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Supplementary Information for

Peak grain forecasts for the U.S. High Plains amid withering waters

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Supporting Information Text

Methods. How does a groundwater withdrawal reduction extend aquifer lifespan? An order of magnitude lower rate of groundwater withdrawals for Texas and Kansas would have resulted in an extension in the lifespan of the aquifer. In 2012, Kansas implemented a Local Enhanced Management Area program enforcing a five-year groundwater conservation through cooperation between farmers and local and state officials. As a result, groundwater use decreased by 30% (1). To model the effect of such a reduction, k_1 and k_2 were reduced by 30% starting in 2012 in Kansas. The effect of such a reduction is that, by 2020, 7.2 km^3 of groundwater would have been saved and water depth was 58 cm shallower. By 2050, those numbers would be 17 km^3 of groundwater and 137 cm of depth. Usually, what accompanies such reductions in groundwater withdrawal is a reduction in A and a shift to crops that maintain high yields with shallower irrigation depths. This last point could be explored with amplified responses of crop production to groundwater availability through less pronounced reductions in k_2 compared to the k_1 in the model but this is not elaborated upon here.

Numerical values of state variables from model parameters. Table S1 features relevant computations based solely on the parameters of the dynamical systems model presented in the main text through equations 1 and 2. From equation 2, the value of W at peak grain can be determined as $W = k_3/k_2$. The withdrawal rate at peak grain is $k_1\, C\, W$ where the value of C is extracted from figure 1 in the main text. Sustainable C is calculated by first setting $W_{sust} = k_3/k_2$, its steady-state value $dW/dt = 0$, and solving for the remaining terms in equation 1 to obtain $C_{sust} = k_2\, R\, A_{HPA}/(k_3 k_1)$. Then, the sustainable withdrawal rate is $R\, A_{HPA}$. From these estimates, the ratios of peak crop production and peak water withdrawal to their respective sustainable values can be computed.

33 ## 1. Tables

Table S1. Computations performed from model parameters. Details of these computations are available in section 1 of the supplementary material. 'Sustainable rates' and 'Peak results' for Nebraska are Not Determined (ND) because no peak grain is expected within the projection time frame as explained in the Methods section.

	Texas, pre-LEPA	Texas, post-LEPA	Kansas	Nebraska	Units
k_1	7.2e-9	5.5e-9	6.2e-9	8.6e-9	tons^{-1}
k_2	2.9e-4	3.2e-4	3.3e-4	5.6e-4	km^{-3} years^{-1}
k_3	0.075	0.046	0.020	0	years^{-1}
R	8	8	18	64	mm years^{-1}
A_{HPA}	94017	94017	80031	167314	km^2
$R \times A_{HPA}$	0.75	0.75	1.44	10.71	km^3 years^{-1}
Peak results					
C(peak grain)	4.94e6	6.60e6	8.08e6	ND	tons years^{-1}
W(peak grain)	258.6	143.8	60.6	ND	km^3
groundwater withdrawal at peak grain	9.2	5.2	3.0	ND	km^3
Sustainable rates					
Sustainable C	4.04e5	9.51e5	3.83e6	ND	tons years^{-1}
Ratio of peak C to sustainable C	12.2	7.0	2.1	ND	-

2. Figures

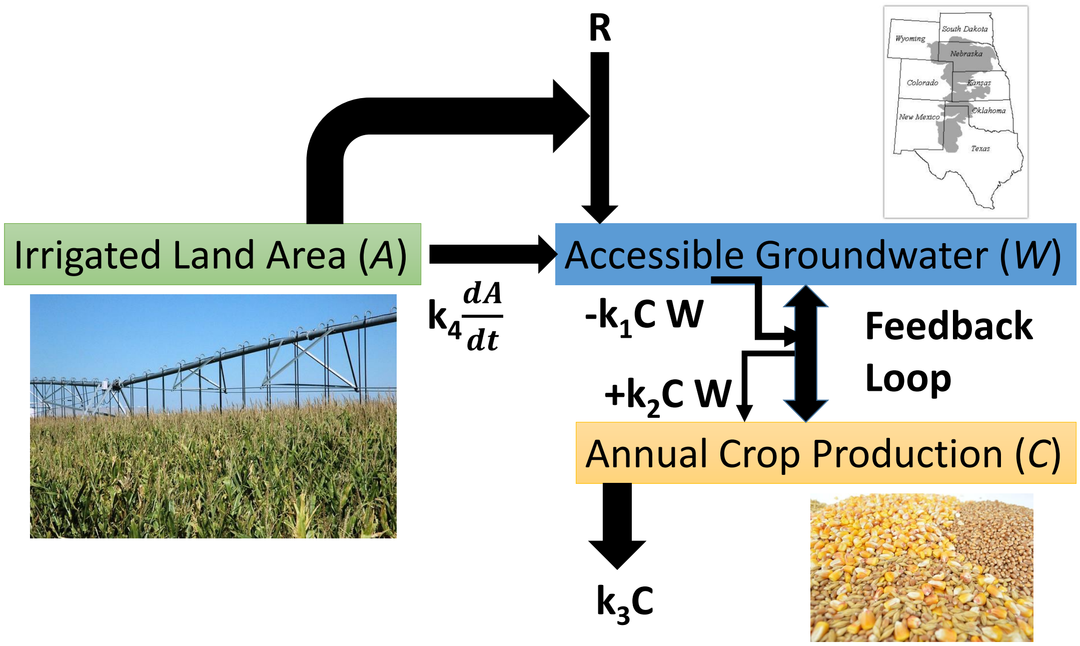

Fig. S1. The main components of the proposed dynamical system, where W is the volume of 'accessible' groundwater, C is the annual rate of crop production by weight, A is the groundwater-irrigated area, and R is the groundwater recharge per unit area. The coefficients k_1, k_2, k_3, and k_4 are determined from statistical fit to data.

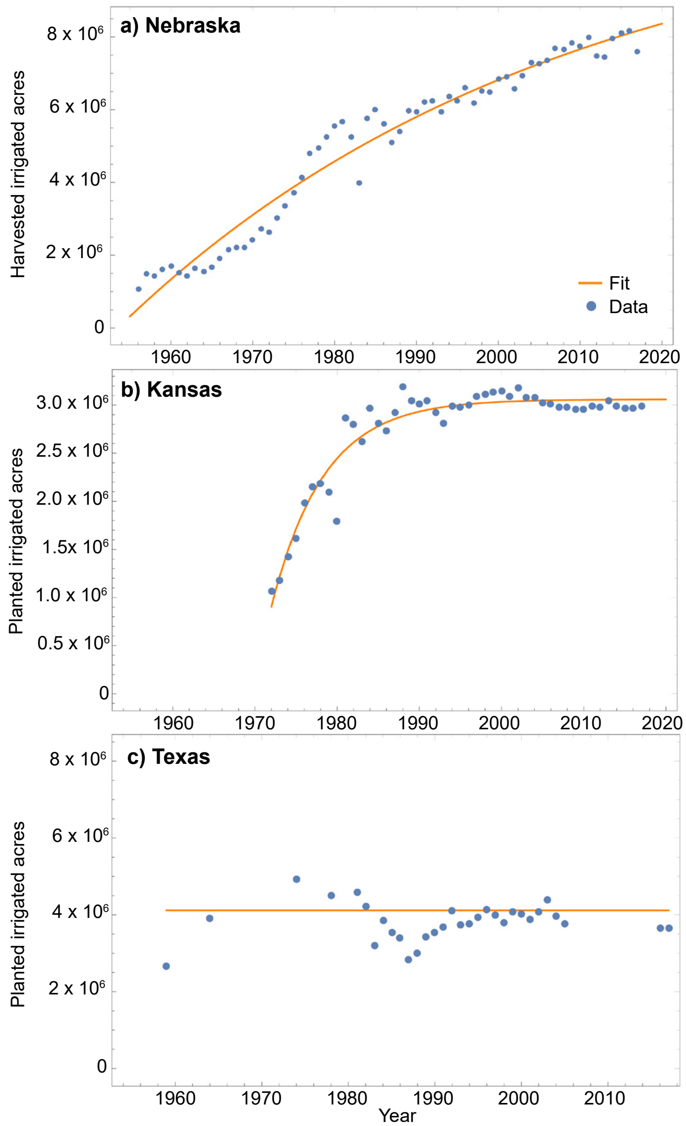

Fig. S2. Temporal trends in irrigated cropland area for the three states.

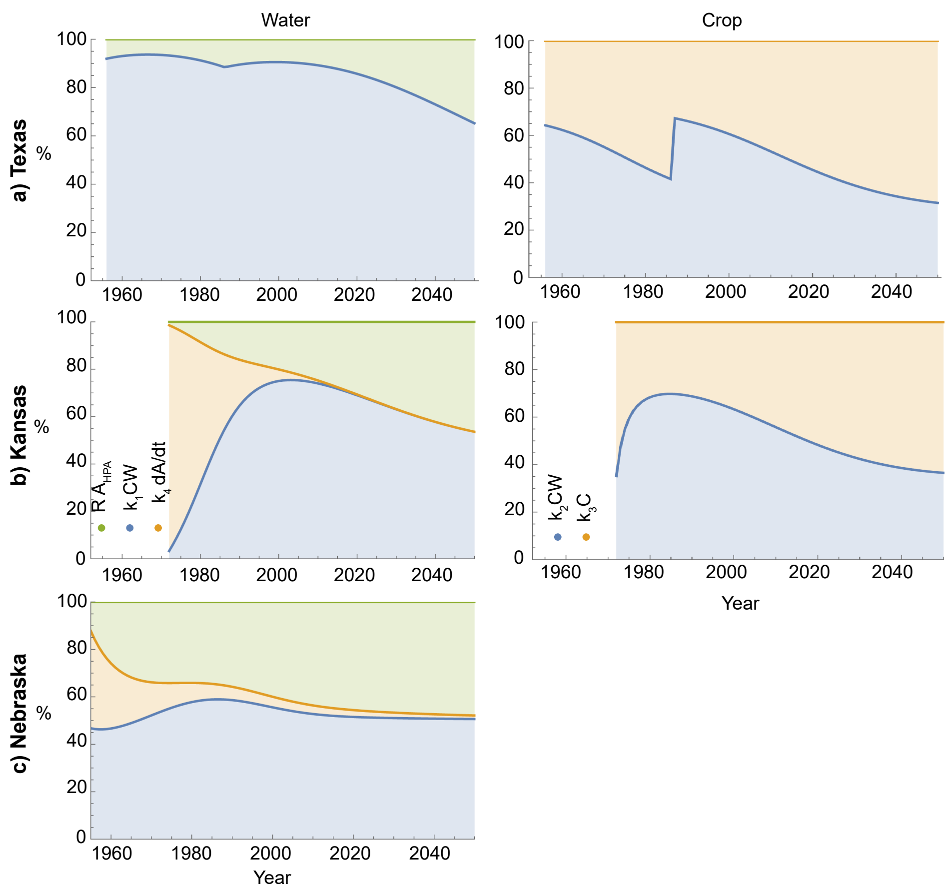

Fig. S3. Contribution of each term in equations 1 and 2 of the main text. The total contributions were calculated by summing the absolute value of the constituent terms in each equation. The individual term contributions were obtained by dividing their absolute values by the appropriate total.

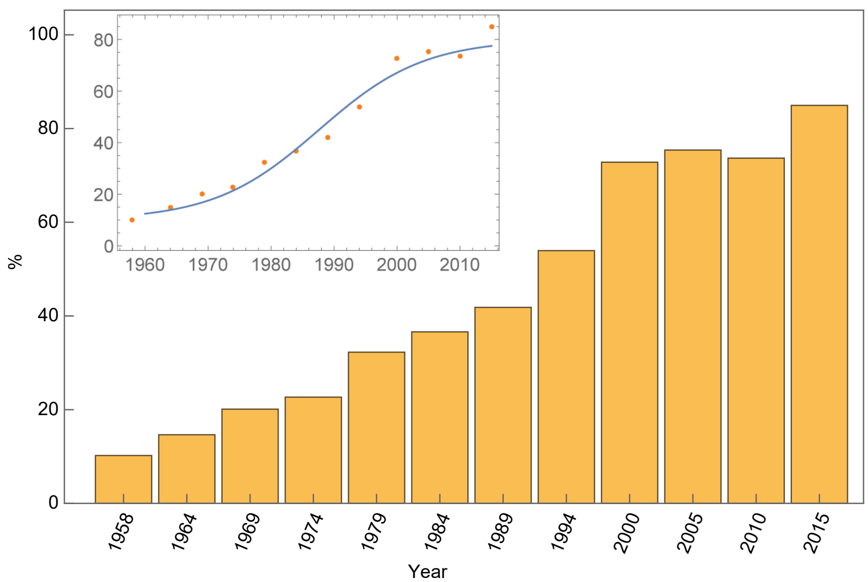

Fig. S4. Ratio of the Texas High Plains under sprinkler irrigation to its total area. The proportions for 2005, 2010, and 2015 were computed from (2) and the rest was compiled from (3, 4). The inset shows the same data points (in orange) fitted to the logistic function: $10 + 70[1 + (70/x_0 - 1)e^{-r(t-1984)}]^{-1}$. $x_0 = 27.5\%$ and $r = 0.12$ years^{-1}.

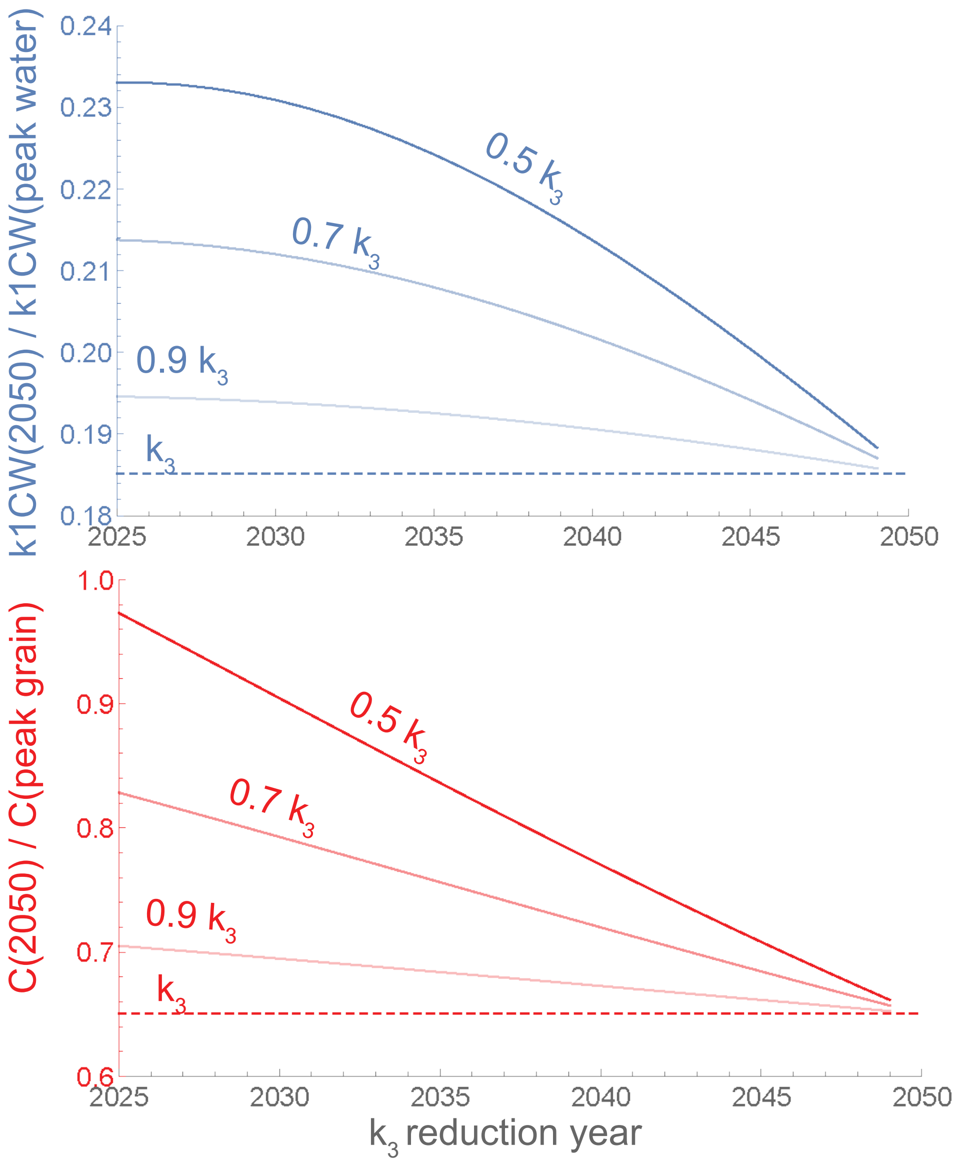

Fig. S5. Sensitivity of Texas groundwater pumping and crop production in 2050 as a function of k_3 reduction time. Water pumping is expressed as the ratio of its value in 2050 to its value at the second peak water event. Crop production is expressed as the ratio of its value in 2050 to its value at the second peak grain event.

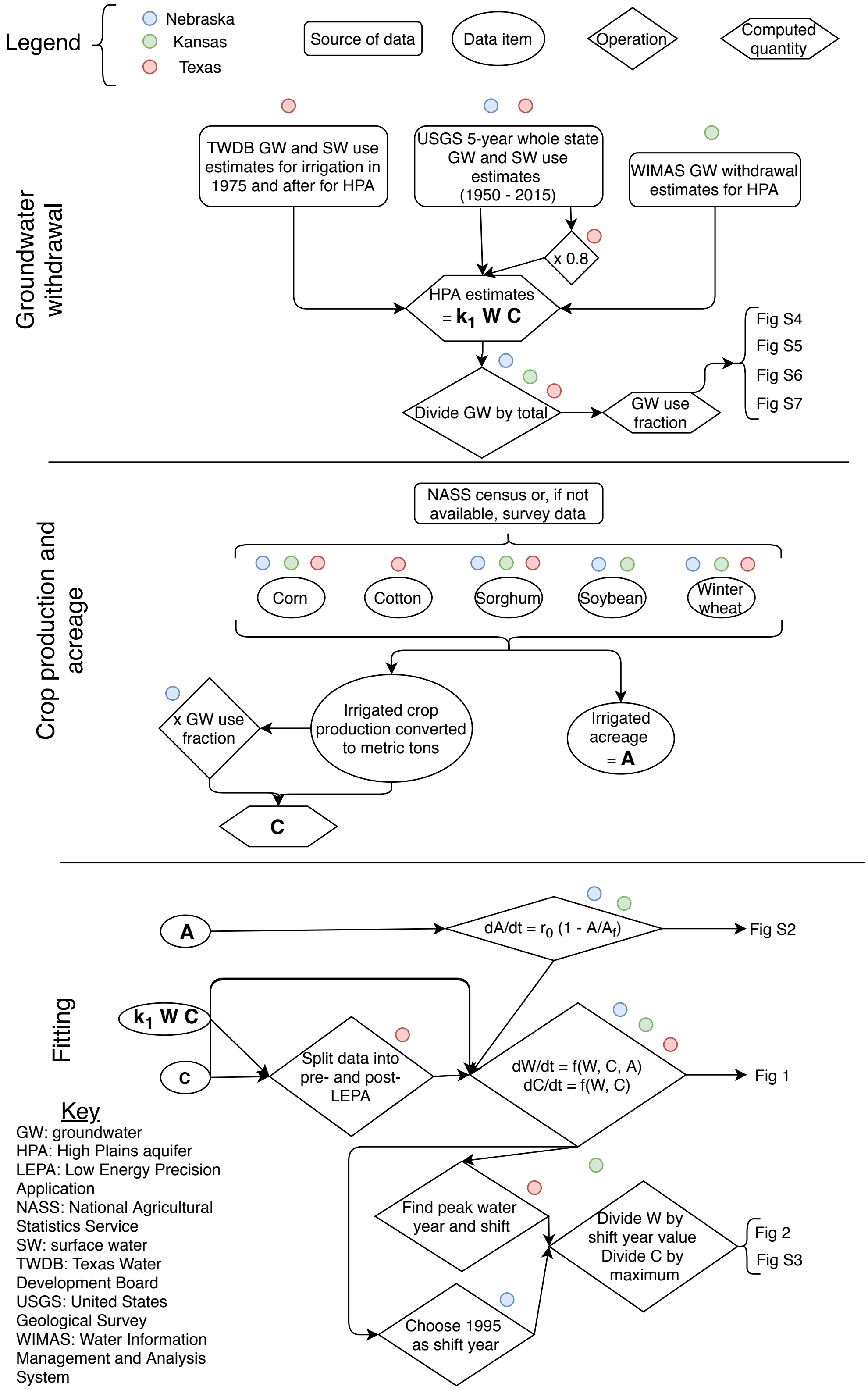

Fig. S6. Flow chart detailing data sourcing and processing. In bold are terms in equations 1 and 2.

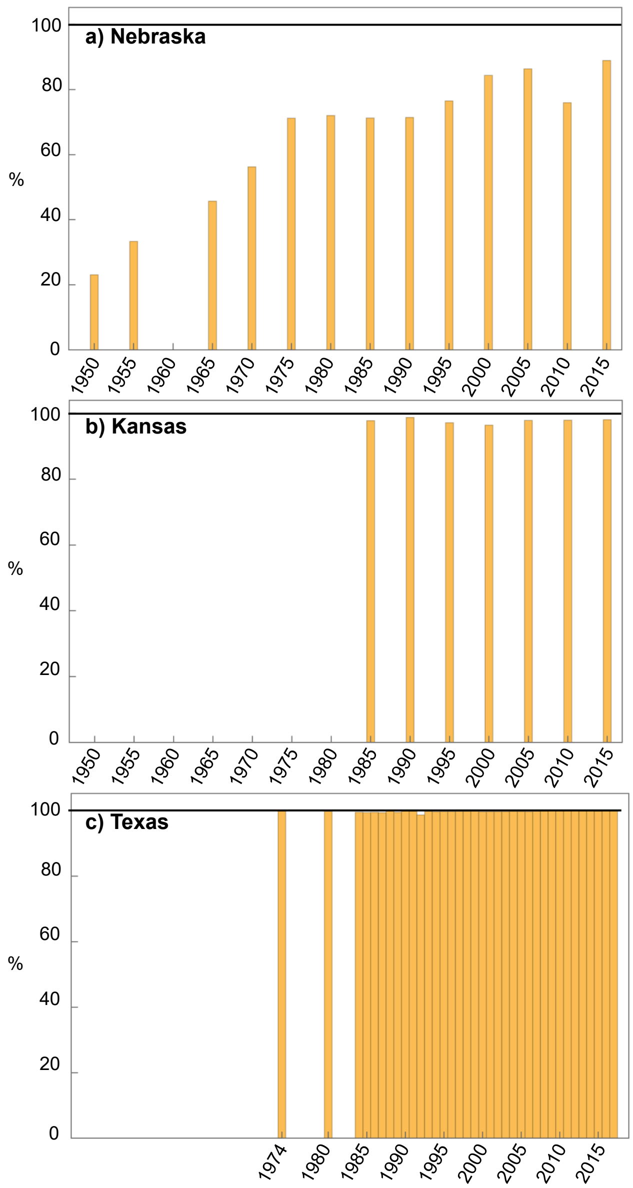

Fig. S7. Ratio of groundwater withdrawal to total withdrawal for irrigation in three High Plains regions. a) For Nebraska, water use estimates are used instead of withdrawal because of lack of data. Water use data for Nebraska are sourced from the (2). b) Data for freshwater withdrawal in Kansas are sourced from (5). c) Data for freshwater withdrawal in Texas are sourced from (3, 4)

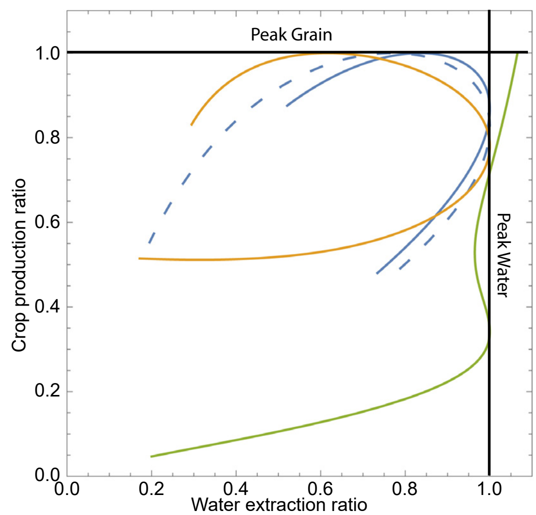

Fig. S8. Phase space of the normalized model fits. Water withdrawals are normalized by their value at peak water year. Crop production is normalized by its value at peak crop year. Such normalization is necessary so as to compare model results across states. Blue line: Texas pre-LEPA, dashed blue line: Texas post-LEPA, orange line: Kansas, green line: Nebraska. Nebraska is projected not to undergo peak water or peak grain through 2050, which explains why its curve extends past the normalization bounds.

References

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