Supplementary Materials: The Tradeoffs between Market Returns from Agricultural Crops and Non-Market Ecosystem Service Benefits on an Irrigated Agricultural Landscape in the Presence of Groundwater Overdraft

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Table S1 indicates the initial 2013 crop mix and aquifer conditions for the study area. Table S2 indicates the economic and irrigation model parameters. Variable irrigation costs from wells or reservoirs include fuel, lube and oil, irrigation labor, and poly pipe for furrow irrigation plus the levee gates for the flood irrigation of rice [1]. The next two tables indicate the water purification model parameters for nutrient and sediment pollution, respectively. Table S3 shows the values for nutrient loading, evapotranspiration, rooting depth, available water capacity, and vegetation filtering. Table S4 reports the values for crop/vegetation and management factor, support practice factor, and sediment filtering. Table S5 summarizes the carbon model parameters used while Figure S1 provides a visual summary of GHG emission and sequestration differences across crops and CRP.

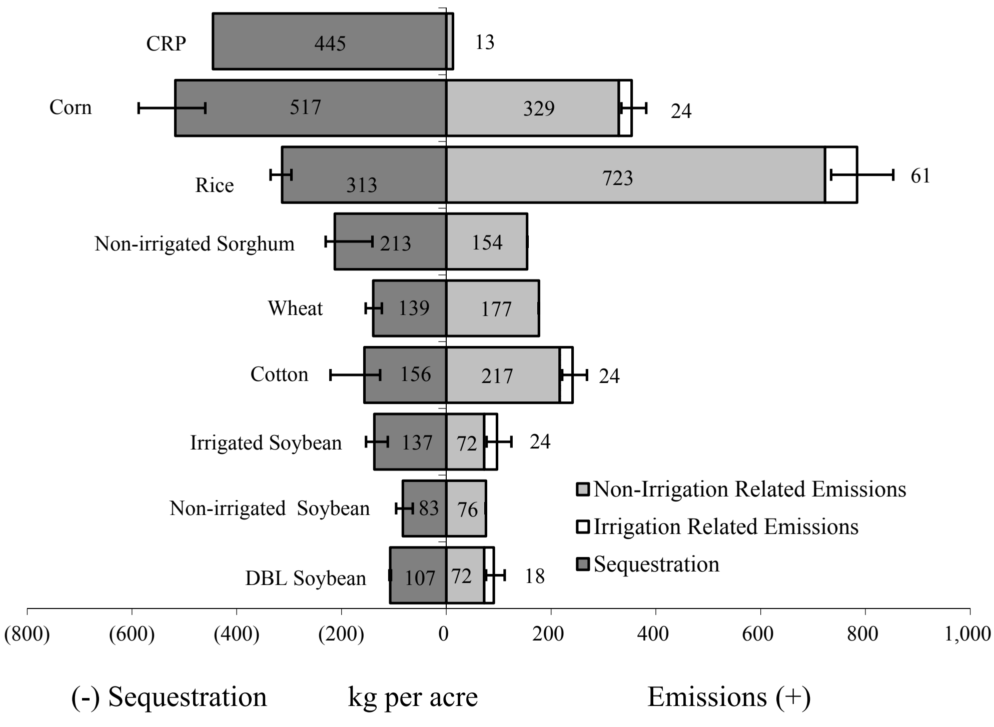

Figure S1. Summary of Soil Carbon Sequestration and GHG Emissions by Crop. Note: The Error bars provide the range of sequestration and irrigation fuel use emissions associated with yield and irrigation depth and irrigation type (well vs. reservoir) changes across the study region. Additional variation is modeled with changes in soil texture but not included in this diagram. Conservation reserve program carbon equivalent footprint is taken from [2] where regional variation due to yield is not taken into consideration.

Table S1. Descriptive statistics of the spatially variable data across the sites of the study area.

Variable	Definition	Mean	Std. Dev.	Sum (Thousands)
$L_{i,rice}$, $L_{i,corn}$, $L_{i,cotto}$, $L_{i,isoy}$, $L_{i,dsoy}$, $L_{i,dsor}$, $L_{i,dbl}$	Initial acres of rice, corn, cotton, irrigated soybean, dry land soybean, dry land sorghum, double crop irrigated soybean and winter wheat	81; 52; 10; 165; 57; 7; 47	99; 77; 40; 97; 49; 23; 73	221; 143; 26; 449; 155; 20; 129
$y_{i,rice}$, $y_{i,cotton}$, $y_{i,corn}$, $y_{i,isoy}$, $y_{i,dsoy}$, $y_{i,dsorg}$, $y_{i,dbl}$, $y_{i,wheat}$	Annual rice yield (cwt per acre), cotton yield (pounds per acre), corn, irrigated soybean, dry land soybean, dry land sorghum, double crop irrigated soybean, and winter wheat yields (bushels per acre) [1]	71; 1054; 166; 42; 25; 66; 34; 57	3; 168; 11; 4; 3; 12; 1; 5	-
dp_i	Depth to water (feet)	57	31	-
AQ_i	Initial aquifer size (acre-feet)	27,587	12,514	82,016
K	Hydraulic conductivity (feet per day)	226	92	-
nr_i	Annual natural recharge of the aquifer per acre (acre-feet)	0.001	0.04	547

Note: Number of sites is 2724. [1] The mean and the standard deviation of the county yields come from the 11 counties in the study area.

Table S2. Value of economic and irrigation model parameters.

Parameter	Definition	Value
pr_{rice}, pr_{cot}, pr_{corn}, pr_{soy}, pr_{sorg}, pr_{wht}, pr_{crp}	Price of rice ($/cwt), cotton ($/lbs), corn, soybeans, sorghum, and wheat ($/bushel), and the government payment per acre for CRP	14.00, 0.88, 5.50, 11.99, 5.23, 6.39, 69.5
ca_{rice}, ca_{corn}, ca_{cotton}, ca_{isoy}, ca_{dsoy}, ca_{dsorg}, ca_{dbl}, ca_{wht}, ca_{crp}	Annual production cost excluding irrigation fuel for rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, double crop irrigated soybean, winter wheat, and conservation reserve program ($/acre)	646, 605, 715, 326, 289, 270, 326, 307, 26
wd_{rice}, wd_{corn}, wd_{cotton}, wd_{isoy}, wd_{dbl}	Annual irrigation per acre of rice, corn, cotton, full-season soybean, and double crop soybean (acre-feet)	2.5, 1.0, 1.0, 1.0, 0.75
$\omega_{\min}$, $\omega_{\max}$	Annual minimum and maximum capacity of a one acre reservoir (acre-feet)	1.4, 11
c^{r}	Estimated annual per acre cost of reservoir ($/acre)	376.8 [a]
c^{rw}	Cost to re-lift an acre-foot to and from the reservoir ($/acre-foot)	22.62
c^{p}	Cost to raise an acre-foot of water by one foot ($/foot)	0.55
δ_t	Discount factor	0.95
ξ,	Soil factor, fraction of carbon lost to respiration due to soil related microbial activity	0.72

Notes: [a] This is the amortized cost to construct an additional acre of reservoir. The first acre of the reservoir constructed is more expensive, and the last acre of reservoir constructed is less expensive.

Table S3. Values for nutrient loading, evapotranspiration, rooting depth, available water capacity, and vegetation filtering.

LULC	Evapotranspiration	Rooting Depth	Phosphorus Loading	Phosphorus Filtering	Nitrogen Loading	Nitrogen Filtering
Corn	1200(e)	900(c)	2210(a)	25(b)	12,420(a)	50(d)
Cotton	1200(e)	1000(j)	4310(a)	25(b)	9310(a)	25(b)
Rice	1200(e)	550(i)	450(f)	80(h)	600(f)	90(l)
Soybeans, Dbl Crop Winter Wht/Soybean	1150(e)	740(c)	1907(k)	62(k)	4712(k)	70(k)
Sorghum, Sunflower, Winter Wheat, Oats, Millet, Safflower, Other Crops, Peas, Peaches, Pecans, Squash, Dbl Crop Winter Wht/Corn, Dbl Crop Soybeans/Oats, Cabbage	600(b)	700(b)	2320(a)	62(k)	5630(a)	70(k)
Fallow/Idle Cropland	200(b)	500(b)	100(b)	50(b)	3400(b)	50(b)
Pasture/Hay	850(b)	1000(b)	100(b)	25(b)	3100(b)	25(b)
Open Water	1000(b)	1000(b)	1(b)	5(b)	1(b)	5(b)
Developed/Open Space, Developed/Low Density, Developed/Medium Density, Developed/High Density	100(b)	10(b)	500(b)	5(b)	4000(b)	5(b)
Barren	200(b)	10(b)	1(b)	5(b)	4000(b)	5(b)
Deciduous Forest, Evergreen Forest, Mixed Forest, Shrubland	1000(b)	7000(b)	35(a)	70(g)	2862(a)	80(b)
Grassland Herbaceous	650(b)	2000(b)	50(b)	60(g)	4000(b)	40(b)
Woody Wetlands, Wetlands	1000(b)	7000(b)	50(b)	80(b)	2000(b)	80(b)

Notes: Source: (a) [2]; (b) [3]; (c) [4]; (d) [5]; (e) [6]; (f) [7]; (g) [8]; (h) [9]; (i) [10]; (j) [11]; (k) [12]; (l) [13].

Table S4. Values for crop/vegetation and management factor, support practice factor, and sediment filtering.

LULC	Crop/Vegetation and Management Factor	Support Practice Factor	Sediment Filtering
Corn	130(c)	400(c)	25(a)
Cotton	170(c)	400(c)	25(a)
Rice	90(c)	400(c)	25(a)
Soybeans, Dbl Crop Winter Wht/Soybean	120(c)	400(c)	25(a)
Sorghum, Sunflower, Winter Wheat, Oats, Millet, Safflower, Other Crops, Peas, Peaches, Pecans, Squash, Dbl Crop Winter Wht/Corn, Dbl Crop Soybeans/Oats, Cabbage	170(c)	400(c)	25(a)
Fallow/Idle Cropland	8(c)	200(c)	5(a)
Pasture/Hay	20(a)	250(a)	40(a)
Open Water	1(a)	1(a)	80(a)
Developed/Open Space, Developed/Low Density, Developed/Medium Density, Developed/High Density	1(a)	1(a)	5(a)
Barren	250(a)	10(a)	20(a)
Deciduous Forest, Evergreen Forest, Mixed Forest, Shrubland	3(b)	200(b)	60(a)
Grassland Herbaceous	8(c)	200(c)	40(a)
Woody Wetlands, Herbaceous Wetlands	10(a)	200(a)	60(a)

Notes: Source: (a) [14]; (b) [15]; (c) [16].

Table S5. Value for carbon model parameters.

Parameter	Definition	Value
λ_{rice}, λ_{corn}, λ_{cotton}, λ_{isoy}, λ_{dsoy}, λ_{dsorg}, λ_{dbl}, λ_{wht}	Yield multiplier to convert from conventional yield units to kg per acre for rice (hundred weight), corn (bushels), cotton (pounds of lint), irrigated soybean (bushels), non-irrigated soybean (bushels), non-irrigated sorghum (bushels), double crop irrigated soybean (bushels), and wheat (bushels)	45.5, 25.4, 1.19, 27.2, 27.2, 25, 27.2
α_{rice}, α_{corn}, α_{cotton}, α_{isoy}, α_{dsoy}, α_{dsorg}, α_{dbl}, α_{wht}	Moisture content (wet basis) of rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, and double crop irrigated soybean and winter wheat	0.13, 0.155, 0, 0.13, 0.13, 0.14, 0.13, 0.135
H_{rice}, H_{corn}, H_{cotton}, H_{isoy}, H_{dsoy}, H_{dsorg}, H_{dbl}, H_{wht}	Harvest index (grain weight to total above ground biomass weight) of rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, and double crop irrigated soybean and winter wheat	0.45, 0.43, 0.45, 0.45, 0.45, 0.39, 0.45, 0.46
β_{rice}, β_{corn}, β_{cotton}, β_{isoy}, β_{dsoy}, β_{dsorg}, β_{dbl}, β_{wheat}	Crop residue C content of rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, and double crop irrigated soybean and winter wheat in g per kg.	360, 410, 420, 430, 430, 420, 430, 340
δ_{low} , $\delta_{conventioal}$	Fraction of aboveground biomass C remaining in the soil with low tillage, and conventional tillage	0.40, 0.70
η_{low} , $\eta_{conventional}$	Fraction of belowground biomass C remaining in the soil with low tillage, and conventional tillage	0.45, 0.40
χ_{rice}, χ_{corn}, χ_{cotton}, χ_{isoy}, χ_{dsoy}, χ_{dsorg}, χ_{dbl}, χ_{wheat}	Root C content of rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, and double crop irrigated soybean and winter wheat in g per kg.	350, 420, 360, 430, 430, 380, 430, 280
ϕ_{rice}, ϕ_{corn}, ϕ_{cotton}, ϕ_{isoy}, ϕ_{dsoy}, ϕ_{dsorg}, ϕ_{dbl}, ϕ_{wheat}	Root/shoot ratio (below ground biomass weight/above ground biomass weight) of rice, corn, cotton, irrigated soybean, non-irrigated soybean, non-irrigated sorghum, and double crop irrigated soybean and winter wheat	0.16, 0.19, 0.21, 0.16, 0.16, 0.08, 0.16, 0.18
σ_g , σ_r	Conversion factors to track the carbon emitted from fuel combustion to lift an acre-foot of water one foot and the carbon emitted from fuel combustion to pump an acre-foot of water into a reservoir and back out to the field.	10.37, 190.95

Note: Source: [17].

Tables S6–S9 indicates the land covers, the irrigation water use, and the ecosystem services in the final period of the model for points along the efficiency frontiers that optimize all ecosystem service value, groundwater buffer value, water purification value, and greenhouse gas reduction value, respectively. Tables S10 indicates the same features of the landscape in the final period when conservation policies influence the economic returns objective for the landscape with reservoirs.

Table S6. Land, water use, and ecosystem service in the final period for a selected point on the efficiency frontiers optimizing all ecosystem service values.

Land and Water Use and Ecosystem Services	Without Reservoirs			With Reservoirs		
	A	**C**	**E**	**F**	**H**	**J**
Rice	0	0	164	0	0	204
Irrigated corn	0	266	379	0	383	412
Irrigated cotton	0	16	96	0	5	99
Irrigated soybeans	0	49	183	0	16	192
Non-irrigated soybeans	0	0	0	0	0	0
Non-irrigated sorghum	0	160	206	0	109	178
Double crop soybean	0	0	15	0	0	26
Reservoirs	0	0	0	0	17	17
CRP	1,141	650	98	1,141	611	13
Groundwater use (thousand acre-feet)	0	331	1080	0	204	1031
Reservoir water use (thousand acre-feet)	0	0	0	0	201	204
Aquifer (thousand acre-feet)	91,711	83,135	59,141	91,711	86,674	61,931
Net carbon emissions (thousand tons)	−493	−227	823	−493	−262	830
Methane emissions (thousand tons)	0	0	80	0	0	100
Annual phosphorus exports (tons)	4	63	123	4	62	125
Annual nitrogen exports (tons)	124	259	359	124	276	361
Annual sediment exports (thousand tons)	101	471	948	101	446	985

Notes: Land use is reported in thousands of acres. Net carbon emissions are positive when emissions exceeds sequestration and negative when sequestration exceed emissions.

Table S7. Land, water use, and ecosystem service in the final period for a selected point on the efficiency frontiers optimizing only groundwater buffer value.

Land and Water Use and Ecosystem Services	**Without Reservoirs**			**With Reservoirs**		
	L	**M**	**N**	**Q**	**R**	**S**
Rice	0	49	25	171	176	181
Irrigated corn	91	326	378	411	412	412
Irrigated cotton	2	37	93	98	99	99
Irrigated soybeans	0	0	83	92	102	172
Non-irrigated soybeans	2	2	0	0	0	0
Non-irrigated sorghum	322	321	316	250	251	186
Double crop soybean	0	0	4	25	28	30
Reservoirs	0	0	0	78	58	43
CRP	725	456	242	16	16	18
Groundwater use (thousand acre-feet)	93	363	620	154	408	666
Reservoir water use (thousand acre-feet)	0	0	0	892	664	491
Aquifer (thousand acre-feet)	89,169	81,454	73,793	88,964	81,305	73,634
Net carbon emissions (thousand tons)	−275	−89	176	230	306	458
Methane emissions (thousand tons)	0	0	12	83	86	88
Annual phosphorus exports (tons)	47	91	119	115	121	122
Annual nitrogen exports (tons)	197	316	367	335	349	354
Annual sediment exports (thousand tons)	427	662	857	873	916	945

Notes: Land use is reported in thousands of acres. Net carbon emissions are positive when emissions exceeds sequestration and negative when sequestration exceed emissions.

Table S8. Land, water use, and ecosystem service in the final period for a selected point on the efficiency frontiers optimizing only water purification value.

Land and Water Use and Ecosystem Services	Without Reservoirs			With Reservoirs		
	V	W	X	AA	BB	CC
Rice	110	116	129	138	151	170
Irrigated corn	199	231	269	214	245	289
Irrigated cotton	25	29	38	24	28	37
Irrigated soybeans	89	104	130	91	109	132
Non-irrigated soybeans	0	0	0	0	0	0
Non-irrigated sorghum	64	63	81	48	57	71
Double crop soybean	8	8	9	15	16	18
Reservoirs	0	0	0	13	14	16
CRP	647	592	486	597	520	407
Groundwater use (thousand acre-feet)	592	658	765	536	605	705
Reservoir water use (thousand acre-feet)	0	0	0	151	167	191
Aquifer (thousand acre-feet)	65,580	64,120	62,487	68,776	67,410	65,858
Net carbon emissions (thousand tons)	182	250	374	176	261	388
Methane emissions (thousand tons)	53	56	62	67	74	83
Annual phosphorus exports (tons)	28	35	48	28	36	49
Annual nitrogen exports (tons)	173	190	217	170	185	212
Annual sediment exports (thousand tons)	270	306	396	277	321	408

Notes: Land use is reported in thousands of acres. Net carbon emissions are positive when emissions exceeds sequestration and negative when sequestration exceed emissions.

Table S9. Land, water use, and ecosystem service in the final period for a selected point on the efficiency frontiers optimizing only greenhouse gases value.

Land and Water Use and Ecosystem Services	Without Reservoirs			With Reservoirs		
	FF	GG	HH	KK	LL	MM
Rice	0	0	10	0	0	0
Irrigated corn	199	0	0	244	355	412
Irrigated cotton	2	22	93	2	3	39
Irrigated soybeans	1	184	216	0	3	69
Non-irrigated soybeans	0	0	0	0	0	0
Non-irrigated sorghum	19	171	284	0	24	185
Double crop soybean	0	4	28	0	0	0
Reservoirs	0	0	0	8	15	17
CRP	920	759	511	888	741	417
Groundwater use (thousand acre-feet)	203	211	354	147	187	313
Reservoir water use (thousand acre-feet)	0	0	0	99	174	208
Aquifer (thousand acre-feet)	86,748	86,610	82,597	88,694	87,040	83,474
Net carbon emissions (thousand tons)	−388	−300	−120	−390	−318	−139
Methane emissions (thousand tons)	0	3	47	0	0	0
Annual phosphorus exports (tons)	35	49	81	35	54	94
Annual nitrogen exports (tons)	211	184	233	216	265	332
Annual sediment exports (thousand tons)	280	425	650	286	403	667

Notes: Land use is reported in thousands of acres. Net carbon emissions are positive when emissions exceeds sequestration and negative when sequestration exceed emissions.

Table S10. Land, water use, and ecosystem service in the final period that result when conservation policies influence the economic returns objective for the landscape with reservoirs.

Land and Water Use and Ecosystem Services	Baseline (Point J)	Conservation Policies			
		Cost-Share Reservoir Construction Costs [a]	Tax on Ground-Water [b]	Total Maximum Daily Load [c]	Carbon Credits [d]
Rice	204	212	199	211	162
Irrigated corn	412	412	412	406	412
Irrigated cotton	99	98	100	84	101
Irrigated soybeans	192	200	178	179	171
Non-irrigated soybeans	0	0	0	0	0
Non-irrigated sorghum	178	160	183	142	200
Double crop soybean	26	23	28	20	31
Reservoirs	17	29	26	21	32
CRP	13	8	17	78	34
Groundwater use (thousand acre-feet)	1031	922	909	969	744
Reservoir water use (thousand acre-feet)	204	333	298	242	366
Aquifer (thousand acre-feet)	61,931	65,867	66,300	63,757	71,222
Net carbon emissions (thousand tons)	830	719	685	753	487
Methane emissions (thousand tons)	100	103	97	103	79
Annual phosphorus exports (tons)	125	123	124	101	124
Annual nitrogen exports (tons)	361	355	357	315	360
Annual sediment exports (thousand tons)	985	974	970	783	945

Notes: [a] The cost share for irrigation reservoir construction is 65% based on the rate from Natural Resource Conservation Service's (USDA-NRCS) Agricultural Water Enhancement Program [16]; [b] A tax on groundwater pumping cost of 15% is chosen to achieve groundwater conservation similar to the cost share on reservoir construction; [c] The total maximum annual load is chosen as the phosphorus and sediment exports from point CC on the efficiency frontier optimizing water purification value in the final period; [d] The value of a carbon credit is $28.51 per metric ton of carbon according to the clearing price of the March 2015 auction by the European Union Emission Trading Scheme and an exchange rate of $0.87 per euro [18].

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