9-2018

County-wide Assessment of Irrigation Expansion on Air Temperature, Humidity and Evapotranspiration Rates in Nebraska, 1979-2015

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September 2018

ISBN 1-56161-076-3
ISBN-13 978-1-56161-076-1

Suggested citation for this report:
Szilagyi, J., 2018, County-wide Assessment of Irrigation Expansion on Air Temperature, Humidity and Evapotranspiration Rates in Nebraska, 1979-2015. University of Nebraska–Lincoln, Conservation and Survey Division, Conservation Bulletin 10 (New Series), 24 p.

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ABSTRACT

Total irrigated land area has been expanding in Nebraska over the last 40 years, propelling the state into a leading position within the US in terms of irrigated acreages. Typically, those counties which display the largest degree of irrigation development had a significant portion of their land area already irrigated in 1978. Large-scale irrigation in Nebraska affects its atmospheric environment. During the typical irrigation season of May to August, counties with the largest rate of irrigation expansion have cooled by about 0.2 – 0.3 °F per decade in the summer months of June, July and August, while counties with the smallest rate of development warmed by about 0.15 °F per decade during the same period. In the summer months, relative humidity increased three times faster, by about 1.5 % per decade, in well irrigated counties than in least irrigated ones. Finally, ET rates increased by 0.05 inch (1.3 mm) per decade in well-irrigated counties while they stayed about constant in the least irrigated ones.

INTRODUCTION

Irrigated land area in Nebraska (Table 1) has grown from about 8,000 mi^2 in 1978 to 13,000 mi^2 in 2012 (USDA, 2012) making the state the leading irrigator (mostly center-pivot) in the nation. This growth, however, is not evenly distributed among the 93 counties (Fig. 1). The largest rate (> 6 % increase per decade) of irrigation development took place in Adams, Antelope, Boone, Dodge, Fillmore, Kearney, Madison, Platte, Polk, and York counties (Fig. 2), predominantly situated in east-central and eastern Nebraska. These counties typically boasted the largest irrigated land area in 1978 (Fig. 2). In fact the relationship of irrigated land area in 1978 and the rate of development by county has a linear correlation coefficient value of 0.68, which is indicative of a moderately strong association.

By 2012, counties with the largest portion of their area irrigated (i.e., in excess of 50%) included (Fig. 2) Adams, Clay, Fillmore, Hall, Hamilton, Kearney, Merrick, Phelps, Polk, and York counties, in southeastern-central Nebraska, forming a

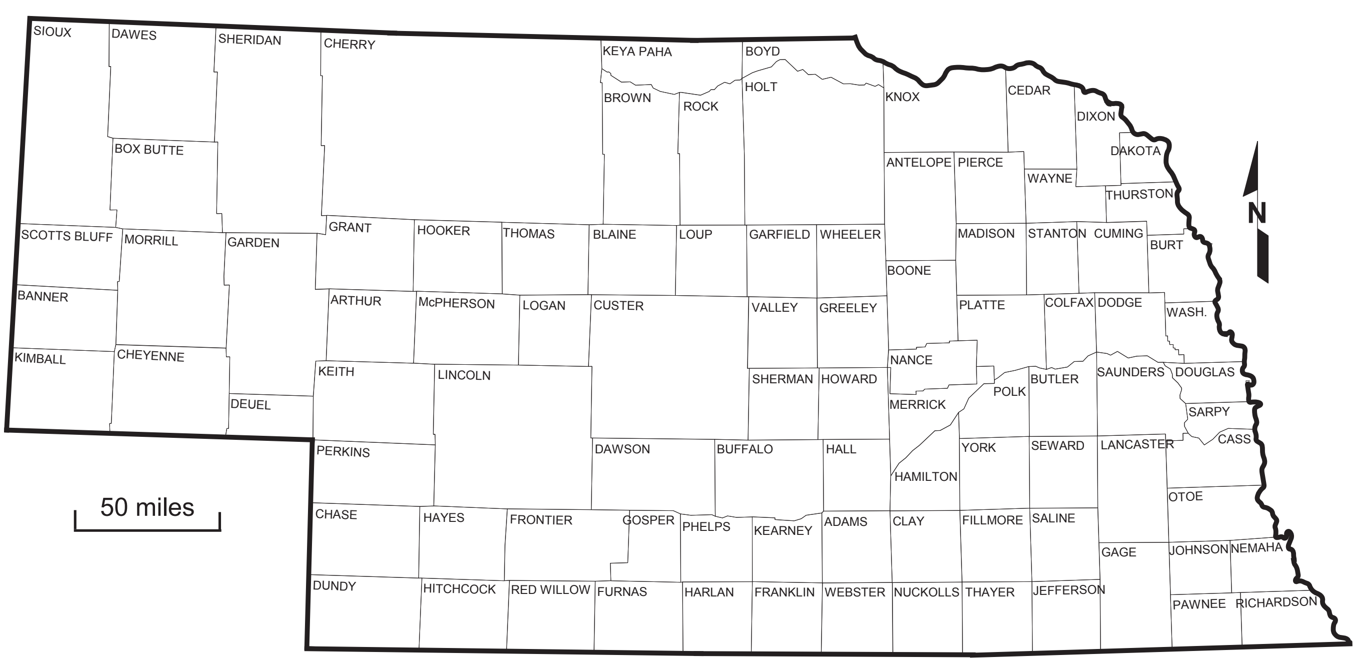


Figure 1. Counties of Nebraska.

continuous region of the most intensively irrigated land within the state. In contrast, in 1978 there were only three counties with a combined irrigated land area greater than 50% of their total area: Hamilton, Phelps, and York.

On such a massive scale of irrigation, the extra moisture that is pumped into the atmosphere by direct evaporation of irrigation water and evapotranspiration (ET) of vegetation, boosted by the enhanced moisture status of the soils, must show up in standard meteorological measurements taken in the area. Similarly, the cooling effect of evaporation and ET on the air and the land surface must also be detectable by these measurements.

In this study irrigation-triggered changes are investigated on a county-wide basis. In particular, the long-term effect of expanding irrigation is scrutinized in terms of the ensuing linear rate of change in air

Table 1. Irrigated land area by year and county (USDA, 2012).

County name	County area (mi^2)	Irrigated (mi^2) in 1978	Irrigated (mi^2) in 1982	Irrigated (mi^2) in 1987	Irrigated (mi^2) in 1992	Irrigated (mi^2) in 1997	Irrigated (mi^2) in 2002	Irrigated (mi^2) in 2007	Irrigated (mi^2) in 2012
Adams	563.32	223.45	242.12	219.99	256.87	288.52	310.24	318.04	336.35
Antelope	857.14	195.22	231.29	220.9	253.14	287.82	352.19	408.22	390.21
Arthur	717.37	10.08	12.38	11.61	13.52	25.15	12.11	12.87	19.37
Banner	744.79	33.02	31.65	24.05	30.37	34.86	31.76	25.08	23.7
Blaine	713.13	15.72	15.8	11.98	12.01	13.83	15.35	21.32	10.9
Boone	686.87	121.74	155.75	147.35	182.15	201.64	253.26	270.44	288.59
Box Butte	1074.52	131.2	175.57	183.89	203.37	212.28	207.58	223.47	221.19
Boyd	543.24	4.64	7.7	5.31	6.45	8.43	8.64	7.01	8.15
Brown	1222.39	104.54	101.99	60.82	76.78	80.88	81.76	81.12	62.74
Buffalo	970.66	286.03	311.57	273.73	325.25	324.66	364.95	420.53	376.24
Burt	496.52	56.32	46.49	51.56	53.66	58.97	79.22	67.09	58.71
Butler	582.62	115.96	118.28	124.31	128.69	148	172.12	184.33	173.18
Cass	565.63	6.44	4.93	5.92	3.72	3.72	3.33	4.62	5.48
Cedar	747.49	69	74.21	75.36	79.95	97.99	132.04	175.19	217.26
Chase	896.14	239.33	243.5	221.54	247.27	261.83	264.33	289.49	249.51
Cherry	5998.86	65.33	61.5	46.81	49.21	68.32	54.02	69.89	79.49
Cheyenne	1193.82	48.77	56.98	52.96	69.77	75.18	79.9	80.18	76.05
Clay	572.58	246.7	258.27	247.01	272.17	284.42	314.67	340.79	299.53
Colfax	418.53	60.86	56.34	62.31	64.11	81.62	92.28	97.62	104.36
Cuming	573.36	35.43	29.35	45.98	41.14	49.4	67.66	79.93	81.96
Custer	2571.43	227.71	269.63	234.19	282.51	310.62	323.79	521	408.59
Dakota	265.25	12.7	15.09	17.61	21.35	18.94	17.25	31.89	45.78
Dawes	1398.46	19.88	19.94	21.92	22.67	25.45	23.46	27.45	33.42
Dawson	1018.15	308.85	328.52	304.81	324.31	341.81	352.35	412.29	388.23
Deuel	440.15	38.67	34.56	25.27	25.66	25.27	26.6	27.89	27.15
Dixon	481.85	21.06	18.83	18.81	13.03	25.4	27	33.72	37.44
Dodge	541.31	109.15	85.65	108.85	108.75	146.07	172.87	181.32	184.32
Douglas	338.99	19.14	17.14	25.04	20.48	24.26	20.2	21.56	30.89
Dundy	919.3	117.33	117.98	129.17	139.73	133.28	138.5	176.05	148.18
Fillmore	575.67	234.83	243.91	228.74	270.04	304.55	315.01	349.25	329.65
Franklin	575.29	110.15	119.44	105.83	114.48	136.31	144.98	136.39	133.98
Frontier	978.76	97.17	95.44	84.87	84.41	85.88	98.14	83.9	83.25
Furnas	719.69	68.74	65.3	66.15	66.45	83.63	106.26	81.08	103.67
Gage	858.69	61.39	63.45	58.52	64.18	75.17	84.55	92.61	99.67
Garden	1727.8	45.23	57.26	56.24	48.37	59.53	54.34	70.08	55.82
Garfield	570.65	27.59	46.22	20.59	16.25	20.28	21.13	32.21	35.12
Gosper	462.16	93.32	93.3	84.14	94.35	106.07	130.36	127.19	154.32
Grant	782.24	3.02	4.67	5.2	3.07	2.15	1.8	2.3	2.66
Greeley	569.5	75.67	85.52	84.24	92	89.96	95.94	119.36	137.79

Hall	551.35	269.97	269.6	239.28	284.03	273.71	292.22	323.27	324.43
Hamilton	546.33	334.81	333.08	308.57	336.37	371.3	418.1	402.73	367.95
Harlan	573.36	91.05	91.63	96.05	95.64	118.58	112.1	168.04	145.83
Hayes	712.35	40.11	51.6	51.03	50.36	53.98	78.55	102.58	89.23
Hitchcock	717.37	51.29	49.76	45.74	41.02	45.92	49.61	29.68	33.57
Holt	2413.52	289.26	318.24	270.83	348.07	326.83	366.42	529.81	437.86
Hooker	721.23	5.33	4.27	3.09	4.92	4.36	8.08	4.67	4.88
Howard	574.51	137.87	152.39	129.5	157.57	172.94	161.71	162.92	180.36
Jefferson	574.9	61.26	71	67.85	80.52	85.94	110.57	126.52	144.95
Johnson	376.06	12.22	9.91	11.64	13.27	15.83	19.95	17.62	22.34
Kearney	517.76	229.93	263.72	237.47	274.71	295.24	337.24	338.02	303.97
Keith	1107.72	101.78	112.12	104.32	121.84	121.92	142.15	181.41	180.16
Keya Paha	772.59	23.66	17.24	18.52	18.74	16.99	24.65	28.31	31.46
Kimball	950.96	34.2	35.75	28.96	31.39	38.58	41.84	52	53.67
Knox	1137.84	43.5	51.6	46.79	50.08	59.81	71.8	80.86	99.92
Lancaster	845.17	20.32	17.57	17.77	19.64	19.71	27.17	24.3	33.48
Lincoln	2571.43	218.4	252.27	225.18	279.47	306.95	324.08	504.55	374.71
Logan	570.27	19.65	23.66	20.35	24.68	23.9	29.7	38.68	35.88
Loup	570.27	23.59	22.42	15.6	16.8	16.81	15.01	16.21	12.84
McPherson	858.3	14.31	9.36	15.03	14.59	11.71	19.64	15.11	11.11
Madison	574.13	79.8	93.47	86.81	100.42	123.36	152.88	168.57	190.68
Merrick	492.66	222.22	226.01	208.37	257.17	253.98	275.1	255.94	261.6
Morrill	1427.41	134.23	163.4	155.48	169.32	182.74	192.23	225.9	200.98
Nance	446.72	65.16	66.19	67.82	69.32	93.8	84.66	108.48	98.93
Nemaha	403.47	3.39	2.32	2.7	3.75	5.65	6.45	13.18	17.81
Nuckolls	575.29	72.97	67.27	69.71	66.2	77.5	91.32	95.49	101.94
Otoe	617.76	4.93	5.07	6.14	4.52	7.02	7.06	6.48	13.14
Pawnee	432.04	3.07	3.03	4.42	5.08	5.08	4.19	7.21	11.41
Perkins	883.4	139.54	153.99	167.47	167.9	188.15	190.12	208.42	199.77
Phelps	540.15	305.1	337.44	292.85	343.1	350.03	391.48	385.55	362.33
Pierce	573.36	101.74	118.48	125.97	136.63	143.02	179.79	201.4	203.16
Platte	688.8	156.93	160.7	184.48	184.31	232.01	278.94	325.6	303.18
Polk	439.77	179.92	163.53	165.58	156.89	206.6	224.44	257.13	235.96
Red Willow	716.6	89.23	83.36	73.18	66.1	83.91	69.57	86.05	83.01
Richardson	555.6	1.73	2.54	1.75	3.85	2.39	1.64	3.4	7.32
Rock	1009.27	85.58	73.71	57.58	64.94	63.94	53.73	68.1	56.7
Saline	575.29	94.51	94.53	99.96	99.5	117.5	146.12	127.89	168.92
Sarpy	247.1	6.83	6.15	6.53	7.11	12.5	14.85	18.5	16.22
Saunders	758.69	70.93	68.52	81.71	99.05	118.46	151.93	145.98	165.02
Scotts Bluff	744.4	260.59	270.74	239.51	283.11	270.56	270.24	243.08	311.24
Seward	575.29	128.65	126.85	134.16	132.79	168.57	200.54	199.11	203.01
Sheridan	2467.57	80.56	107.55	105.87	83.78	88.21	80.1	89.02	94.84
Sherman	571.04	64.94	68.67	76.76	82.34	91.86	95.67	112.9	111.1
Sioux	2063.71	55.95	59.17	54.97	61.57	64.79	62.38	80.46	61.76
Stanton	430.11	26.5	28.46	29.48	30.07	36.6	33.29	48.75	44.37
Thayer	573.74	136.33	146.1	136.12	153.61	181.09	207.91	205.33	211.73
Thomas	711.58	4.45	3.9	4.8	4.64	3.05	3.4	5.01	4.6
Thurston	395.36	5.68	5.02	5.17	6.39	9.54	15.31	12.2	18.61
Valley	569.5	98.38	96.49	94.16	98.94	112.81	121.65	155.19	145.43
Washington	393.82	16.13	13.03	16.51	21.56	24.13	30.52	28.87	26.99
Wayne	442.47	20.27	25.46	27.21	28.1	27.76	47.62	66.77	77.82
Webster	574.13	47.29	44.88	36.52	56.3	57.56	76.49	97.44	85.94
Wheeler	574.51	42.07	80.38	55.17	56.66	76.29	72.35	68.86	61.5
York	574.9	289.68	294.81	275.36	311.08	356.55	377.38	397.98	394.43

temperature, relative humidity and ET rate over the 1979-2015 time-period for which atmospheric data were available. Certainly, most of these long-term changes/trends are non-linear functions of time, thus the calculated linear rate of change over the 1979-2015 period yields an average rate of change, and can be considered as a first step in mapping the extent/magnitude and direction of the changes investigated. The rate of irrigation expansion found for 1978-2012 was also assumed valid for 1979-2015, the available temporal coverage of the atmospheric data.

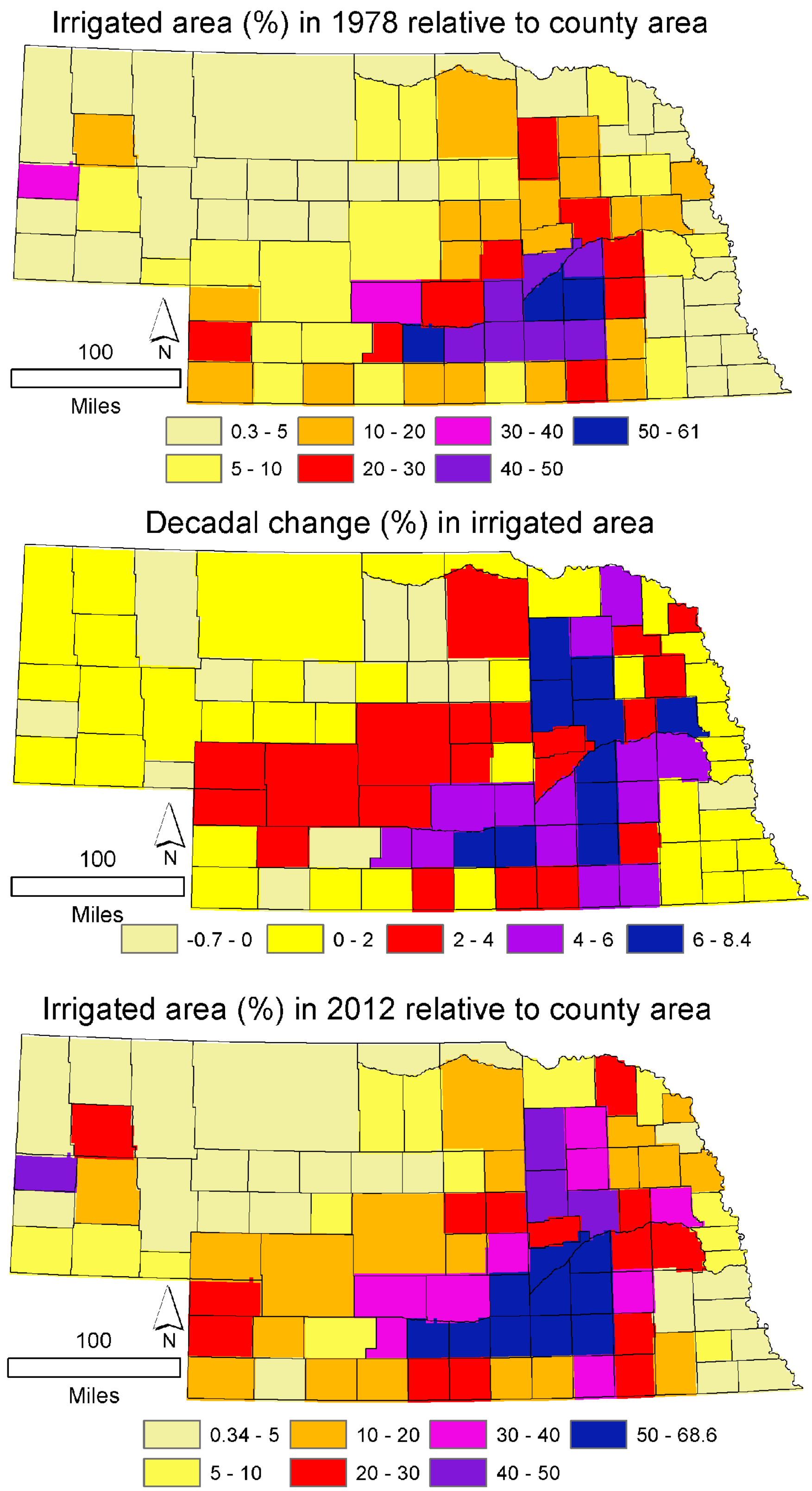


Figure 2. Irrigated land area in 1978 and 2012, as well as the decadal rate of change by county.

METHODS

Monthly mean air- (T_a) and dew-point temperature (T_d) data for 1979-2015 came from the 4.2 km spatial resolution PRISM (Daly et al., 1994) dataset (available from www.prism.oregonstate. edu). Monthly ET rates were estimated by the complementary-relationship based method of Szilagyi (2018a, 2018b) at the PRISM spatial resolution, with additional data (wind speed and net surface radiation) from the North American Regional Reanalysis (Mesinger et al., 2006) dataset (available from www.esrl.noaa.gov/psd/data/gridded/data.narr.html). Relative humidity (*RH* in percentages) was calculated as

$$RH = 100\frac{e^{\frac{17.27T_d}{237.3+T_d}}}{e^{\frac{17.27T_a}{237.3+T_a}}} \quad (1)$$

where the temperature values are supplied in degrees centigrade. Note that T_d is a measure of how much moisture is found in the air.

The 4.2-km resolution monthly mean T_a, *RH*, and ET values were spatially averaged over the counties of Nebraska for the typical irrigation months of May through August. For these county-wide monthly values (i.e., 37 for each month and county) first-order polynomial functions were fit in the least sum-of-squares sense. The slopes of the so-derived straight lines serve as the linear rate of change for the given variable, month, and county.

The rate of change values for each county were subsequently plotted against the rate of change in the irrigated area for the identification of any possible association/relationship (in a statistical sense) between the two. The latter was visualized with the help of second-order best-fit polynomials that allow for any possible non-linear behavior in the spatial associations (since the counties are spatially distributed) between the rate of irrigation development and rate of change in the given variable.

To test the significance of any observable spatial change in the trend values, a two-sample t-test was administered (with the unequal variance option due to the typically observed heteroscedasticity of the values which manifested in decreasing variance among counties with a high rate of change in irrigation development) for each month and variable at the customary 5% significance level. The two samples were taken from 30 counties with the smallest rate of irrigation development and also from 30 counties with the highest rate of irrigation development, to see if irrigation expansion affected the variable significantly or not.

RESULTS AND DISCUSSION

Figs. 3-6 display the mean monthly air temperatures and their decadal rate of change for the months of May through August by county. As expected, for each month the warmest counties are found in southeastern Nebraska while the coldest are in the northwestern part of the State. The long-term change in the monthly temperatures, however, does not show any clear pattern in May, but during the summer months of June-August the eastern part of the state has been cooling at a rate of about 0.2 – 0.4 °F per decade while the rest has been warming at about the same rate.

For the relative humidity values presented (Figs. 7-10) a spatial distribution similar to that of temperature is observable: the southeastern part is the most humid while the western part is the least so. Trends in RH values in the summer months are positive (i.e., increasing) in general over the entire state except in several counties in the west and southwest.

The spatial distribution of the ET rates (Figs. 11-14) and their long-term trends follow by-and-large those of the relative humidity values which is not surprising as the latter (as effect) is the result of the former (as cause).

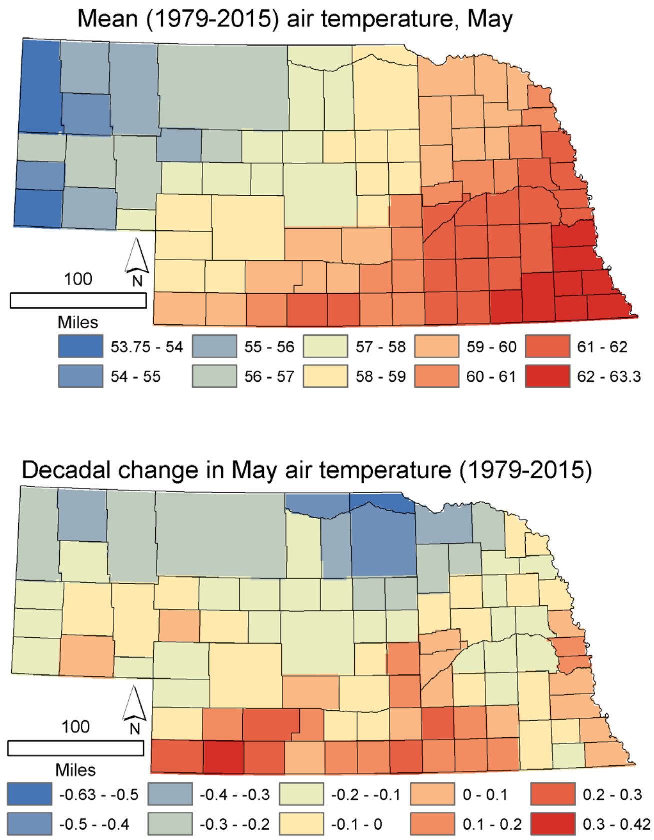


Figure 3. Mean May air temperature (°F) and its decadal change by county. The minimum and maximum values are displayed in the legend.

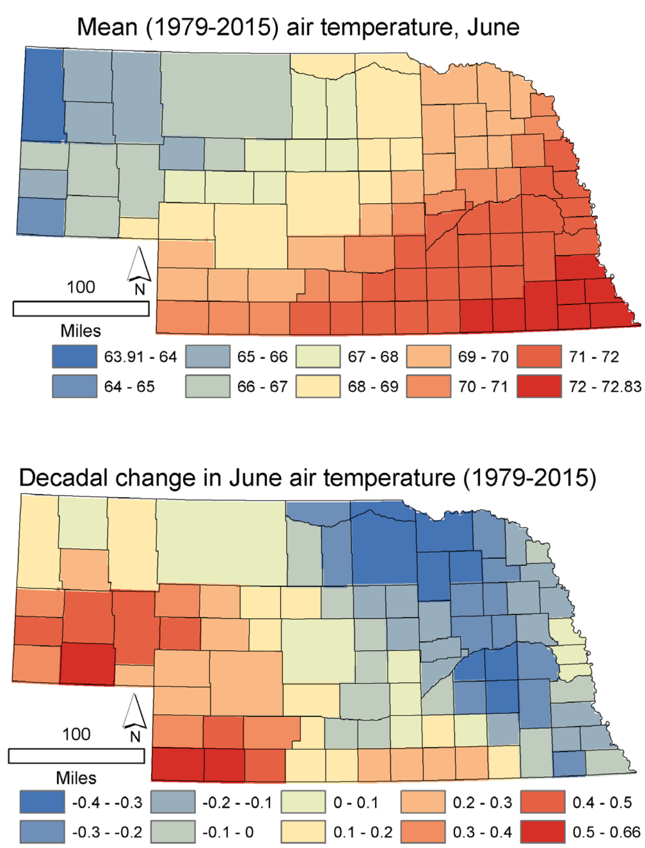


Figure 4. Mean June air temperature (°F) and its decadal change by county. The minimum and maximum values are displayed in the legend.

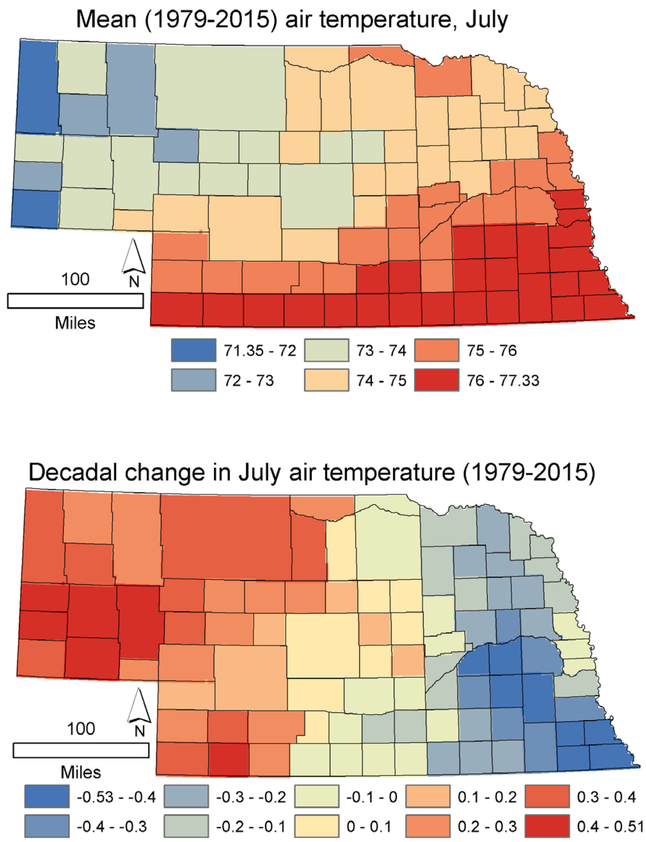


Figure 5. Mean July air temperature (°F) and its decadal change by county. The minimum and maximum values are displayed in the legend.

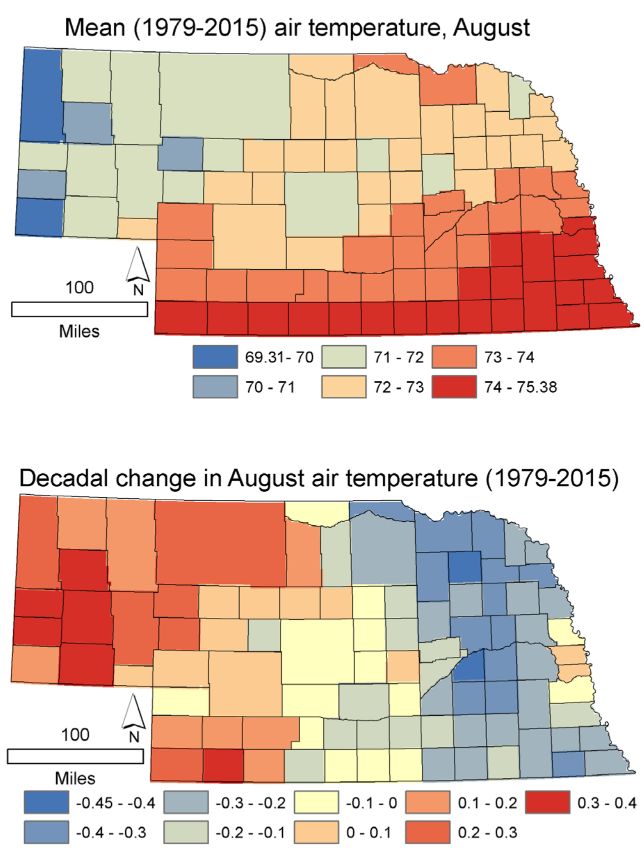


Figure 6. Mean August air temperature (°F) and its decadal change by county. The minimum and maximum values are displayed in the legend.

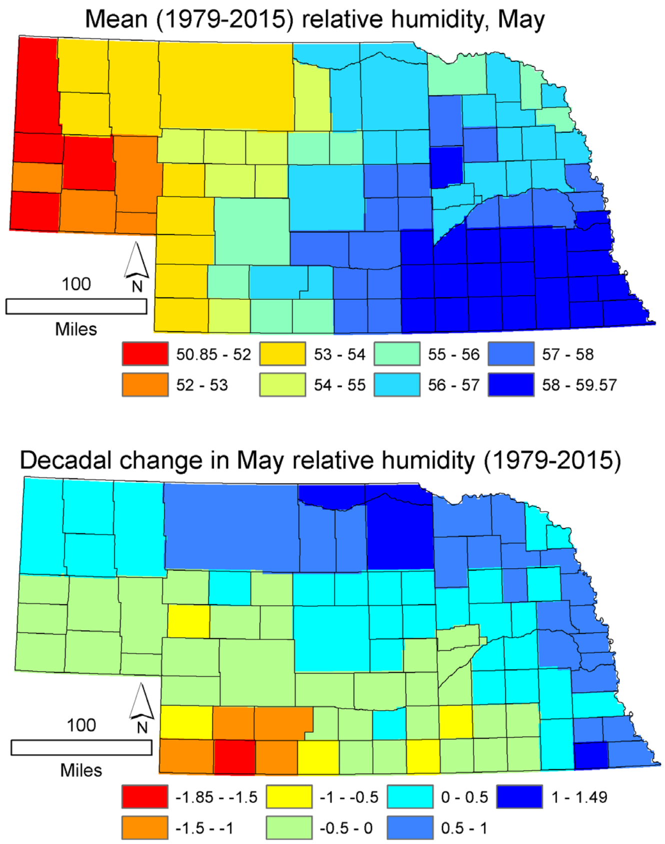


Figure 7. Mean relative humidity (%) in May and its decadal change by county. The minimum and maximum values are displayed in the legend.

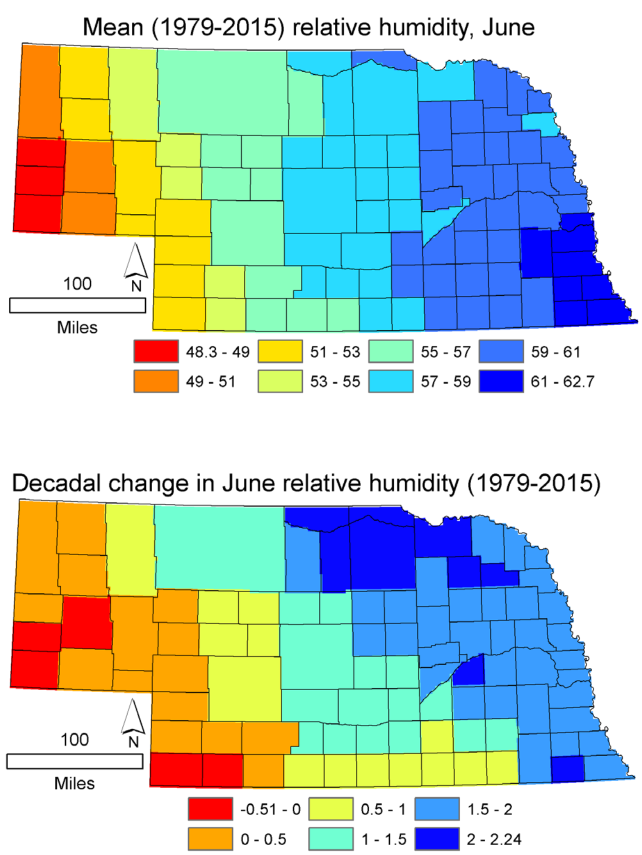
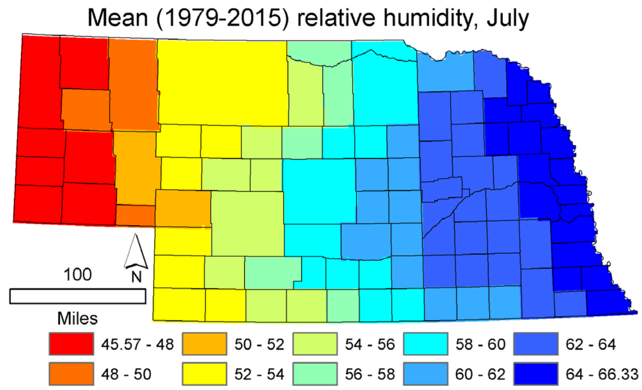


Figure 8. Mean relative humidity (%) in June and its decadal change by county. The minimum and maximum values are displayed in the legend.



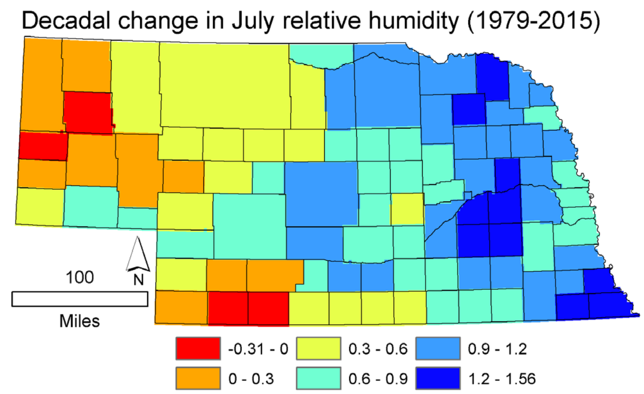
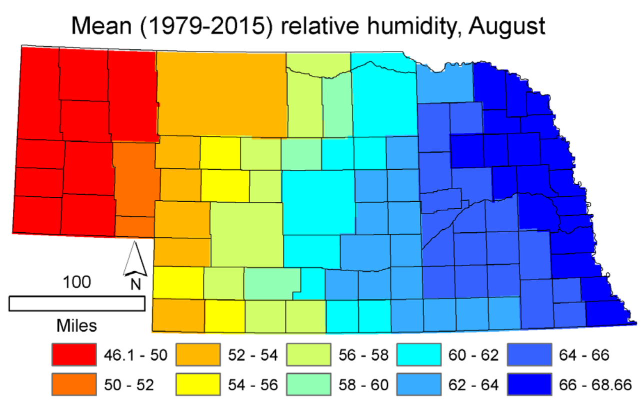


Figure 9. Mean relative humidity (%) in July and its decadal change by county. The minimum and maximum values are displayed in the legend.



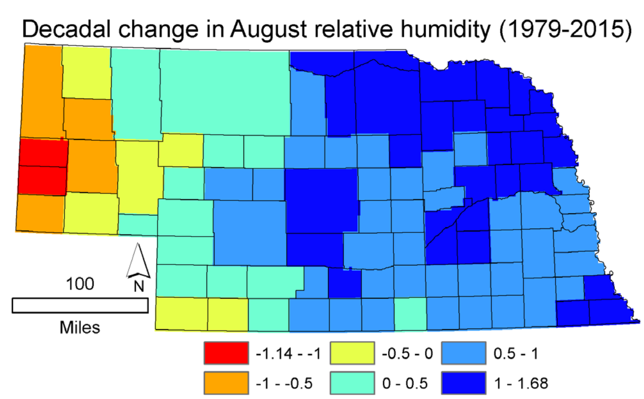
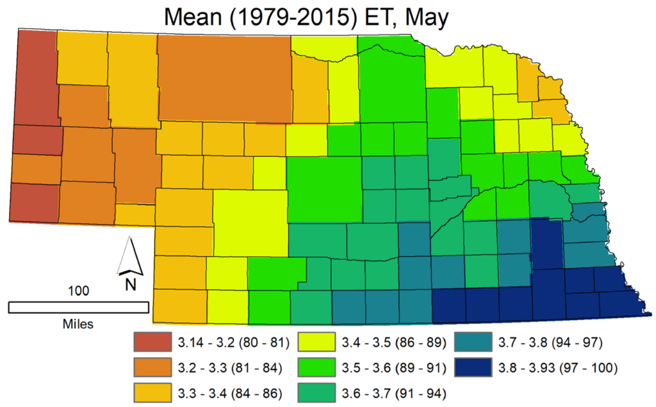


Figure 10. Mean relative humidity (%) in August and its decadal change by county. The minimum and maximum values are displayed in the legend.



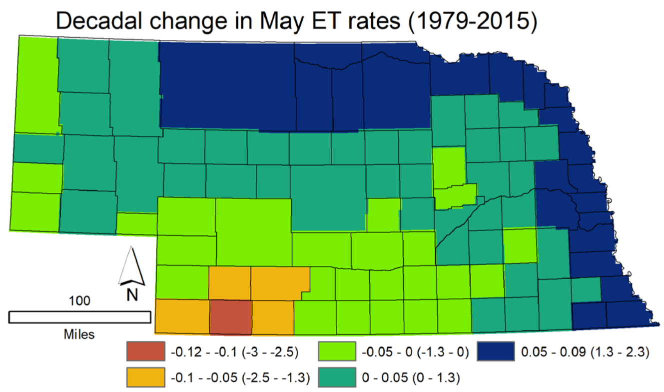
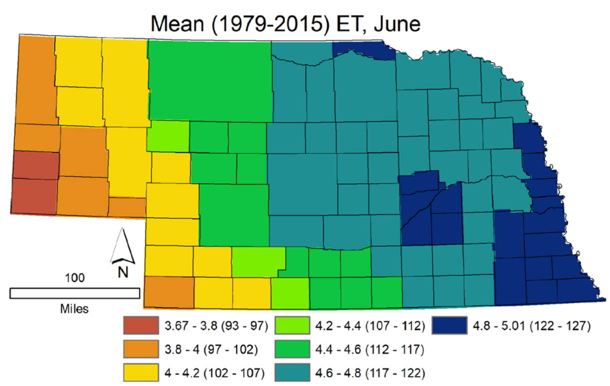


Figure 11. Mean ET rate (in) in May and its decadal change by county.
The minimum and maximum values are displayed in the legend. The values in parentheses are in mm.



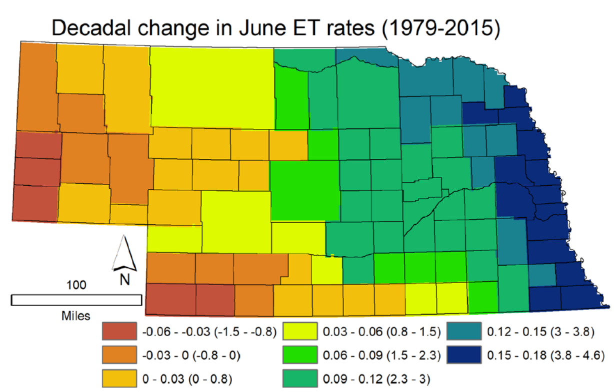


Figure 12. Mean ET rate (in) in June and its decadal change by county.
The minimum and maximum values are displayed in the legend. The values in parentheses are in mm.

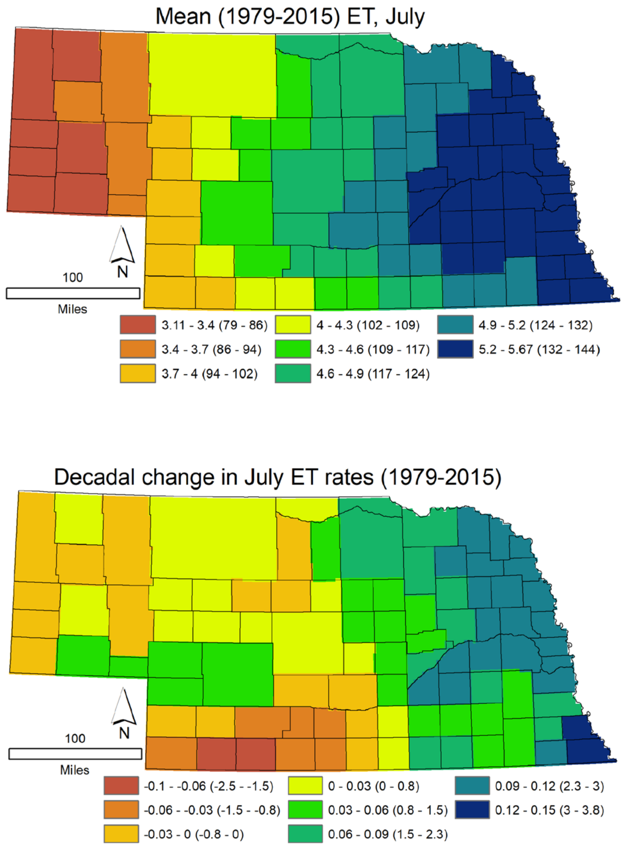


Figure 13. Mean ET rate (in) in July and its decadal change by county.
The minimum and maximum values are displayed in the legend. The values in parentheses are in mm.

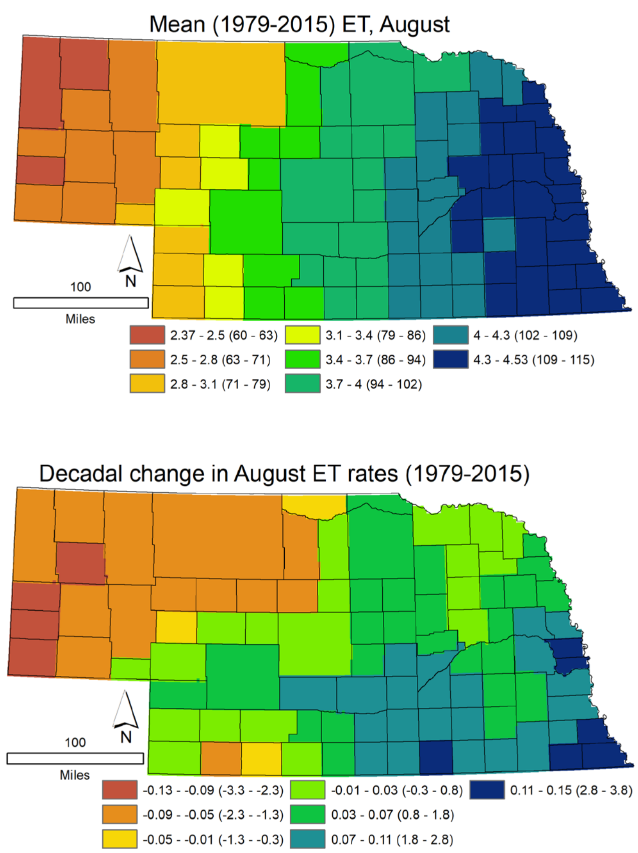


Figure 14. Mean ET rate (in) in August and its decadal change by county.
The minimum and maximum values are displayed in the legend. The values in parentheses are in mm.

A much clearer relationship forms for visual inspection between irrigation and the studied environmental variables when the long-term changes of the variables are plotted against similar changes in irrigated area in Figs. 15-17.

In Fig. 15 it becomes evident that the larger the irrigation expansion in a county, the cooler it becomes over time, at least in the summer months of June-August. While counties with the smallest (or negative) change in irrigated areas warmed in the summer months, irrigated areas cooled. All summer-month differences in the temperature trends between the least and most-irrigated counties are statistically significant, with the largest such spatial change occurring in July and August. In these latter months, precipitation drops from about a 3.8-inch (97 mm) monthly value in May and June to 3 inches (76 mm) in July and 2.8 inches (71 mm) in August. This means that the surface temperature of irrigated land is much lower than that of non-irrigated land (as the latter is drier than in May or June). Thus when irrigation expansion becomes significant in a county, so does the long-term temperature change in these drier summer months.

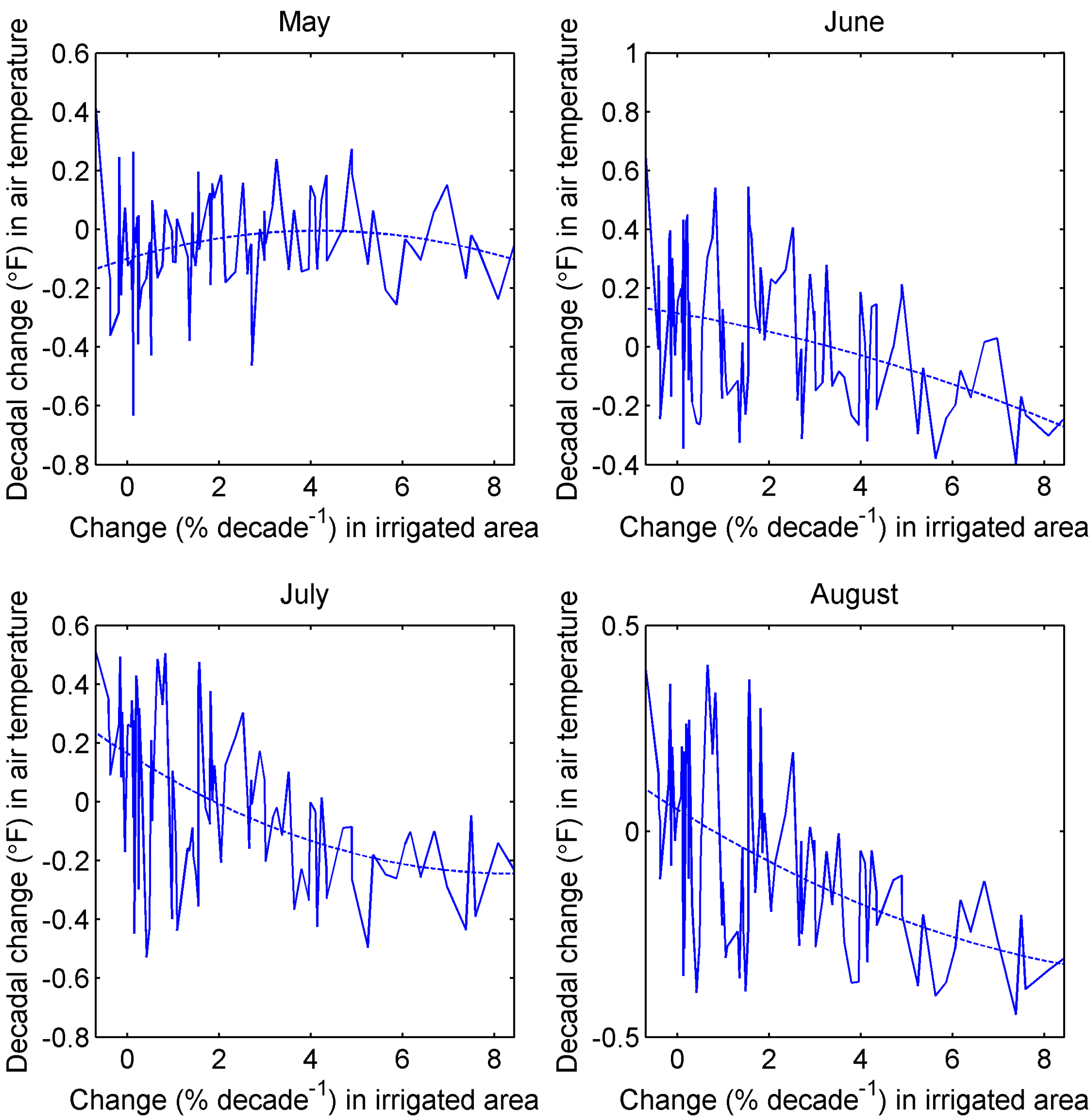


Figure 15. Decadal change in air temperature (T_a) versus change in irrigated area. The intermittent line is the best-fit 2nd-order polynomial curve. The sample mean of T_a for the 30 counties with the smallest rate of irrigation development is significantly different in June, July, and August from the mean of those 30 counties that display the largest rate of development, according to the 5% significance level of the two-sample t-test.

Long-term relative humidity trends (Fig. 16) are positive for each month studied, due to increasing trends in precipitation (not shown) and/or the resulting increases in ET rates (either due to precipitation, irrigation, or both). The relative humidity increase intensifies with irrigation expansion due to the entailing temperature decrease [see Fig. 15 and Eq. (1)] and the simultaneous irrigation-enhanced ET rate increase (Fig. 17), boosting the T_d values in Eq. (1). So the air becomes cooler and simultaneously more humid with irrigation expansion.

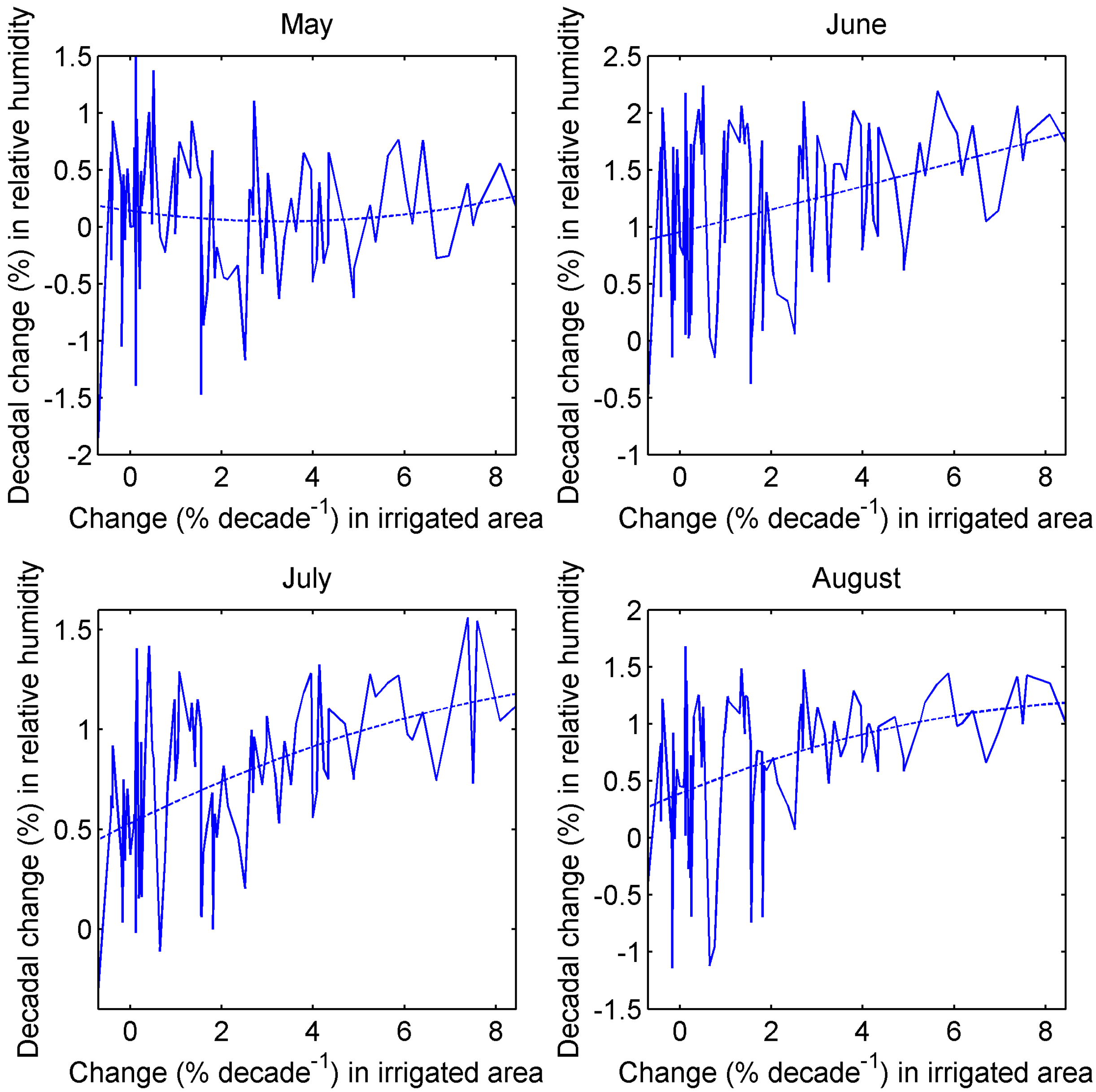


Figure 16. Decadal change in relative humidity (RH) versus change in irrigated area. The intermittent line is the best-fit 2nd-order polynomial curve. The sample mean of RH for the 30 counties with the smallest rate of irrigation development is significantly different in June, July, and August from the mean of those 30 counties that display the largest rate of development, according to the 5% significance level of the two-sample t-test.

Finally, Fig. 17 illustrates the not-surprising finding of elevated ET rates with increasing irrigation levels. The largest spatial change is found in August, when counties with shrinking or no irrigation have less evaporation over time, while counties with the largest growth in irrigated area increase their evaporation output the most over time.

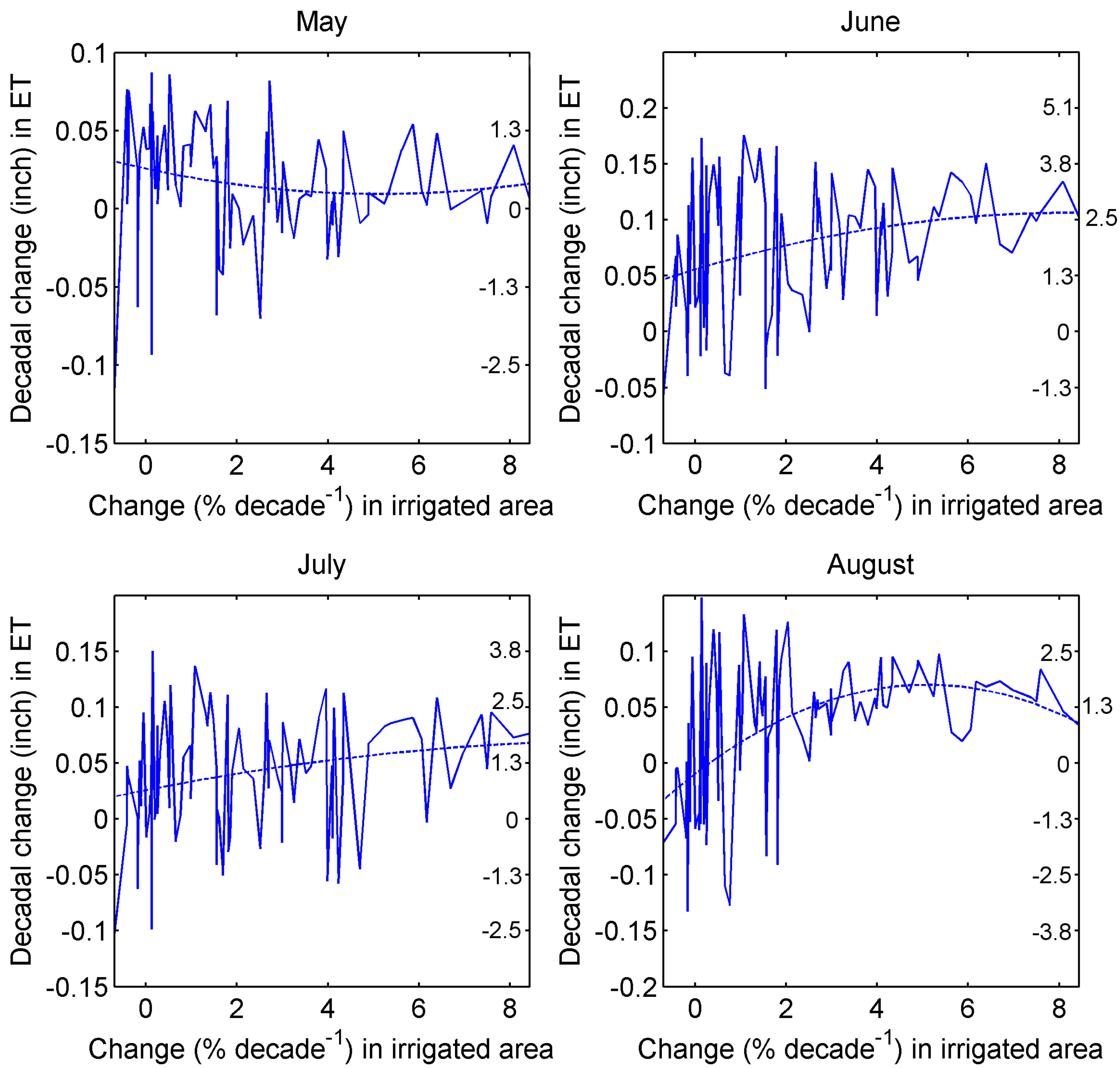


Figure 17. Decadal change in ET rate versus change in irrigated area. The intermittent line is the best-fit 2nd-order polynomial curve. The sample mean of ET for the 30 counties with the smallest rate of irrigation development is significantly different in June, July, and August from the mean of those 30 counties that display the largest rate of development, according to the 5% significance level of the two-sample t-test. The values on the right side of the panels are in mm.

CONCLUSIONS

Long-term irrigation expansion occurring on a large scale in Nebraska has a significant effect on the environment. The temperature difference that existed in 1979 between counties having the fastest expansion and those with no-expansion grew on average 1.5 °F greater in the summer months of June-August by the year of 2015. This cooling trend was accompanied by a roughly 3% increase in the relative humidity value difference that already existed in 1979 during the summer months. Finally, the 1979 summer month ET rate difference grew 0.2 inch (5.1 mm) greater (which is about 5-7% of the long-term mean summer month value) by 2015 between well irrigated and no- or hardly irrigated counties.

Irrigation boosted summer evaporation rates in Nebraska have been known to enhance precipitation rates as far as Illinois and Indiana (Kustu et al., 2011). These observations that irrigation enhanced ET rates on a regional scale will generate increases in precipitation rates far downwind, have also been supported by numerical models of the atmosphere (DeAngelis et al., 2010; Harding and Snyder, 2012; Alter et al., 2015). Such teleconnections in irrigation-induced moisture transport across geographically distant areas should be taken into account during future water resources sustainability/vulnerability planning and investigations. This is especially important because the ever increasing global population will continue to present sustained pressure for global food production intensification (in a world with dwindling per capita water resources) which cannot be achieved and maintained without economically and environmentally sustainable large-scale irrigation projects all over the world.

ACKNOWLEDGMENTS

The author is grateful to Matt Joeckel and R.F. Diffendal, Jr. for their comments on the original version of the manuscript.

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ISBN 1-56161-076-3
ISBN-13 978-1-56161-076-1