Using `R-INLA` to understand institutional moderators of drought

Emily Burchfield
Department of Civil and Environmental Engineering
Vanderbilt University
emily.k.burchfield@vanderbilt.edu

Katherine Nelson
Department of Civil and Environmental Engineering
Vanderbilt University
katherine.s.nelson@vanderbilt.edu

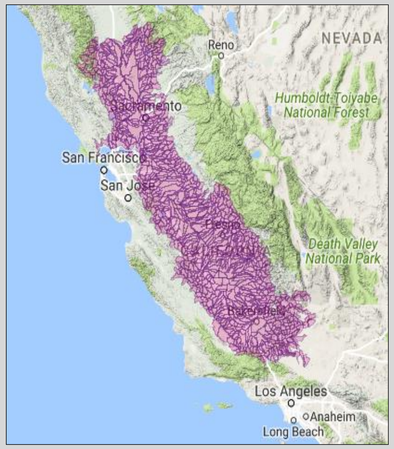
BACKGROUND

California's Central Valley region is home to one of the most productive agricultural systems on the planet. Surface water access in the Central Valley is governed by a complex hierarchy of water rights; CA is the only state to recognize both **riparian** and **appropriativ**e rights.

- **Riparian** rights belong to a land owner and apply to the use of naturally flowing water within, or adjoining, a parcel of land.
- **Appropriative** water rights are rights that divert water far from the original stream system for use on land that is not classified as riparian.

Riparian rights are considered "senior" to appropriative water. Appropriative rights are themselves subject to an internal hierarchy that is often described as "first in time, first in right" whereby rights holders with the oldest claim have higher priority access to water. We apply Bayesian multilevel spatiotemporal modeling techniques to a novel dataset to examine the influence of the structure of surface water rights in the Central Valley on agricultural production during the recent drought.

DATA



Annual data for years 2007-2014 of the recent drought were obtained for the entire Central Valley with outcome, control, and predictor variables available at one of two different spatial scales: field-level (62,000 1km pixels) or watershed-level (849 USGS HUC-12 units).

We computed the integral of the annual smoothed time series of NASA MODIS MOD13A2 EVI data to obtain a pixel-level estimate of **total vegetative production (TVP)** for farmland pixels.

We controlled for land use at the pixel-level (CropScape) and included the following watershed-level variables:

- **GROUNDWATER ELEVATION:** Annual change in groundwater elevation created using `spacetime` to apply space-time kriging to well data (GeoTracker GAMA, 2016; Graler et al., 2016)
- **WATER RIGHTS DENSITY:** Density of surface water points of diversion (PODs) in a watershed (CA SWRCB eWRIMS)
- **PERCEPT RIPARIAN:** Percent of riparian PODs in a watershed
- **PERCENT APPROPRIATIVE:** Percent of appropriative PODs in watershed
- **PRECENT PRE-1914:** Percent of pre-1914 appropriative PODs in watershed
- **CROP DIVERSITY**: Diversity of agricultural land within a watershed
- **STANDARDIZED PRECIPITATION INDEX:** Index of drought

California State Water Resources Control Board. Electronic Water Rights Information Management System (eWRIMS).
GeoTracker GAMA. (2016). Groundwater Ambient Monitoring and Assessment: Statewide Depth-to-Water and Groundwater Elevation data
Gräler, B., Pebesma, E., and Heuvelink, G. (2016). Spatio-temporal interpolation using gstat. R Journal.

MODEL

In order to examine the effects of the structure of water rights on agricultural productivity during times of water scarcity the observed TVP ($\boldsymbol{y_{ijk}}$) was fit to the following multi-level model (Model A):

$$y_{ijk} = \beta_{0jk} + \beta_{10k}SPI + \boldsymbol{\beta}_{20k}\boldsymbol{X} + \boldsymbol{\beta}_{30k}\boldsymbol{X} * SPI + \boldsymbol{\beta}_{4jk}\boldsymbol{C} + s_{00k} + e_{ijk}$$

where $\boldsymbol{\beta_{1k}}$ represents the linear effect of drought (SPI) on TVP, $\boldsymbol{X}$ is a vector of water rights predictors (Percent Riparian, Percent Pre-1914, and Percent Appropriative), and $\boldsymbol{C}$ is a vector of controlling variables (year, land use category, water rights density, agricultural diversity, and annual groundwater elevation change), $\boldsymbol{s_{00k}}$ is a watershed level spatial effect (Besag-York-Mollié), and $\boldsymbol{e_{ijk}}$ is a random effect accounting for within field variability. The intercept term includes random effects at both the field ($\boldsymbol{u_{0jk}}$) and watershed levels ($\boldsymbol{u_{00k}}$) and can be expressed as:

$$\beta_{0jk} = \beta_{00k} + u_{0jk} + u_{00k}$$

As drought also affects the extent of cultivation, a Bernoulli likelihood model examining the effect of water rights and drought on the likelihood that a field of agricultural land is classified as "barren and fallow" was also run (Model B). The model is the same with a binary outcome variable for barren (0) and cultivated (1) fields.

RESULTS

Our results suggest that meteorological drought stress (SPI) and the structure of water rights within a watershed have significant effects on agricultural production. Percent Riparian, Percent Pre-1914, and Percent Appropriative also all show positive, and significantly different, effects on agricultural production (see Figure 1). Interestingly, the effect for Percent Appropriative water rights indicates that when SPI is zero (at its mean) increasing the percent of water rights in a watershed that are Appropriative produces a larger positive effect on TVP than does increasing the percent of water rights in a watershed that belong to the more senior categories of Riparian and Pre-1914.

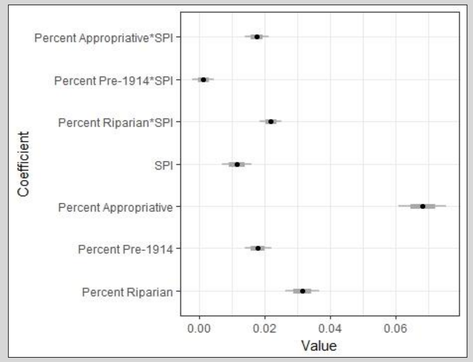


Figure 1. Effect estimates for predictors on TVP (Model A). Posterior median (black dot), median ± standard deviation (thick gray line), and 95% credibility interval (thin gray line) are shown for key predictors.

Figure 2 illustrates how the effect of SPI on TVP changes as a function of each water right type. These interactions indicate that agricultural production in watersheds that have a larger than average proportion of Riparian and Appropriative water rights generally exhibit higher sensitivity to changes in SPI than other watersheds.

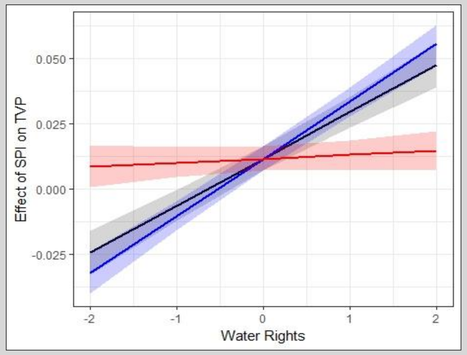


Figure 2. The effect of SPI on TVP as a function of water rights predictors. The median interaction effects for Riparian (blue), Pre-1914 (red), and Appropriative (black) water rights are shown with 95% credibility intervals.

The posterior estimates of the marginal distributions for the Bernoulli model (Model B) indicate that there is generally a low average likelihood that any field is classified as barren and fallow. The estimates of the predictor effects can be interpreted as an incremental change in the probability of a field being classified as barren and fallow. Percent Pre-1914 has the largest effect of the water rights predictors, suggesting that when SPI is zero, a one standard deviation increase in Pre-1914 water rights, is associated with a 39.2% decrease in the probability that a field is left barren and fallow.

	Model A	**Model B**[†]
Intercept	-0.3449*	0.00169597*
SPI	0.0117*	0.956308*
Percent Riparian	0.0316*	0.755709*
Percent Pre − 1914	0.0181*	0.608049*
Percent Appropriative	0.0684*	0.764389*
Percent Riparian ∗ SPI	0.0219*	0.966706
Percent Pre − 1914 ∗ SPI	0.0014	0.922496 *
Percent Appropriative ∗ SPI	0.0178*	1.01101*
Marginal Log-Likelihood	-329332.09	-85668.94
DIC	538590.29	156576.57

*Indicates effect estimate is significantly different from zero at a 95% credibility level.

[†]Anti-logit of the intercept estimate and exponentiated predictor effect estimates are reported.

IMPLICATIONS

•R-INLA is a powerful to account for spatial processes operating at multiple scales (watershed and agricultural field)

•Results suggest that, after accounting for spatiotemporal dependencies in the data, seniority in surface water access significantly improves local capacity to maintain cultivated extent during drought but does not appear to increase agricultural productivity on cultivated lands. In addition, watersheds with more senior surface water rights show less sensitivity to cumulative drought exposure relative to riparian and junior rights.