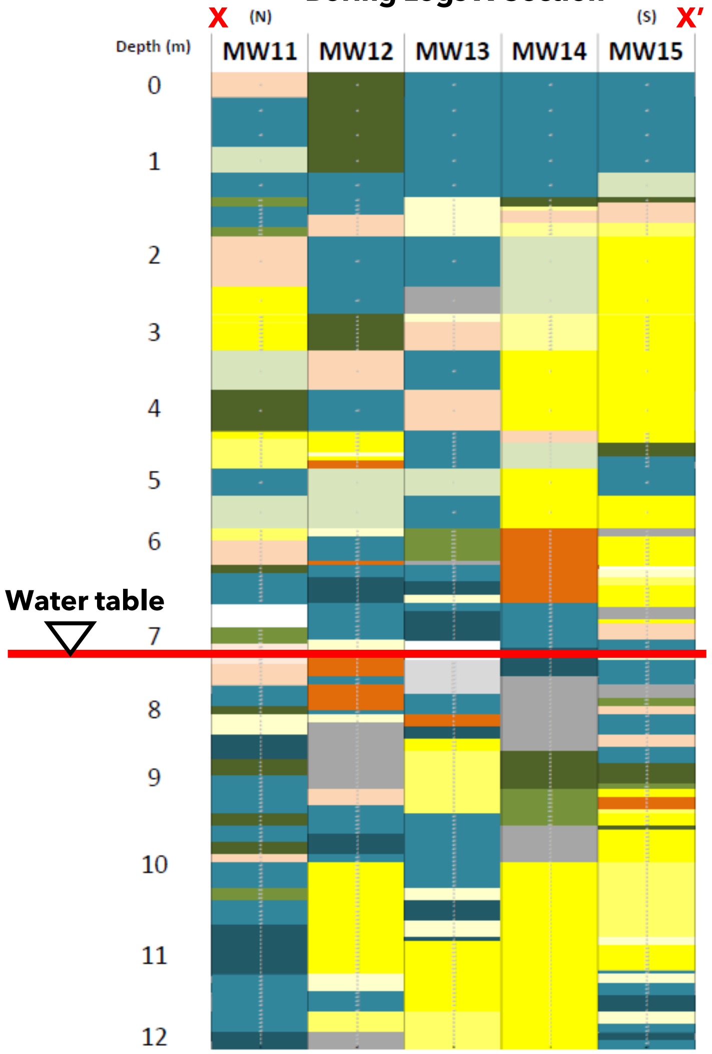
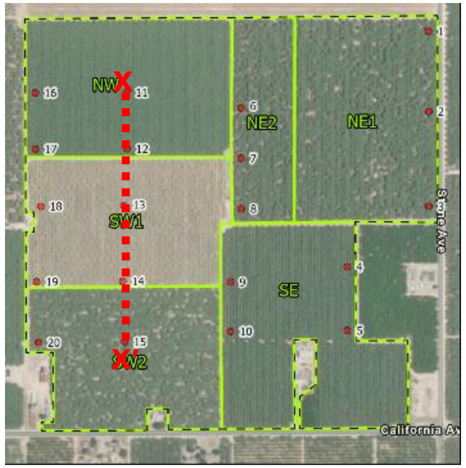
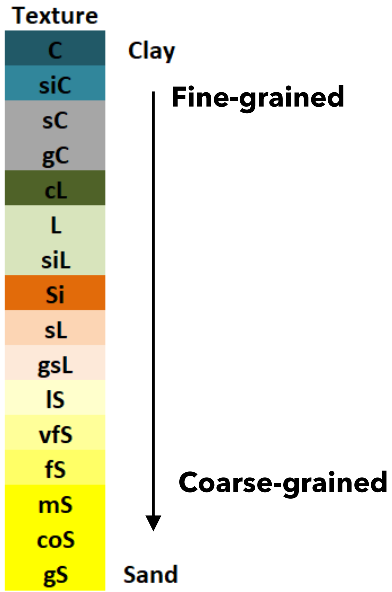
Geology

Boring Logs X-Section







Modified from figures by Hanna Gurevich

Boring logs: complex coarse and fine sediment layers

- floodplain deposits and buried channels
- Heterogeneous geology

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Paper #1

Gurevich, H, Baram, S, Harter, T. Measuring nitrate leaching across the critical zone at the field to farm scale. *Vadose Zone J*. 2021; 20:e20094. https://doi.org/10.1002/vzj2.20094

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DOI: 10.1002/vzj2.20094

Vadose Zone Journal

SPECIAL SECTION: TRANSDISCIPLINARY CONTRIBUTIONS AND OPPORTUNITIES IN SOIL PHYSICAL HYDROLOGY II

Measuring nitrate leaching across the critical zone at the field to farm scale

Hanna Gurevich[1] | **Shahar Baram**[2] | **Thomas Harter**[1]

[1] Land, Air Water Resources, Univ. of California Davis, One Shields Ave., Davis, CA 95616-5270, USA

[2] Institute of soil, water and environmental science, ARO Volcani Cente, Bet Dagan, 50250, Bet-Dagan 50250, Israel

Correspondence
Thomas Harter, Land, Air Water Resources, Univ. of California Davis, One Shields Ave., Davis, CA 95616-5270, USA.
Email: Thharter@ucdavis.edu

Assigned to Associate Editor Scott Bradford.

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Abstract

Research is lacking monitoring beyond the root zone for programmatic or regulatory assessment and for onsite monitoring of field- or farm scale agricultural nitrate leaching to groundwater. Here, we investigate the relationship between measurements of N at the sediment core scale, the groundwater monitoring well scale, and the field or farm management scale. Importantly, we monitor across the vertical continuum of root zone (RZ, to 3 m), deep vadose zone (DVZ, to 7 m), and upper saturated zone (SZ, to 14 m) in a highly heterogeneous alluvial sediment system, common to many agricultural groundwater basins. Twenty 14-m-deep sediment cores collected across a 56-ha commercial almond orchard were characterized for texture, water content, nitrate, and ammonium. Groundwater nitrate samples (GW) were also obtained from monitoring wells installed and screened across the SZ at the coring sites. Measured parameters were found highly variable at the 0.05-m core sample scale. Monitoring well nitrate concentrations also span over a half order of magnitude despite the uniform agronomic practices across the orchard. Laterally aggregated, orchard-scale parameter means exhibited significant vertical trends and differed in variability between RZ, DVZ, and SZ. Within the SZ, coarse texture facies nitrate concentrations were most closely correlated to GW nitrate, confirming the significance of preferential flow paths within the SZ. The data also indicate significant correlation between DVZ and GW nitrate concentrations. Our findings have important implications to developing appropriate onsite monitoring tools of field- or farm-scale N emissions to groundwater.

1 | INTRODUCTION

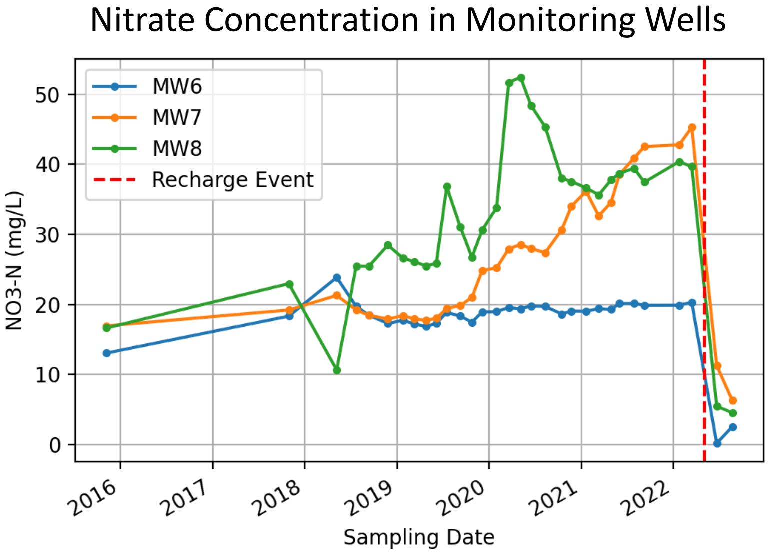
Nitrate in groundwater is a widespread concern, as concentrations continue to rise above drinking water standards in the United States, Europe, Australia, Canada, and elsewhere (Baskaran & Coram, 2009; Dubrovsky, Burow, Clark, & Gronberg, 2004; Schmoll, Howard, Chilton, & Chorus, 2006; Sutton et al., 2011). Nitrate poses several health concerns such as methemoglobinemia (blue baby syndrome), and some types of cancer (Ward et al., 2018). In some of California's most productive agricultural counties, over 40% of tested domestic wells exceed the drinking water limit for nitrate

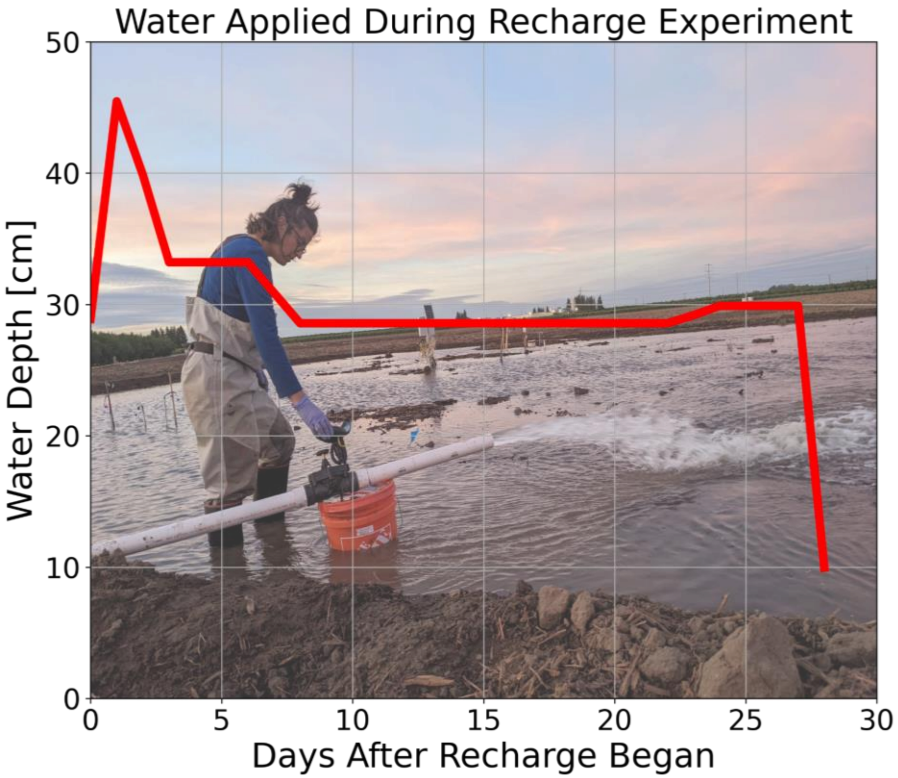
Abbreviations: DVZ, deep vadose zone (3–7 m); GW, groundwater, sampled from monitoring wells (7–14 m); MCL, maximum concentration level; MW, monitoring well; RZ, root zone (0–3 m); SZ, saturated zone, sampled from core samples (7–14 m).

Vadose Zone J. 2021;20:e20094.
https://doi.org/10.1002/vzj2.20094
wileyonlinelibrary.com/journal/vzj2 | 1 of 16

AgMAR Experiment

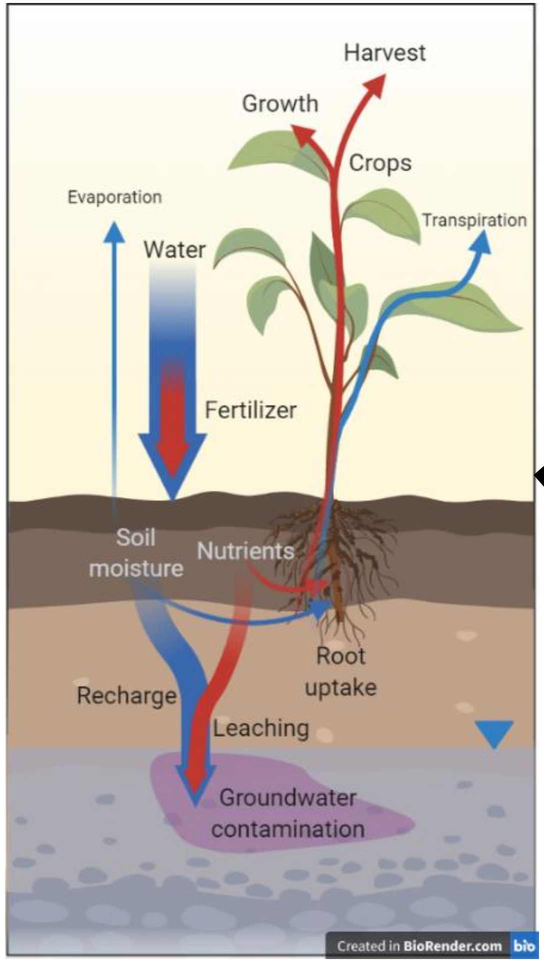
- Flooded three, 700m^2 plots for 4 weeks
- Directly upgradient of monitoring wells
- Measurements:
  - Soil tension, water content, nitrate (VZ)
  - Head, nitrate (GW)



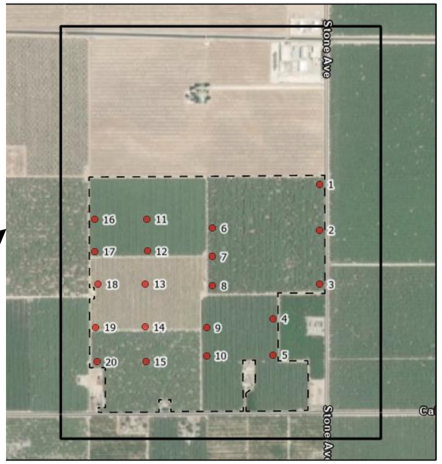


Model Development

Vadose Zone Model
(HYDRUS1D)



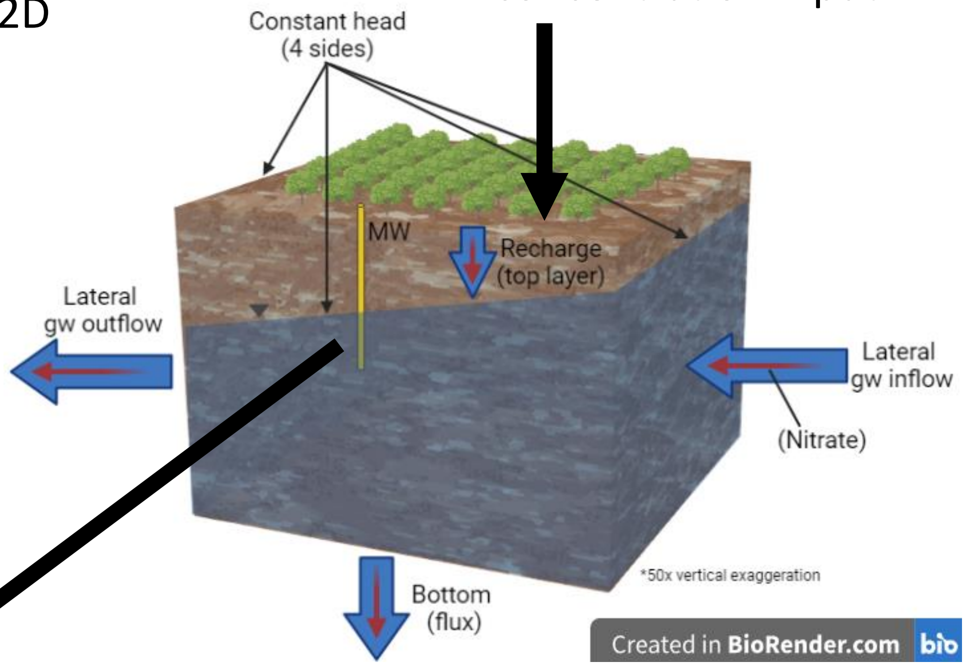
X 20 profiles



Interpolate
to 2D

3D Groundwater Model
(MODFLOW-2005 + MT3DMS)

Recharge,
N concentration input



Output: MW nitrate concentration
Simulation period: 1957-2099 (142 years)

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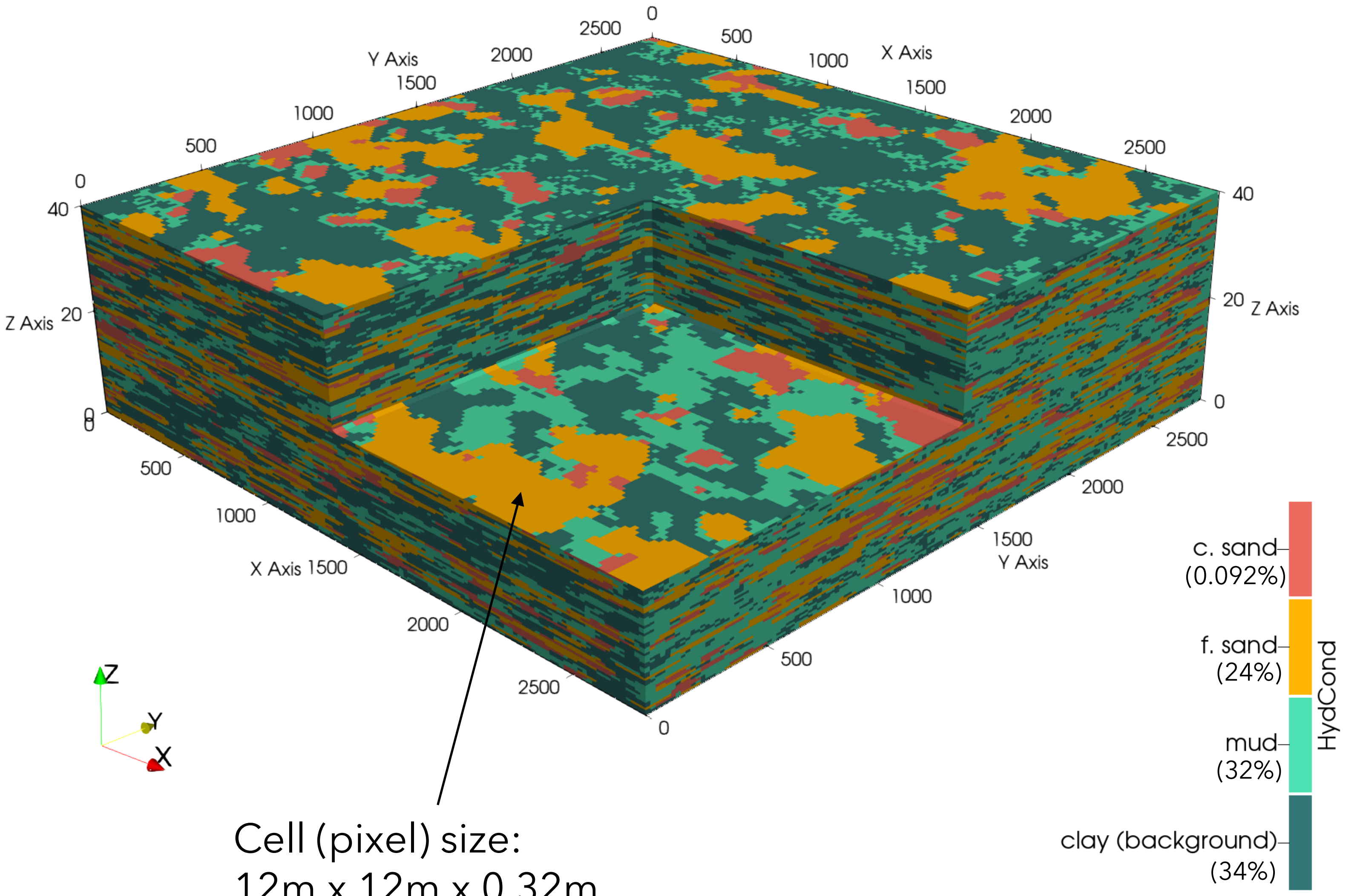
Heterogeneous Geology



Cell (pixel) size:
12m x 12m x 0.32m

- Geologic heterogeneity based on soil maps and detailed boring logs (Gurevich et al. 2020)
- Vadose zone model: 19 sediment textures
- Groundwater model: 4 hydrofacies
- Randomly sample parameter space for estimated soil hydraulic parameter range
- Conditional Monte Carlo simulations
- Tune parameters with field data

Model Calibration

Vadose Zone model:

- Root uptake parameter to reported harvested N (in lbs/ac)
- Unsaturated soil hydraulic parameters to soil moisture during flooding experiment

Groundwater model:

- B.C. parameters to observed gw heads
- Constrain hydraulic conductivity from orchard slug tests (16-18 m/day)

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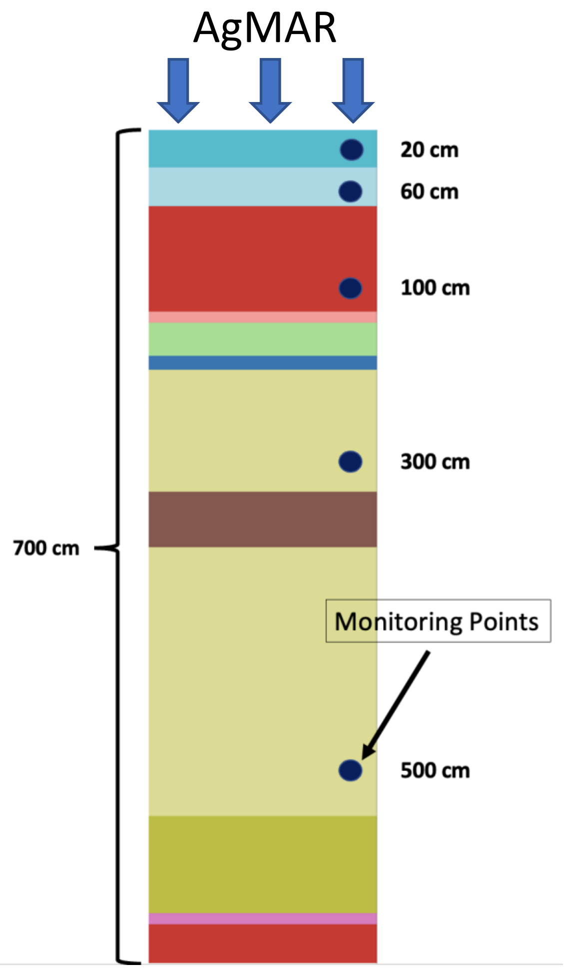
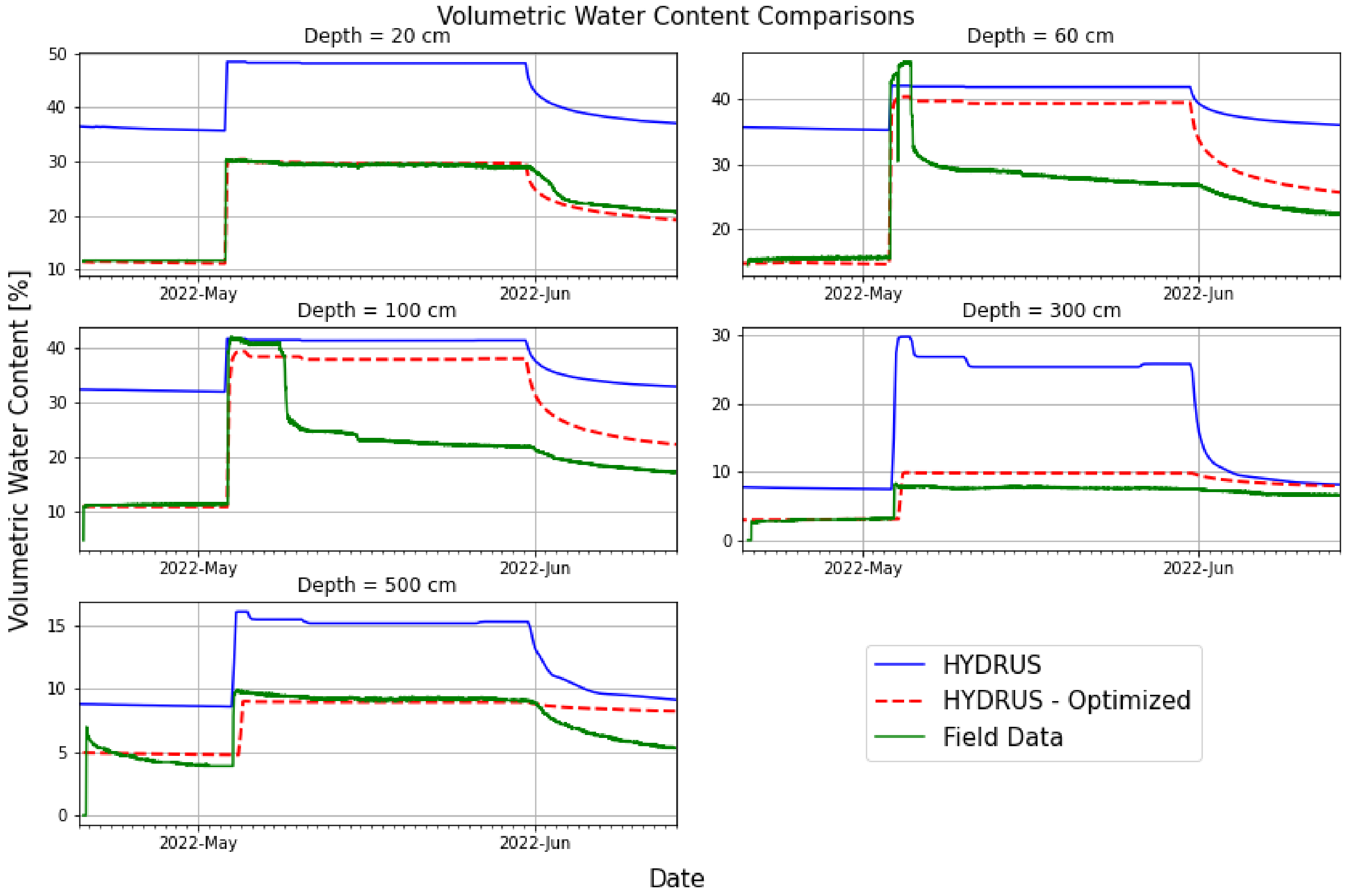
Vadose Zone Model Calibration to AgMAR Field Data

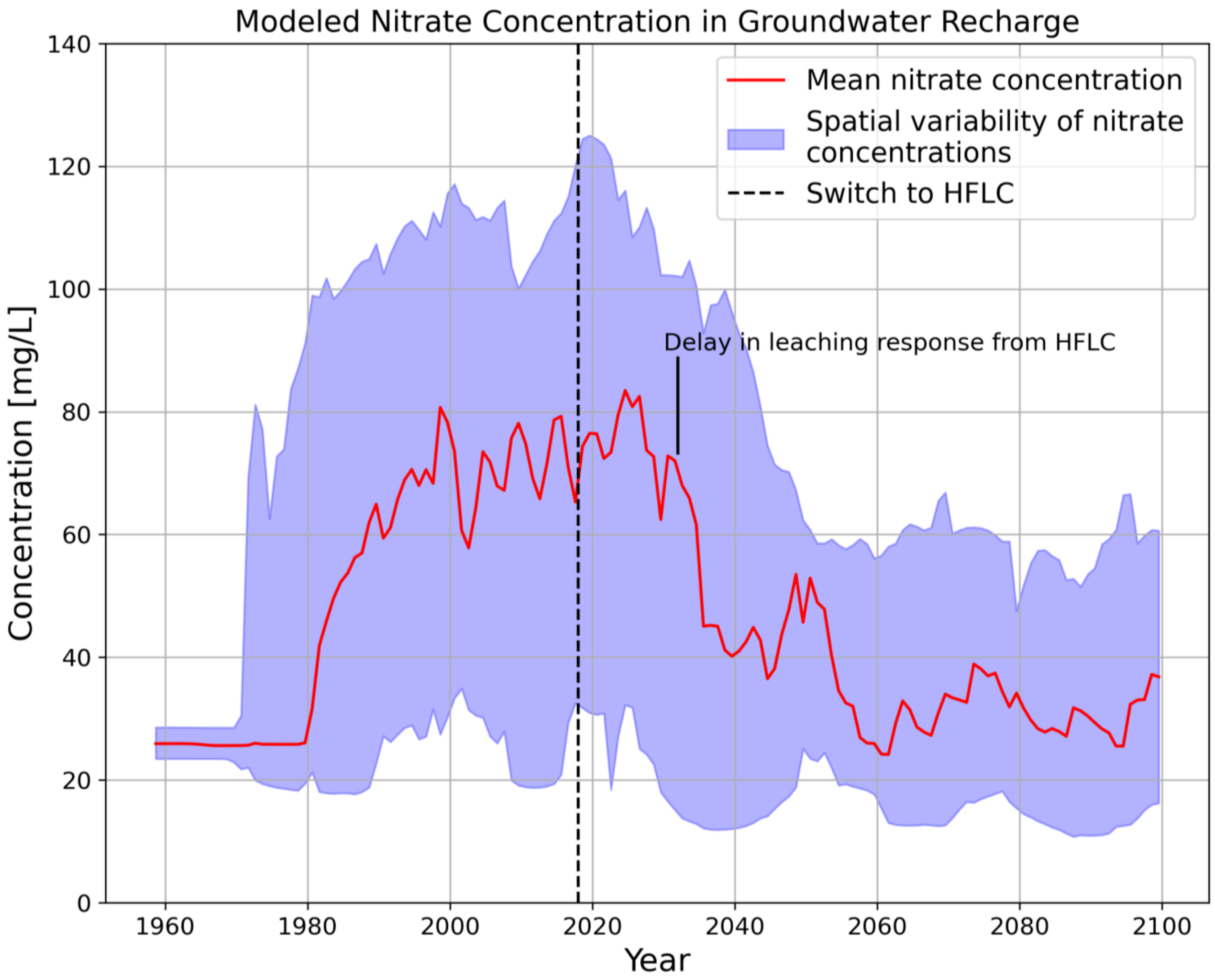
- Volumetric water content in 6 of the 24 sediment textures
- Accounted for 35% of the total profile lengths





Calibrated Vadose Zone Results

- Results from 20 different 1-D profiles, co-located with groundwater wells
- Even under HFLC, recharge nitrate concentrations remain high at a mean of 25mg/L
  - Recharge is low because of efficient irrigation/dry climate
- Compared to mass balance calculated from farmer records (harvest, fertilizer, irrigation)
  - Both ~40% reduction in leaching
- Predicted recharge and nitrate leaching used as input for MODFLOW-MT3DMS groundwater model



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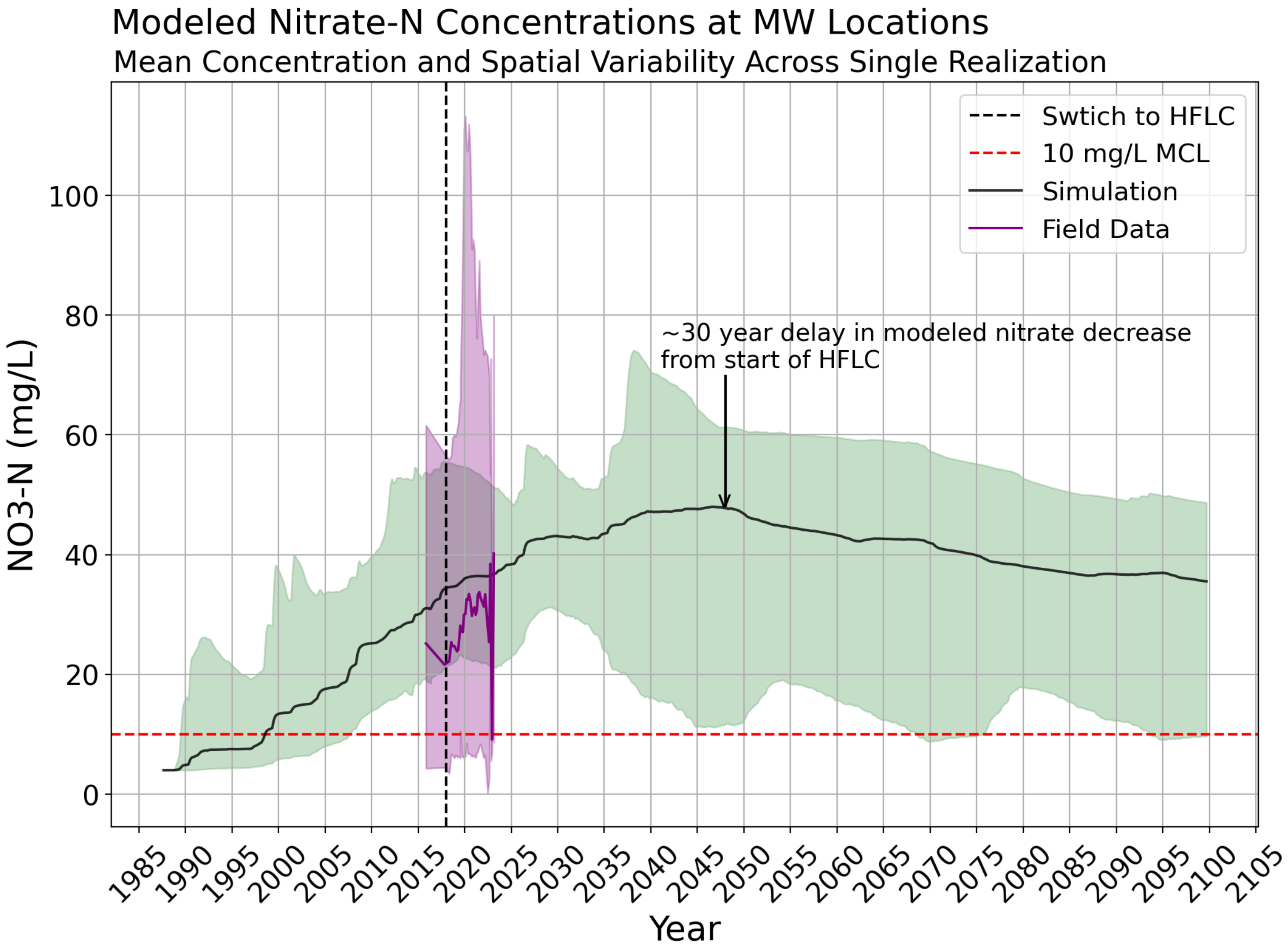
Groundwater Results

- Groundwater results using HYDRUS predicted recharge and N leaching, <u>across the 20 well locations</u>
- Modeled range and rate of increase of nitrate concentrations matches observations
- Average nitrate reduction starts ~30 years from start of HFLC
- Concentrations remain high even with 95% nitrogen use efficiency in model
- Spatial variability in groundwater nitrate concentrations driven by spatial variability in leaching from vadose zone



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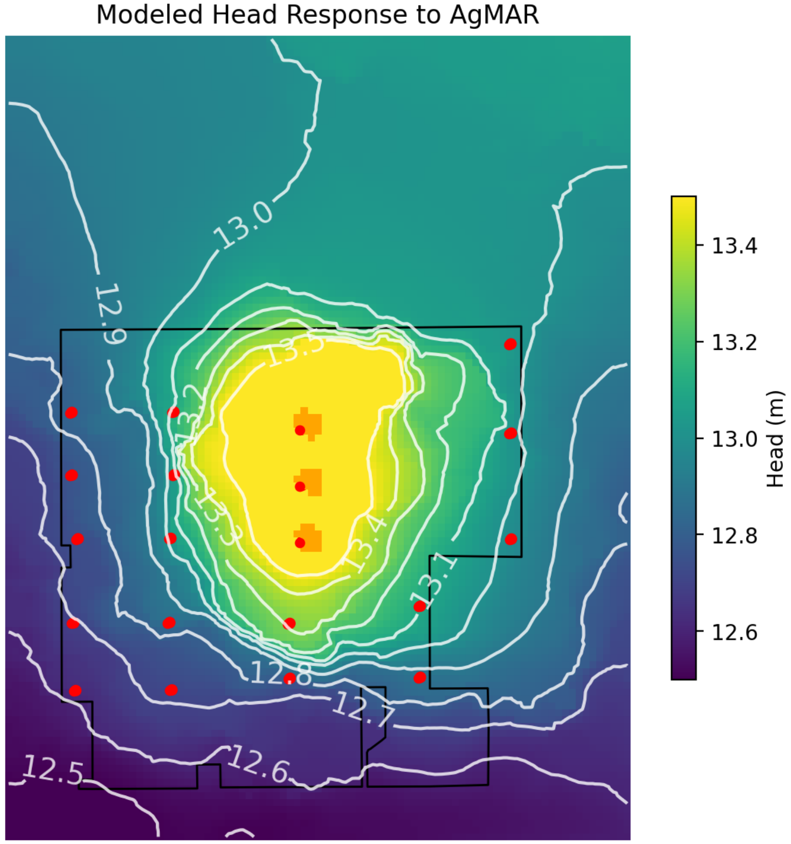
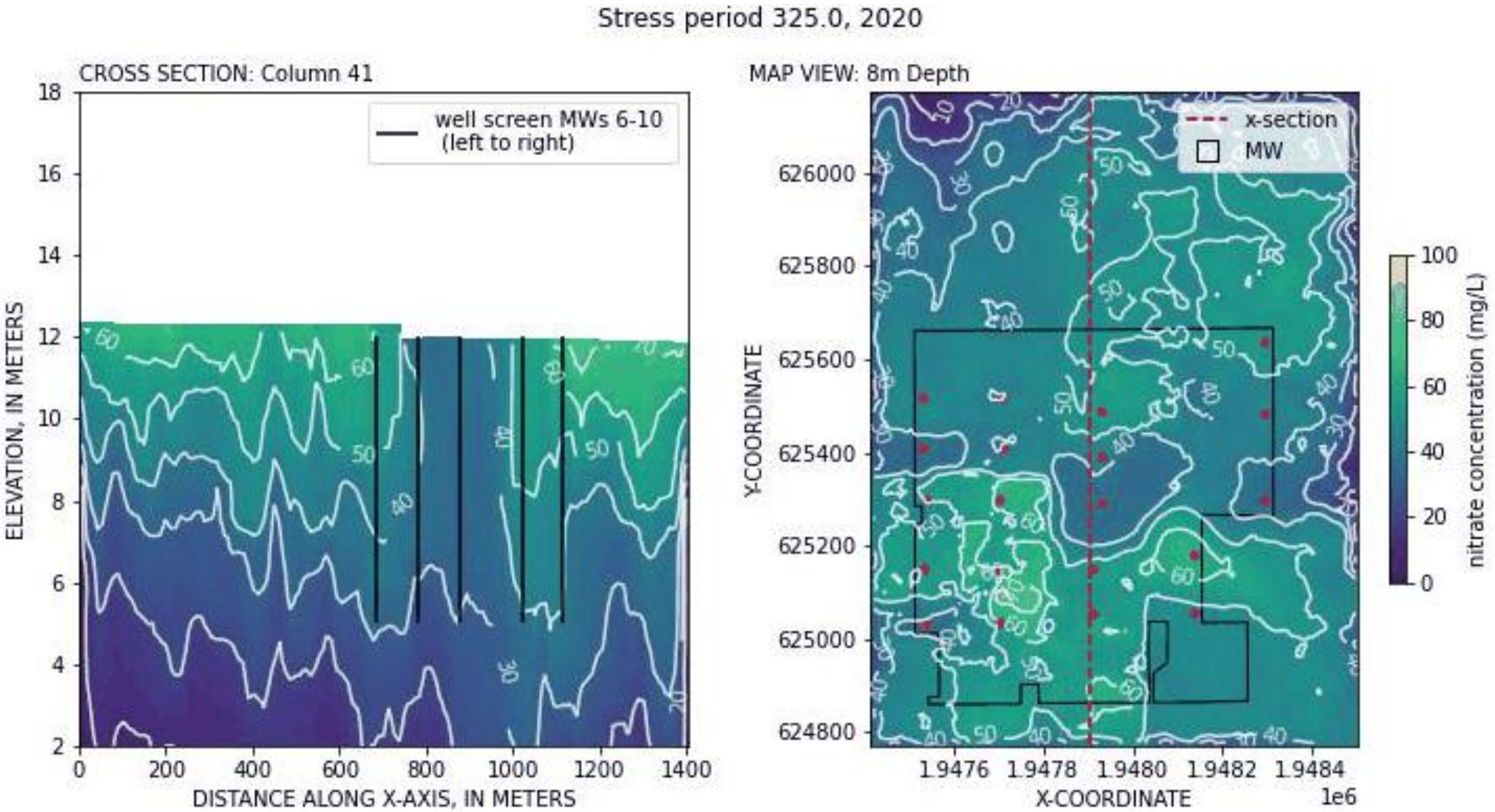
AgMAR Modeling on Single Orchard Plot

- Applied about 900cm of total water to each of the three recharge basins over four weeks
- Model successfully captures increase in hydraulic head and decrease of N concentrations due to flooding
  - 1.5m groundwater mound observed in the field and the model


Modeled Head Response to AgMAR


Stress period 325.0, 2020

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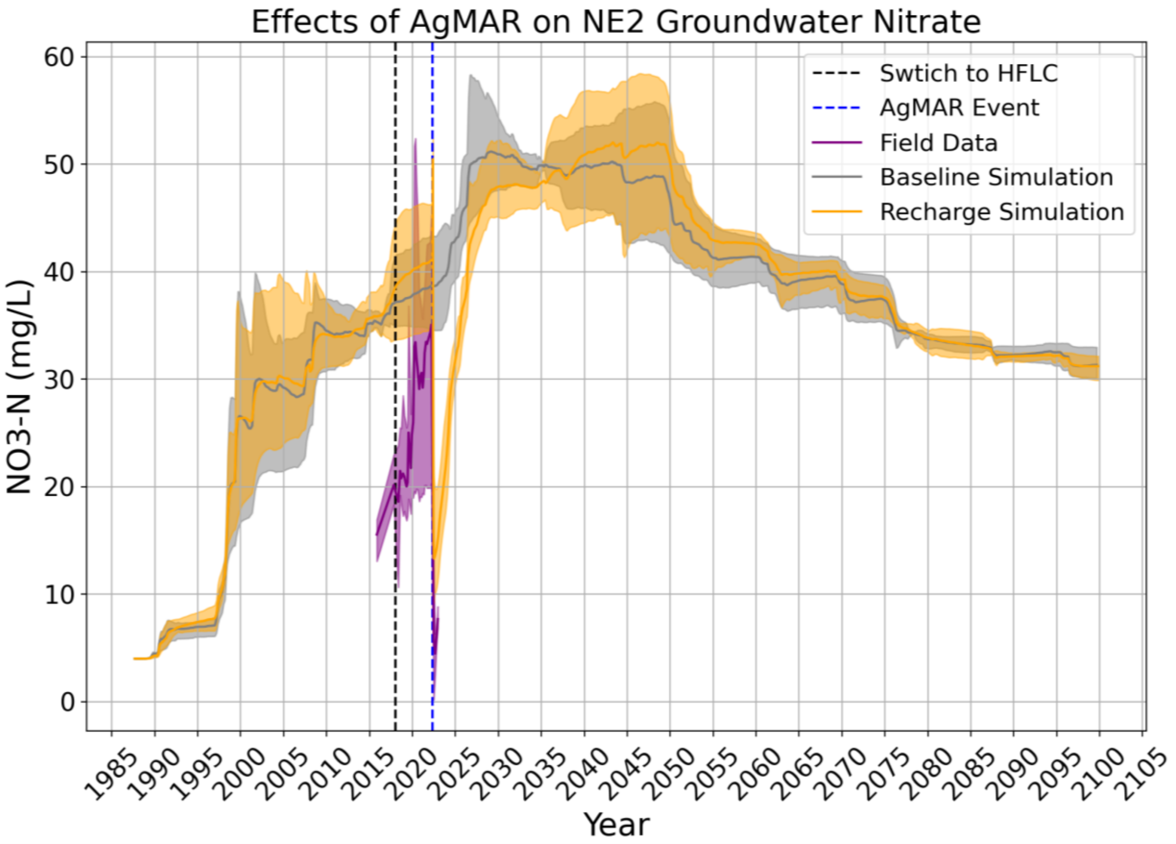
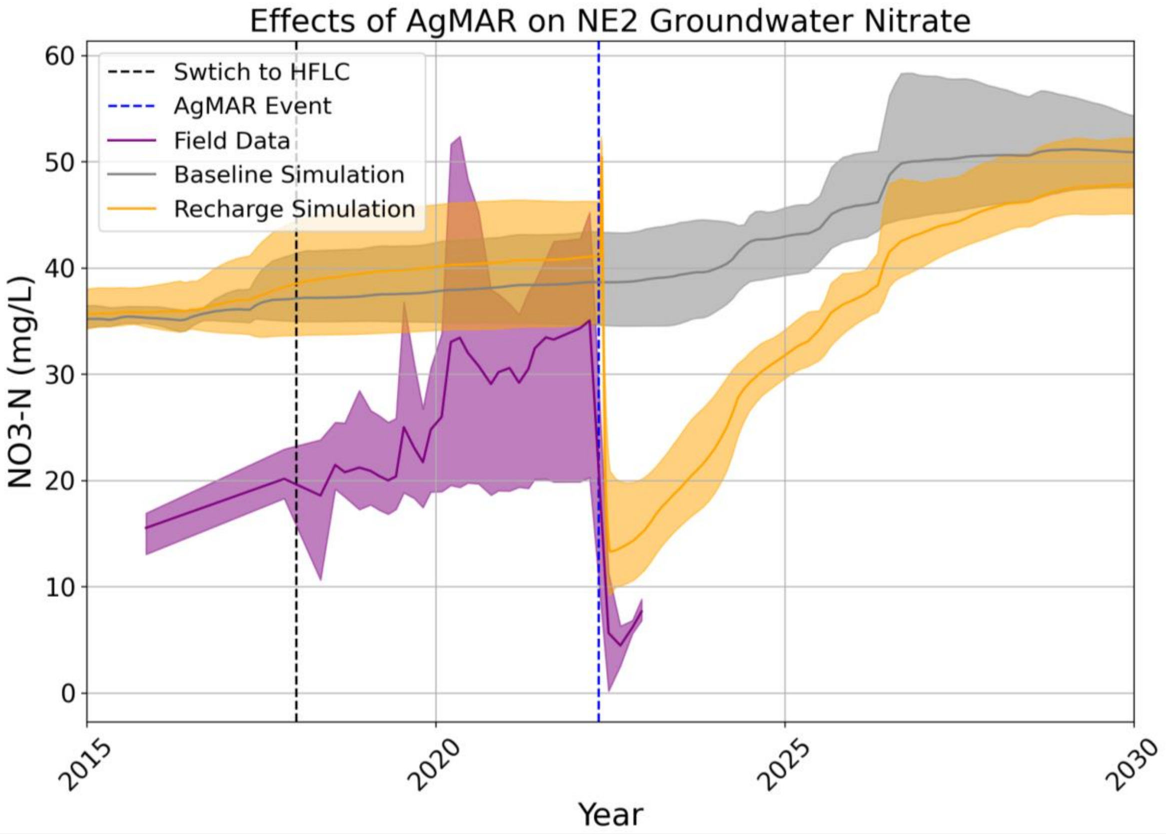
Effect of AgMAR on NO3-N Concentrations

- Rapid reduction of nitrate in the short-term → Matches observed data very well
- Did not improve long-term N reduction, concentrations go back to pre-AgMAR in about 10 years
  - Plot-scale experiment, shows promise for larger scale AgMAR to improve water quality





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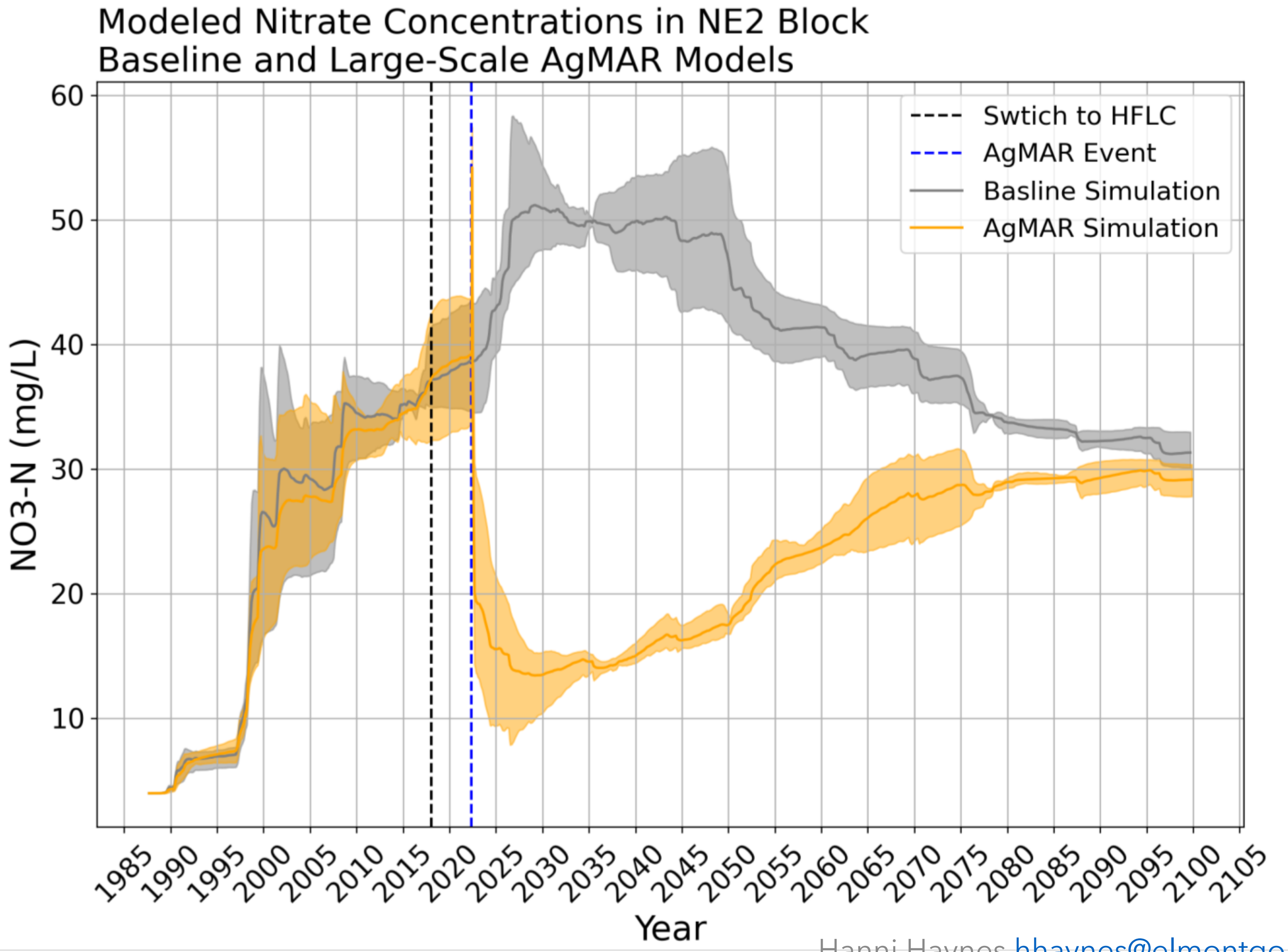
Can we Increase Long-Term Water Quality with AgMAR?

- Yes! But need a lot more water…



- Simulated flooding of entire NE block, about <u>50x the size</u> of recharge basins
- Water use goes up from 15 acre-ft to 750 acre-ft
- Long-term N <u>reduced significantly</u>
- Limitations exist in implementing AgMAR at this scale
- Future work: optimize flooding frequency and magnitude → Realistic scenarios
  - Suggests a small number of larger flooding events could <u>reduce nitrate concentrations below MCL</u>

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Conclusions

What we did:

- Modeled nitrate leaching from an almond orchard at the field-scale and examined resulting shallow groundwater quality
- Modeled nitrate leaching/ groundwater quality response to:
  - Highly efficient fertilization (HFLC)
  - Field flooding (AgMAR)

What we found:

- HFLC = ~40% less nitrate leaching, supported by N mass balance estimates
- Due to low recharge, leaching nitrate concentrations still > MCL
- With AgMAR, diluted nitrate concentrations < MCL

What's next:

- Use model to find scale/frequency of AgMAR to support groundwater quality

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Thomas Harter

Orchard Project Team

Hanna Gurevich, Will Lennon,
Teena Stockert, Iael Raij-Hoffman,
Helen Dahlke Lab

Owners/Growers at our study orchard

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cdfa
CALIFORNIA DEPARTMENT OF FOOD & AGRICULTURE

FERTILIZER RESEARCH AND EDUCATION PROGRAM
FREP

california almonds
Almond Board of California

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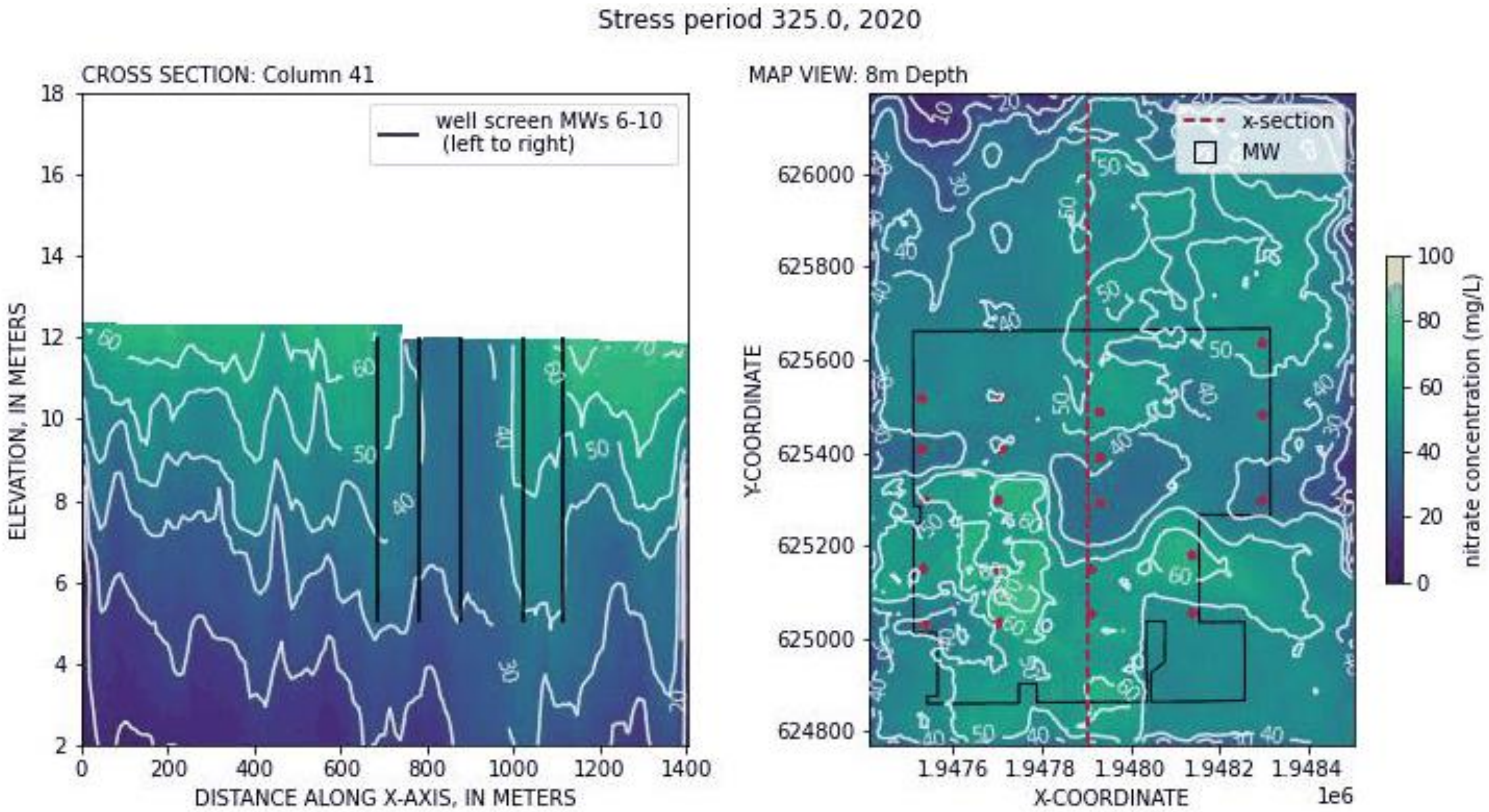
Questions?


Stress period 325.0, 2020
CROSS SECTION: Column 41
well screen MWs 6-10 (left to right)
ELEVATION, IN METERS
18
16
14
12
10
8
6
4
2
0
200
400
600
800
1000
1200
1400
DISTANCE ALONG X-AXIS, IN METERS
60
50
40
30
20
70
MAP VIEW: 8m Depth
x-section
MW
Y-COORDINATE
626000
625800
625600
625400
625200
625000
624800
1.9476
1.9478
1.9480
1.9482
1.9484
1e6
X-COORDINATE
10
20
30
40
50
60
nitrate concentration (mg/L)
100
80
60
40
20
0

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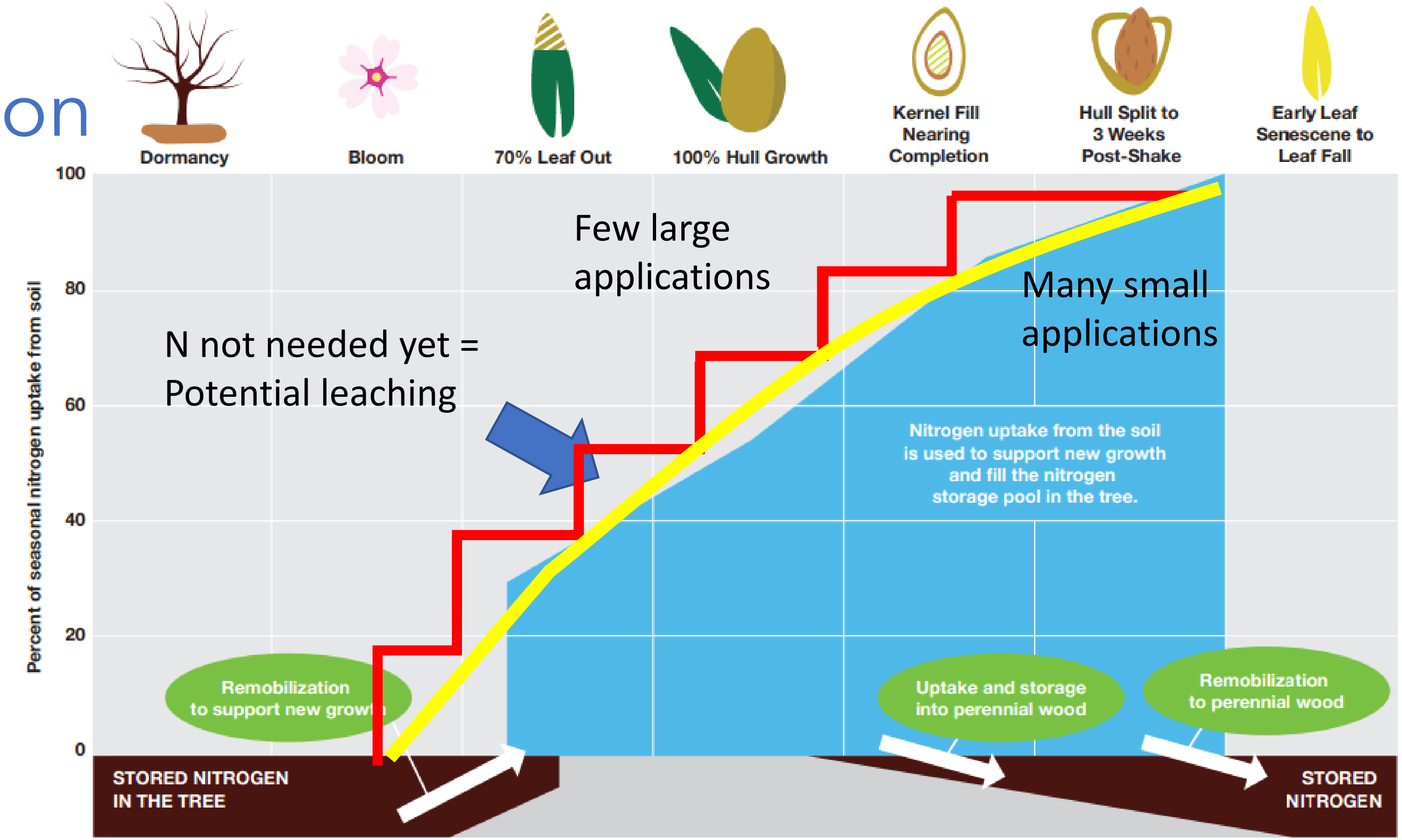
Additional Slides

High Frequency Low Concentration (HFLC)

- Fertilize in frequent, small doses to match the tree's N uptake curve
- Demonstrated to improve NUE



(Figure modified from Almond Board's Nitrogen BMP)

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Mass Balance Example

	N Mass Balance	2013-2017 average* (lbs/acre)	HFLC 2018-2021 average* (lbs/acre)
HARVEST	Kernels	*2,115*	*2,456*
INPUT	Fertilizer	*227*	*190*
	Atmospheric deposition (20 kg/ha)	*18*	*18*
	Mineralization (40 kg/ha)	*36*	*36*
OUTPUT	Crop uptake	*156*	*162*
	Tree growth	*43*	*37*
	Denitrification	*11*	*9*

* Excluding blocks with young trees

HFLC = better yield

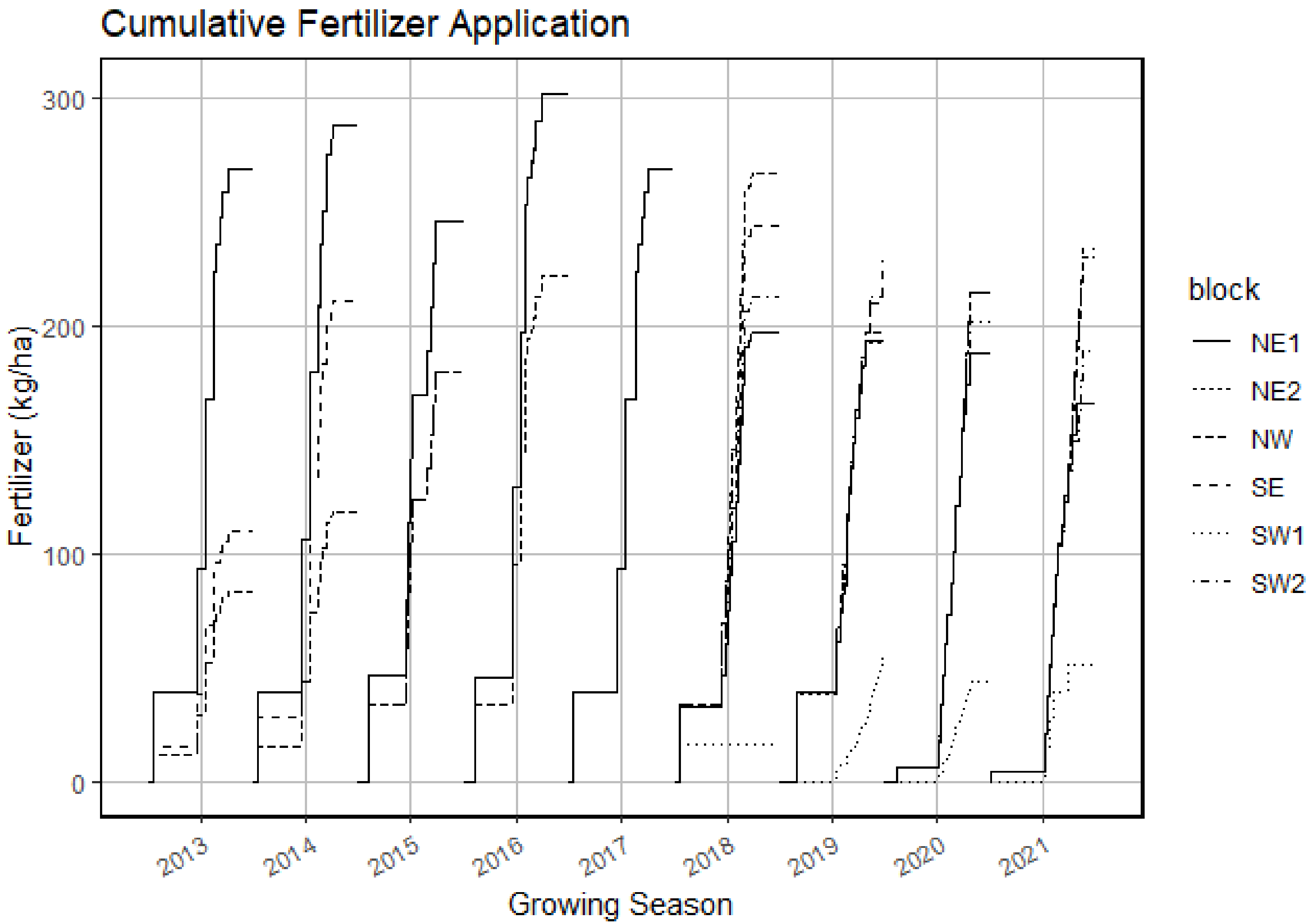
HFLC =
less fertilizer needed

	2013-2017	HFLC 2018-2021
	281	244
	- 210	- 208
Leaching:	71 lbs/ac/yr (80 kg/ha/yr)	36 lbs/ac/yr (40 kg/ha/yr)
Recharge: 4 cm/yr	÷	÷
Concentration:	200 mg/L	100 mg/L

N Mass Balance 2013-2021

		Pre-HFLC					HFLC			
	N Mass Balance (average lbs/acre)	2013**	2014	2015	2016	2017*	2018*	2019*	2020*	2021
HARVEST	Kernels	2,010	2,154	2,047	2,032	2,330	2,638	1,874	3,164	2,146
	+/- std dev.	±184	±691	±339	±180	±320	±406	±266	±615	±885
INPUT	Fertilizer	240	214.8	199.4	242	240	209	190	183	176
	Atmospheric deposition (20 kg/ha)	17.84	17.84	17.84	17.84	17.84	17.84	17.84	17.84	17.84
	Mineralization (40 kg/ha)	35.68	35.68	35.68	35.68	35.68	35.68	35.68	35.68	35.68
OUTPUT	Crop uptake	198	146.5	139.2	138.2	158.4	179.4	127	215	125
	Tree growth	37	46	46	43	41	38	35	35	41
	Denitrification	12.00	10.74	9.97	12.10	12.00	10.45	9.50	9.15	8.80
SUMMARY	NUE$_{growth}$	0.98	0.90	0.93	0.75	0.83	1.04	0.85	1.37	0.94
	NUE	0.84	0.76	0.77	0.65	0.72	0.87	0.70	1.10	0.76
	GW Losses	46.82	65.08	57.75	102.22	81.87	35.17	72.02	-22.63	54.92
Note:	NUE$_{growth}$ is a partial mass balance while NUE is the full mass balance.									
	*Does not include young block SW1									
	**Does not inlude young blocks NW or SE									

Fertilizer Application



Irrigation and Fertilizer Application Adjustment for Tree Age

Age of trees in block (years)	Irrigation adjustment factor	Fertilizer adjustment factor
1	0.5	0.36
2	0.5	0.36
3	0.75	0.45
4	1	0.75
5	1	0.75
6-25	1	1

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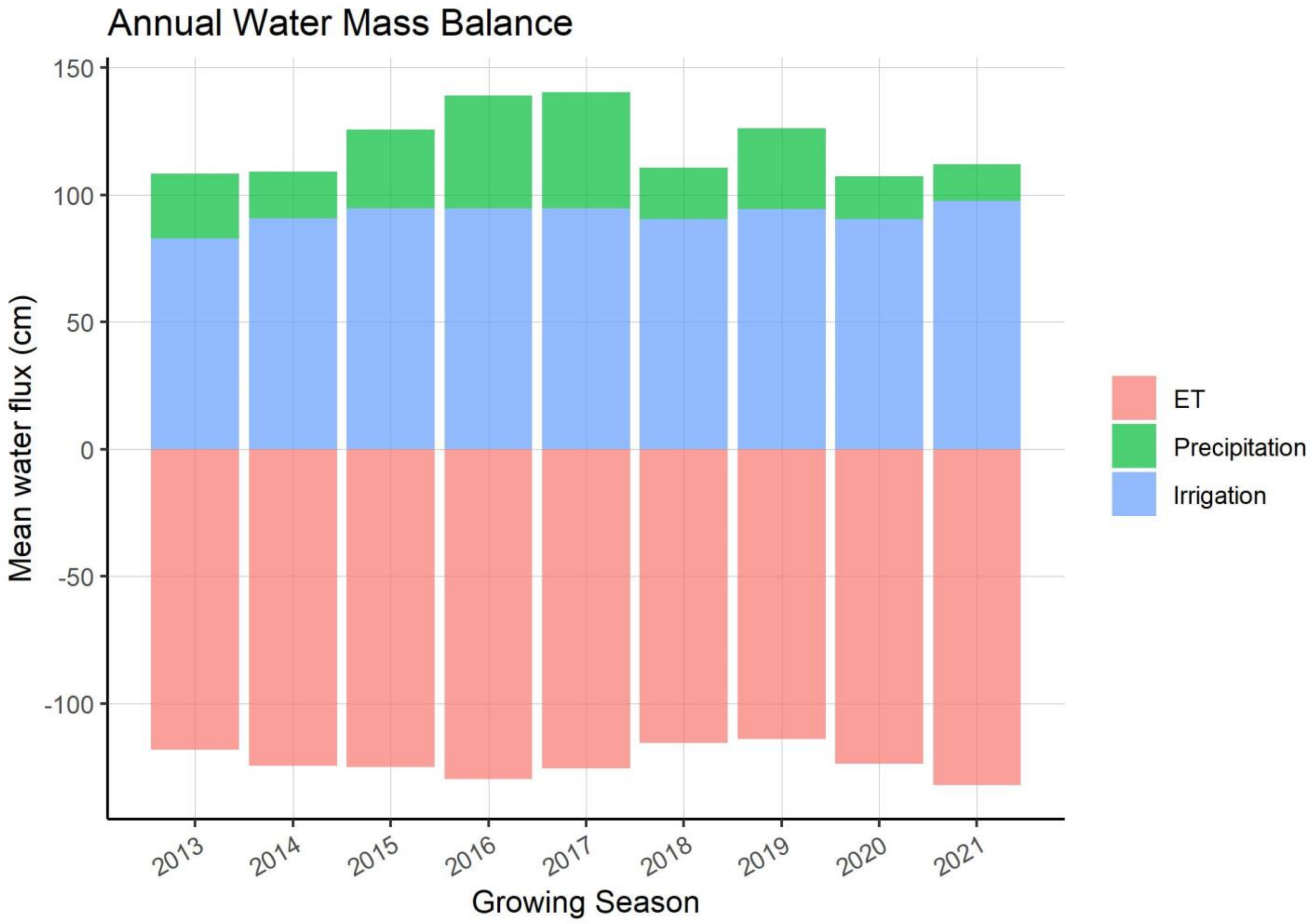
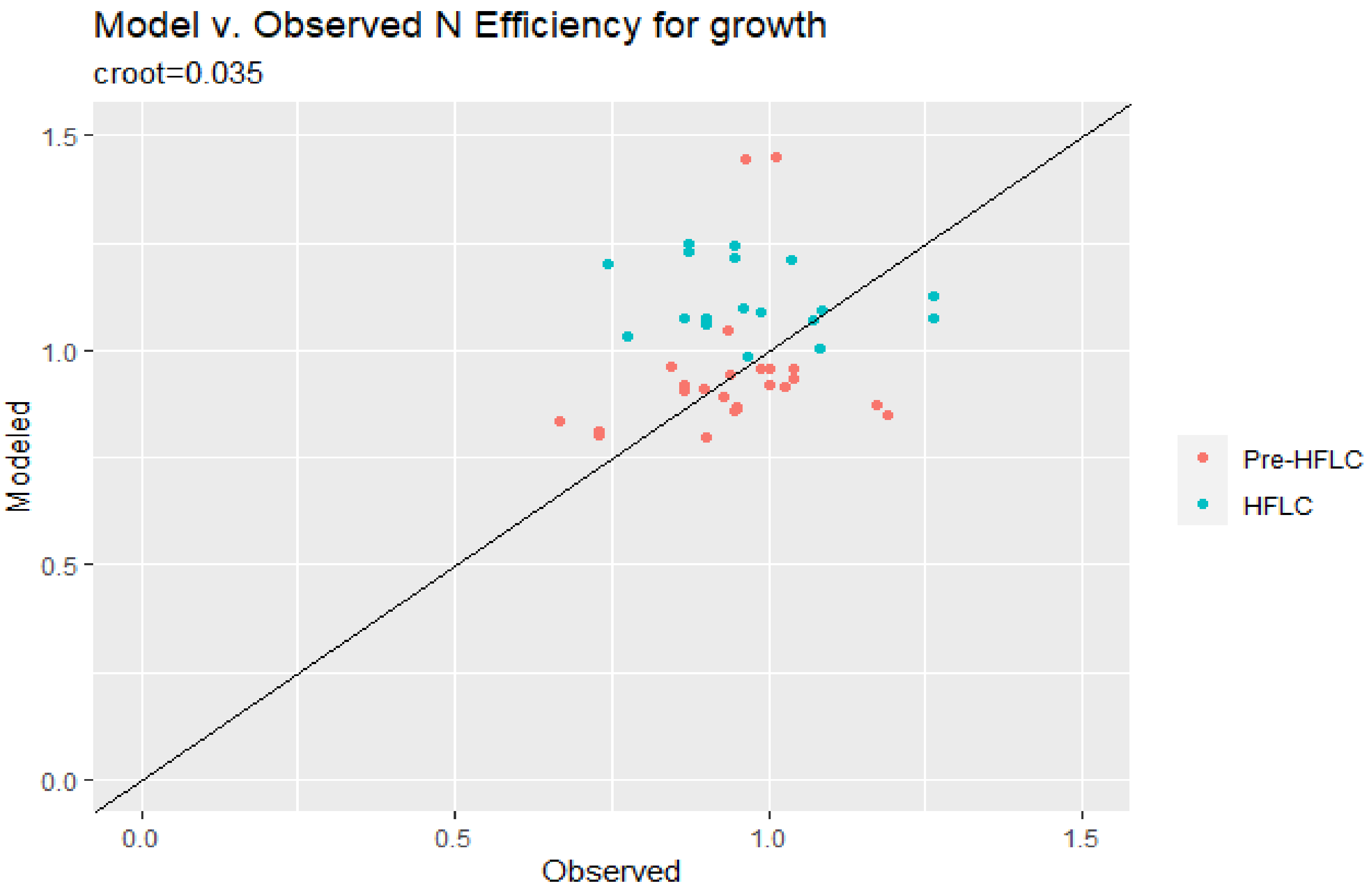
Annual Water Mass Balance



Manual Calibration of $cRoot_{max}$



GW Model Soil Hydraulic Parameters

	Hydrofacies			
	Coarse sand	Fine sand	Mud	Clay
Horizontal hydraulic conductivity (m/d)	120-500	17-120	0.15-1.7	1e-3 – 0.15
Vertical hydraulic conductivity	$k_v = k_h/10$			
Specific yield	0.2-0.3	0.2-0.3	0.03-0.2	0-0.05
Specific storage (m^{-1})	7.53e-6	1.04e-5	1.36e-5	1.47e-5
Porosity	0.2-0.5	0.2-0.5	0.2-0.5	0.2-0.5
Dispersivity	6m			
Molecular diffusion coefficient	8.64×10^{-5} m^2/day			

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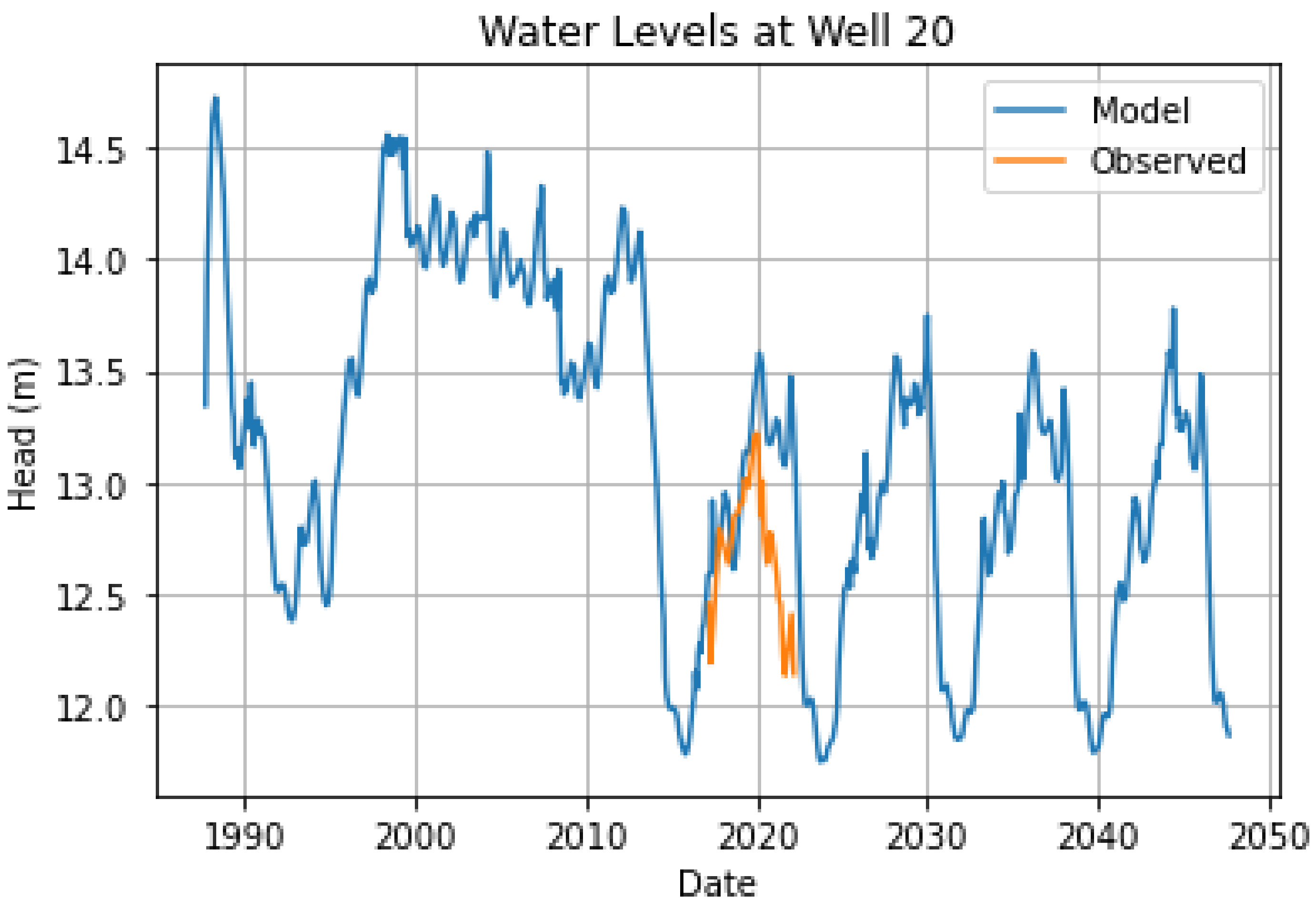
Groundwater Flow Model Performance



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