

**The intervention effect of local alcohol licensing policies on hospital admission and crime:
a natural experiment using a novel Bayesian synthetic time-series method**

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Online Supplementary Materials

BAYESIAN STRUCTURAL TIME SERIES

The data used in these analyses are freely available from:

<http://www.lape.org.uk/data.html>

<http://www.ons.gov.uk/peoplepopulationandcommunity/crimeandjustice/bulletins/crimeinenglandandwales/2015-07-16>

<http://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration>

The statistical methodology is outlined in summary below

Bayesian structural time-series model use a Bayesian state-space time-series model that includes one component of state as a linear regression on the predictors. It is described in detail here (1, 2), but in summary can be described by an ‘observation equation’ (Eq. 1), which links the observed data (y_t ; *i.e.* the measured crime or hospital admission rates) with an unobserved latent state (α_t), and a ‘transition equation’ (Eq. 2); the latter describing the evolution of α_t over time:

$$y_t = Z_t^T \alpha_t + \varepsilon_t \quad (\text{Eq. 1})$$

$$\alpha_{t+1} = T_t \alpha_t + R_t \eta_t \quad (\text{Eq. 2})$$

where $\varepsilon_t \sim N(0, \sigma_t^2)$ and $\eta_t \sim N(0, Q_t)$, and both are independent of all other unknowns, y_t is a scalar observation, Z_t is an output vector, T_t is the transition matrix, R_t the control matrix, η_t describes the system error with a state-diffusion matrix Q_t ($R_t \eta_t$ allows the inclusion of seasonality in these analyses), and ε_t is a scalar observation error with variance σ_t . The errors of different state-component models are assumed to be independent.

This framework includes a regression component which enables the construction of a synthetic time series based on combinations of the control units/areas (*i.e.* the counterfactual). A generalisation of the local linear trend model with the slope having stationary random walk is used, and can be described by equations 3 and 4:

$$\mu_{t+1} = \mu_t + \delta_t + \eta_{\mu,t} \quad (\text{Eq. 3})$$

$$\delta_{t+1} = D + \rho(\delta_t - D) + \eta_{\gamma,t} \quad (\text{Eq. 4})$$

Where μ_t is the value of the trend at time t and δ_t the slope at time t , $\eta_{\mu,t} \sim N(0, \sigma_{\mu}^2)$, and $\eta_{\delta,t} \sim N(0, \sigma_{\delta}^2)$. The two components of η are independent and D signifies the long-term slope. $|\rho| < 1$ represents the learning rate at which the local trend is updated.

A spike-and-slab prior is placed on the regression coefficients and the model averages over the pool of control areas to construct the ‘synthetic control’ (2, 3). The “spike” determines the probability a control area has a non-zero coefficient (*i.e.* being included in the model) based on independent Bernoulli distributions, and the “slab” is a weakly informative Gaussian prior with a large variance.

As a result, the posterior predictive density is a joint distribution over all counterfactual data points rather than a collection of pointwise univariate distribution to ensure a correct serial structure (19).

To account for seasonal differences (*i.e.* here we have quarterly data), a seasonal component is added, and is described by equation 5:

$$Y_{t+1} = -\sum_{s=0}^{S-2} Y_{t-s} + \eta_{Y,t} \quad (\text{Eq. 5})$$

Where S is the number of seasons (*i.e.* 4) and Y_t denotes their joint distribution to the observed y_t . The mean of Y_t over the four seasons is zero.

Prior distributions for the variance are set as Gamma distributions with expectation a/b , and for the seasonal and local linear trend models the incremental error in the state are *a priori* assumed to be small and set to $\frac{1}{\sigma^2} \sim G(10^{-2}, 10^{-2}s_y^2)$, where $s_y^2 = \sum_t (y_t - \bar{y}) / (n - 1)$. Posterior simulation is done using a Gibbs sampler and Kalman filter to simulate from a Markov chain with a stationary distribution (for model parameters θ) $p(\theta, \alpha | Y_{1:n})$, and the posterior incremental effect is described by $p(\tilde{Y}_{n+1:m} | Y_{1:n}, X_{1:m})$, where $\tilde{y}_{n+1}, \dots, \tilde{y}_m$ describe the counterfactual response.

The posterior distribution of the counterfactual time series post-intervention can then be computed based on the pre-intervention time-series data from all areas and the weighted post-intervention time series of the control areas, and by subtracting the estimated trends in the counterfactual ‘synthetic control area’ from the observed post-intervention data at each point in time semiparametric Bayesian posterior distribution for the causal effect of the intervention is obtained.

References

1. BRODERSEN K. H., GALLUSSER F., KOEHLER J., REMY N., SCOTT S. L. Inferring causal impact using Bayesian structural time-series models., *Annals of Applied Statistics* 2015: 9: 247-274.
2. SCOTT S. L., VARIAN H. R. Predicting the present with Bayesian structural time series., *Int J Mathematical Mod and Optimization* 2014: 5: 4-23.
3. GEORGE J., MCCULLOCH R. E. Approaches for Bayesian variable selection., *Statist Sinica* 1997: 7: 339-374.

MARKOV CHAIN MONTE CARLO DIAGNOSTICS

Table S1a . Diagnostic test statistics main analyses alcohol-related hospital admission rates

	Geweke test final state (stationary) (Z- value)	Raftery diagnostic final state stationary (I)	Heidel diagnostic (stationary) P-value	Heidel diagnostic (Halfwidth)	Relative* absolute mean (max) 1-step prediction errors	Durbin Watson 1 step prediction errors (P-value)
Alcohol-related hospital admissions						
Kingston-upon-Thames	0.528	2.120	0.613	0.340/113.78	1.5% (6.9%)	0.203
Enfield	0.599	0.964	0.085	0.895 / 156.986	1.9% (8.4%)	0.204
Derby	-0.056	0.962	0.734	0.878 / 210.597	1.6% (5.7%)	0.201
Southwark	1.315	0.966	0.066	0.783/153.91	1.8% (7.2%)	0.195
North Tyneside	-0.740	0.954	0.366	0.943 / 241.36	1.5% (6.7%)	0.189

*: relative to average alcohol-related hospital admission rate prior to intervention

Table S1b. Diagnostic test statistics main analyses alcohol-related reported violent crime rates

	Geweke test final state (stationary) (Z- value)	Raftery diagnostic final state stationary (I)	Heidel diagnostic (stationary) P-value	Heidel diagnostic (Halfwidth)	Relative* absolute mean (max) 1-step prediction errors	Durbin Watson 1 step prediction errors (P-value)
Alcohol-related violent crimes						
Kingston-upon-Thames	-0.852	0.951	0.926	0.0100/4.609	0.7% (2.9%)	0.196
Enfield**	1.889	0.951	0.063	0.008/4.547	0.7% (2.6%)	0.203
Derby	-0.000	1.97	0.365	0.035/6.739	1.5% (6.7%)	0.188
Southwark	-1.121	0.954	0.848	0.050/8.722	1.7% (7.5%)	0.179
North Tyneside	-0.680	0.953	0.600	0.014/2.580	2.0% (9.0%)	0.200

*: relative to average alcohol-related hospital admission rate prior to intervention. **: MCMC chain of 150,000 to satisfy all criteria

Table S1c. Diagnostic test statistics main analyses alcohol-related reported violent sexual crime rates

	Geweke test final state (stationary) (Z- value)	Raftery diagnostic final state stationary (I)	Heidel diagnostic (stationary) P-value	Heidel diagnostic (Halfwidth)	Relative* absolute mean 1-step prediction errors	Durbin Watson 1 step prediction errors (P-value)
Alcohol-related violent crimes						
Kingston-upon-Thames	-0.501	0.97	0.87	0.001 /0.123	3.7%	0.189
Enfield	1.378	0.96	0.07	0.001/0.134	2.1%	0.197
Derby**	1.585	0.97	0.13	0.001/0.205	2.2%	0.213
Southwark	1.378	0.96	0.37	0.001/0.210	1.5%	0.217
North Tyneside	-0.731	0.95	0.751	0.0003/0.073	2.4%	0.507

*: relative to average alcohol-related hospital admission rate prior to intervention.

Table S1d. Diagnostic test statistics main analyses alcohol-related reported public order offenses

	Geweke test final state (stationary) (Z- value)	Raftery diagnostic final state stationary (I)	Heidel diagnostic (stationary) P-value	Heidel diagnostic (Halfwidth)	Relative* absolute mean (max) 1-step prediction errors	Durbin Watson 1 step prediction errors (P-value)
Alcohol-related violent crimes						
Kingston-upon-Thames	0.514	0.96	0.078	0.021/1.667	3.6%	0.191
Enfield	-0.014	3.02	0.505	0.015/2.174	2.3%	0.207
Derby	0.811	0.95	0.167	0.0118/2.725	1.4%	0.198
Southwark	-0.267	0.98	0.520	0.052/5.201	2.9%	0.199
North Tyneside	1.247	0.96	0.180	0.0228/2.474	2.7%	0.162

*: relative to average alcohol-related hospital admission rate prior to intervention.

GRAPHICAL REPRESENTATIONS OF MODELLED AND MEASURED TIME SERIES IN INTERVENTION AREAS.

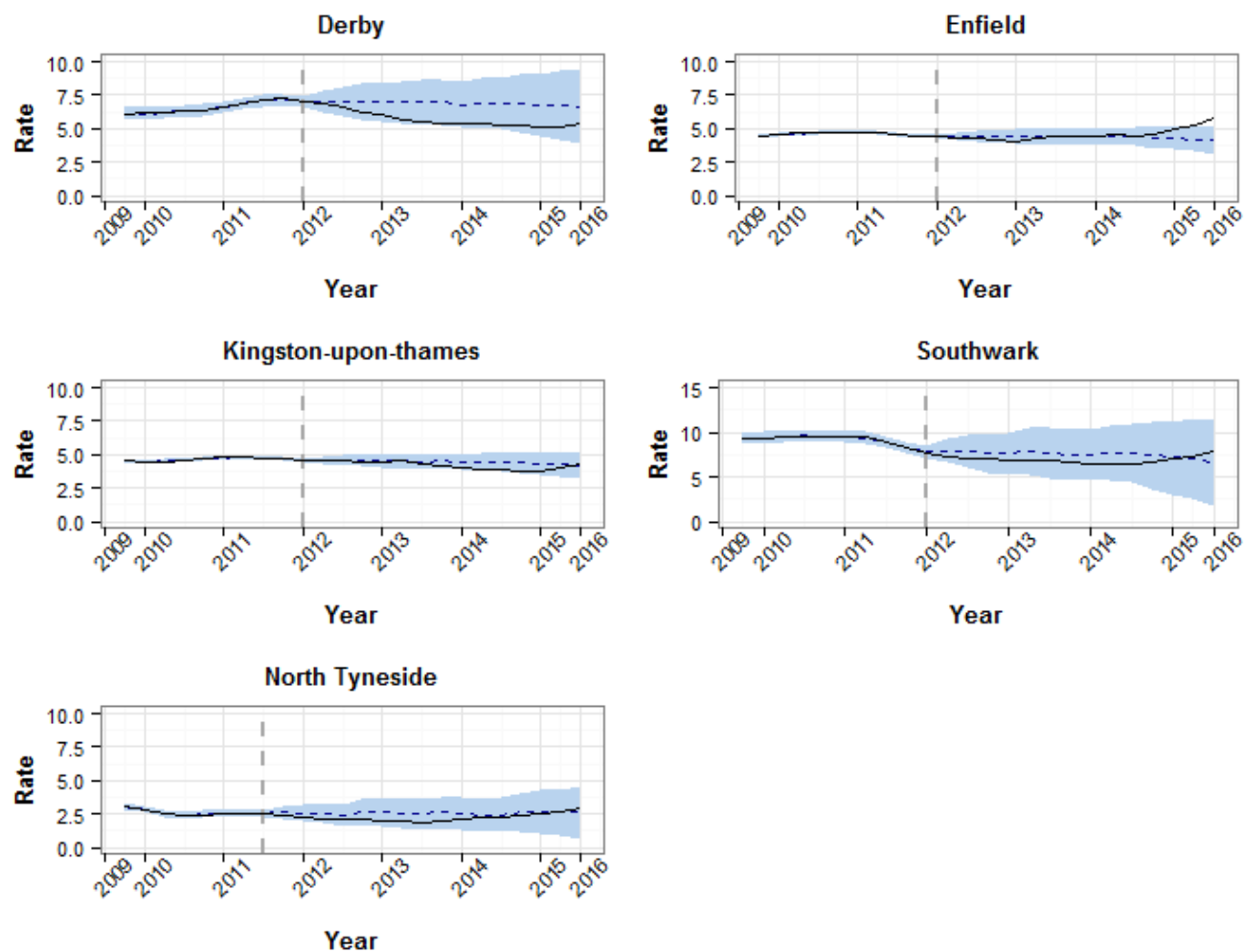


Figure S1a. Measured (solid line) and modelled, synthetic (dotted line) time series for alcohol-related reported violent crime rates in the areas with the intervention. Blue areas represent 95% Bayesian Credible Intervals.

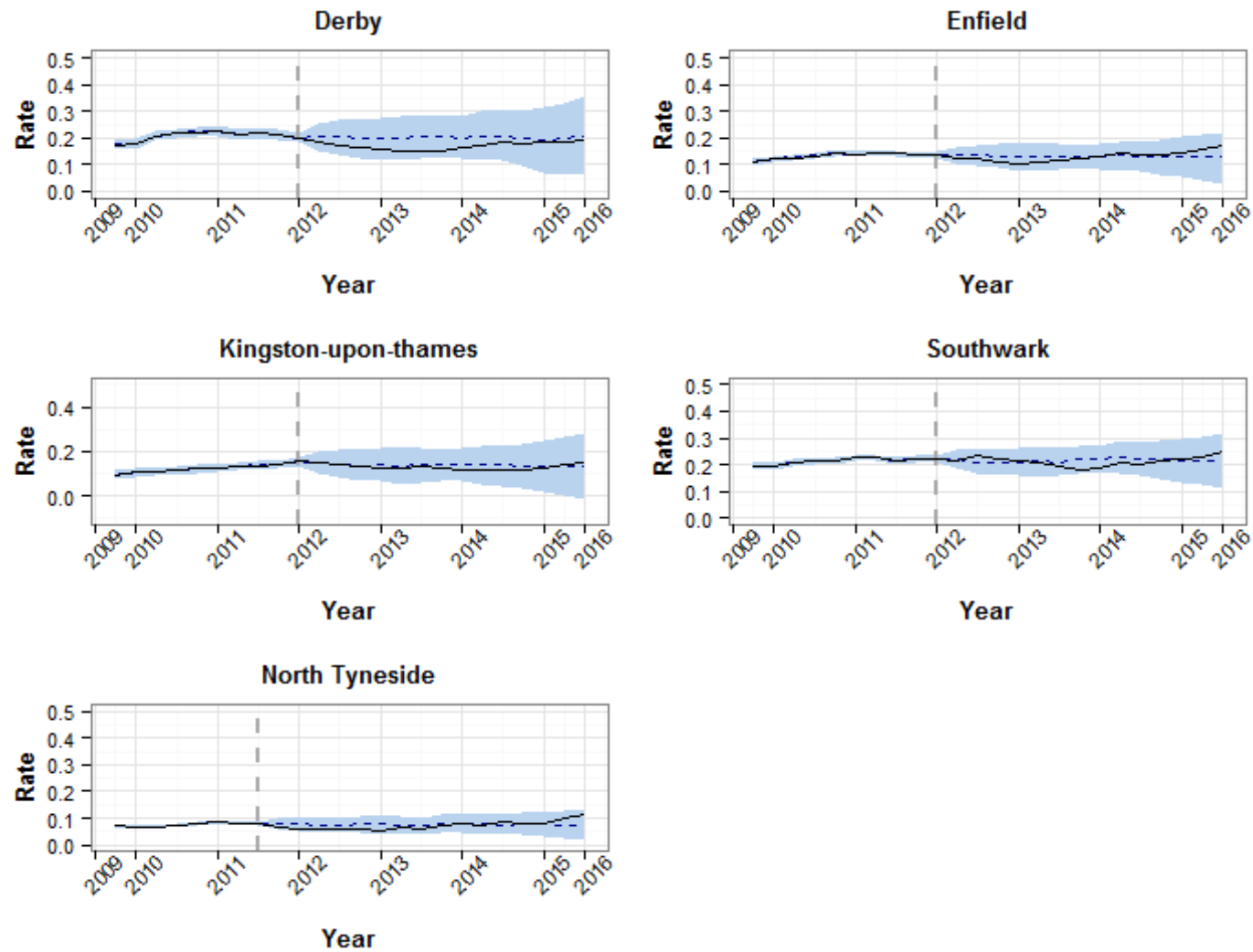


Figure S1b. Measured (solid line) and modelled, synthetic (dotted line) time series for alcohol-related reported sexual crime rates in the areas with the intervention. Blue areas represent 95% Bayesian Credible Intervals.

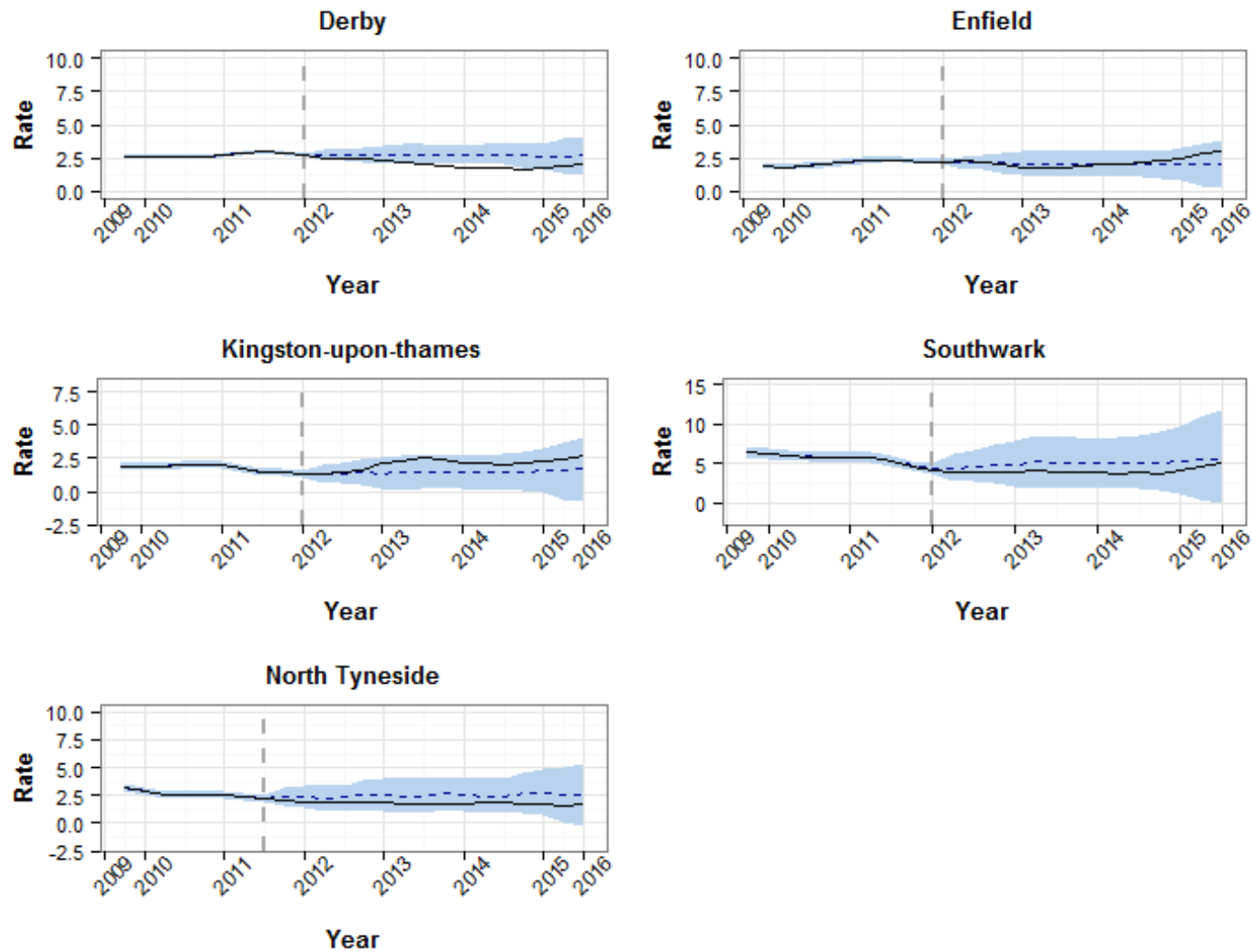


Figure S1c. Measured (solid line) and modelled, synthetic (dotted line) time series for anti-social behaviour rates in the areas with the intervention. Blue areas represent 95% Bayesian Credible Intervals.

OVERVIEW POSTERIOR SUMMARIES ALL OUTCOMES

INTERVENTION AREAS

Table S2a. Posterior summaries of relative intervention effect and 95% credible intervals **alcohol-related hospital admissions.**

Local Area	Posterior 2011-15 causal effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect
Kingston-upon-Thames	-10.4%	-22.3%:1.1%	0.035	96%
Enfield	-11.3%	-31.2%:7.2%	0.114	89%
Derby	-4.4%	-21.4% : 10.3%	0.284	72%
Southwark	-1.4%	-16.6% : 14.0%	0.416	58%
North Tyneside(*)	-2.3%	-18.1% : 12.9%	0.375	62%
Random-effects Meta- analysis (**)	Summary effect	Summary 95% CI	P-value	Causal effect
Summary	-6.3%	-12.8% : 0.2%	0.06	94%

*: Note that data indicate that 'intervention' was initiated about 6 months earlier. **: Test for heterogeneity $I^2 = 0.0\%$ (P-value=0.885)

Table S2b. Posterior summaries of relative intervention effect and 95% credible intervals **alcohol-related violent crimes.**

	2009-2015				2009- (mid)2013		
Local Area	Posterior effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect	Posterior effect of change in licensing policy	95% credible interval	Posterior probability of causal effect
Kingston-upon-Thames	-5.9%	-17.4%:6.1%	0.151	85%	-1.3%	-10.2%:8.2%	63%
Enfield	+4.9%	-7.4%:17.2%	0.209	79%	-3.5%	-13.0%:6.5%	77%
Derby	-17.9%	-39.3%:3.9%	0.049	95%	-12.2%	-28.3%:4.3%	93%
Southwark	-7.9%	-41.9%:26.8%	0.315	69%	-9.3%	-34.7%:16.4%	78%
North Tyneside(*)	-12.3%	-50.0%:27.1%	0.243	76%	-16.7%	-45.5%:13.5%	88%
Random-effects Meta-analysis (**)	Summary effect	Summary 95% CI	P-value	Causal effect	Summary effect	Summary 95% CI	Causal effect
Summary	-4.4 %	-13.7% : 4.9%	0.355	65%	-4.6%	-10.7%:1.4%	87%

*: Note that data indicate that 'intervention' was initiated about 6 months earlier. **: Test for heterogeneity $I^2 = 20.15\%$ (P-value=0.425)

Table S2c. Posterior summaries of relative intervention effect and 95% credible intervals alcohol-related sex crimes.

	2009-2015				2009- (mid)2013		
Local Area	Posterior effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect	Posterior effect of change in licensing policy	95% credible interval	Posterior probability of causal effect
Kingston-upon-Thames	-6.7%	-54.0%,41.7%	0.350	65%	-3.5%	-46.6%,39.5%	58%
Enfield	-0.1%	-33.1%,33.0%	0.481	52%	-12.9%	-43.8%,18.0%	83%
Derby	-15.5%	-48.1%,17.1%	0.148	85%	-18.9%	-50.2%,12.5%	90%
Southwark	-2.0%	-22.6%, 18.7%	0.398	60%	1.0%	-19.4%,21.4%	54%
North Tyneside(*)	-3.6%	-38.1%,30.9%	0.397	60%	-19.1%	-52.2%,14.1%	89%
Random-effects Meta-analysis (**)	Summary effect	Summary 95% CI	P-value	Causal effect	Summary effect	Summary 95% CI	Causal effect
Summary	-4.7%	-18.9%, 9.5%	0.520	50%	-8.4%	-21.4%,4.6%	80%

*: Note that data indicate that 'intervention' was initiated about 6 months earlier.

Table S2d. Posterior summaries of relative intervention effect and 95% credible intervals **anti-social behaviour**.

	2009-2015				2009- (mid)2013		
Local Area	Posterior effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect	Posterior effect of change in licensing policy	95% credible interval	Posterior probability of causal effect
Kingston-upon-Thames	44%	-31%, 117%	0.103	90%	37%	-27%,98%	89%
Enfield	6.4%	-33%, 46%	0.350	65%	-6.2%	-38%,25%	68%
Derby	-25%	-49%, -1.6%	0.020	98%	-16%	-34%,3%	96%
Southwark	-21%	-76%, 33%	0.198	80%	-20%	-66%,25%	83%
North Tyneside(*)	-27%	-76%, 21%	0.114	89%	-22%	-61%,17%	89%
Random-effects Meta-analysis (**)	Summary effect	Summary 95% CI	P-value	Causal effect	Summary effect	Summary 95% CI	Causal effect
Summary	-14.3	-32.9%, 4.4%	0.133	87%	-12.6%	- 26.4%,1.3%	93%

*: Note that data indicate that 'intervention' was initiated about 6 months earlier.

** : Test for heterogeneity $I^2 = 8.34\%$ (P-value=0.329)

SENSITIVITY ANALYSES

ALTERNATIVE BAYESIAN PRIORS

Table S3a. Posterior summaries of relative intervention effect and 95% credible intervals alcohol-related hospital admission rates.

Alternative priors: Stricter priors with sigma prior and sigma guess 1% of sample sd (proposed for stable time series), upper limit for sigma at 100% of sample sd, and prior explained variance set at 90%.

Local Area	Posterior 2011-15 causal effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect
Kingston-upon-Thames	-10.5%	-20.7%:-0.5%	0.021	98%
Enfield	-11.2%	-28.4%:4.6%	0.083	92%
Derby	-4.1%	-19.0%:8.1%	0.278	72%
Southwark	-1.3%	-14.4%:6.6%	0.410	59%
North Tyneside	-2.2%	-15.6%:10.9%	0.362	64%
Random-effects Meta- analysis	Summary effect	Summary 95% CI	P-value	Causal effect
Summary	-6.1%	-11.7%:-0.6%	0.031	97%

Table S3b. Posterior summaries of relative intervention effect and 95% credible intervals alcohol-related hospital admission rates.

Alternative priors: Uninformative priors with sigma prior and sigma guess set to sample standard deviation and upper limit for sigma set to 10*sd, sigma priors for betas set to 10*sd sample, and prior explained variance set at 50%.

Local Area	Posterior 2011-15 causal effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect
Derby	-3.3%	-54.1%:46.8%	0.448	55%
Enfield	-8.8%	-71.1%:53.1%	0.385	61%
Kingston-upon-Thames	-11.8%	-46.6%:23.0%	0.241	76%
Southwark	-1.5%	-54.5%:51.5%	0.475	52%
North Tyneside	-3.5%	-55.5%:47.5%	0.446	55%
Random-effects Meta- analysis	Summary effect	Summary 95% CI	P-value	Causal effect
Summary	-6.8%	-28.0%:14.3%	0.527	47%

Table S3c. Posterior summaries of relative intervention effect and 95% credible intervals alcohol-related reported violent crime rates.

Alternative priors: Stricter priors with sigma prior and sigma guess 1% of sample sd (proposed for stable time series), upper limit for sigma at 100% of sample sd, and prior explained variance set at 90%.

Local Area	Posterior 2011-14 causal effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect
Kingston-upon-Thames	-5.6%	-15.6%:5.0%	0.141	86%
Enfield	+4.9%	-5.7%:15.7%	0.176	82%
Derby	-17.5%	-35.2%:0.8%	0.029	97%
Southwark	-6.8%	-36.7%:22.2%	0.314	69%
North Tyneside(*)	-12.6%	-44.2%:21.2%	0.203	80%
Random-effects Meta- analysis (***)	Summary effect	Summary 95% CI	P-value	Causal effect
Summary	-4.8%	-13.9%:4.4%	0.306	69%

Table S3d. Posterior summaries of relative intervention effect and 95% credible intervals alcohol-related reported violent crime rates.

Alternative priors: Uninformative priors with sigma prior and sigma guess set to sample standard deviation and upper limit for sigma set to 10*sd, sigma priors for betas set to 10*sd sample, and prior explained variance set at 50%.

Local Area	Posterior 2011-14 causal effect of change in licensing policy	95% credible interval	Posterior tail-area probability	Posterior probability of causal effect
Derby	-18.3%	-97.1%:59.9%	0.316	68%
Enfield	-0.1%	-35.5%:35.5%	0.499	50%
Kingston-upon-Thames	-11.3%	-45.5%:23.4%	0.252	75%
Southwark	-21.4%	-110.6%:68.4%	0.311	69%
North Tyneside(*)	-11.0%	-122%:100%	0.419	58%
Random-effects Meta-analysis (***)	Summary effect	Summary 95% CI	P-value	Causal effect
Summary	-8.0%	-30.5%:14.4%	0.483	52%

CONTROL AREAS CONTRIBUTING TO ‘SYNTHETIC CONTROL’ TIMESERIES

Table S4a. Areas contributing most to synthetic control (i.e. top-5 based on inclusion probability)

Alcohol-related hospital admissions					
Highest inclusion probability	1 st	2 nd	3 rd	4 th	5 th
Kingston-upon-Thames	Stevenage	Craven	Hambleton	Cannock Chase	Sefton
Enfield	Ribble Valley	Tunbridge Wells	Rother	Fareham	South Staffordshire
Derby	Ribble Valley	Broxtowe	South Holland	North Warwickshire	Maidstone
Southwark	Taunton Deane	Babergh	Thurrock	South Bucks	Ipswich
North Tyneside	Rother	Ribble Valley	Tunbridge Wells	Torridge	High Peak

Table S4b. Areas contributing most to synthetic control (i.e. top-5 based on inclusion probability)

Alcohol-related violent crime rates					
Highest inclusion probability	1 st	2 nd	3 rd	4 th	5 th
Kingston-upon-Thames	Sefton	Lewes	Harlow	Basildon	Ipswich
Enfield	Nuneaton and Bedworth	South Bucks	Three rivers	North East Lincolnshire	Bracknell Forest
Derby	Newark and Sherwood	North East Lincolnshire	Stevenage	South Derbyshire	Mid Sussex
Southwark	South Bucks	East Hampshire	Bracknell Forest	Nuneaton and Bedworth	Basildon
North Tyneside	Hambleton	Waverley	Three Rivers	Gateshead	Barnsley

Table S4c. Areas contributing most to synthetic control (i.e. top-5 based on inclusion probability)

Alcohol-related sexual crime rates					
Highest inclusion probability	1 st	2 nd	3 rd	4 th	5 th
Kingston-upon-Thames	Hyndburn	South Bucks	Runnymede	South Norfolk	Sefton
Enfield	South Bucks	Fareham	North Somerset	Chichester	St Albans
Derby	High Peak	Braintree	Hillingdon	Stevenage	Blackburn with Darwen
Southwark	Hyndburn	Epsom and Ewell	Gateshead	Swale	Rother
North Tyneside	Barrow in Furness	Hillingdon	Rother	Mole Valley	Chelmsford

Table S4d. Areas contributing most to synthetic control (i.e. top-5 based on inclusion probability)

Anti social behaviour					
Highest inclusion probability	1 st	2 nd	3 rd	4 th	5 th
Kingston-upon-Thames	Vale of White Horse	Rotherham	Maidstone	East Northamptonshire	St. Helens
Enfield	North East Lincolnshire	Epsom and Ewell	Tonbridge and Malling	Blackburn with Darwin	Basildon
Derby	South Bucks	Maidstone	Hillingdon	Tunbridge Wells	Hyndburn
Southwark	East Northamptonshire	Crawley	Rotherham	Chorley	Hambleton
North Tyneside	Rother	North Somerset	Rotherham	Stevenage	Hambleton

META-ANALYTIC RESULTS OF VALIDATION ANALYSES

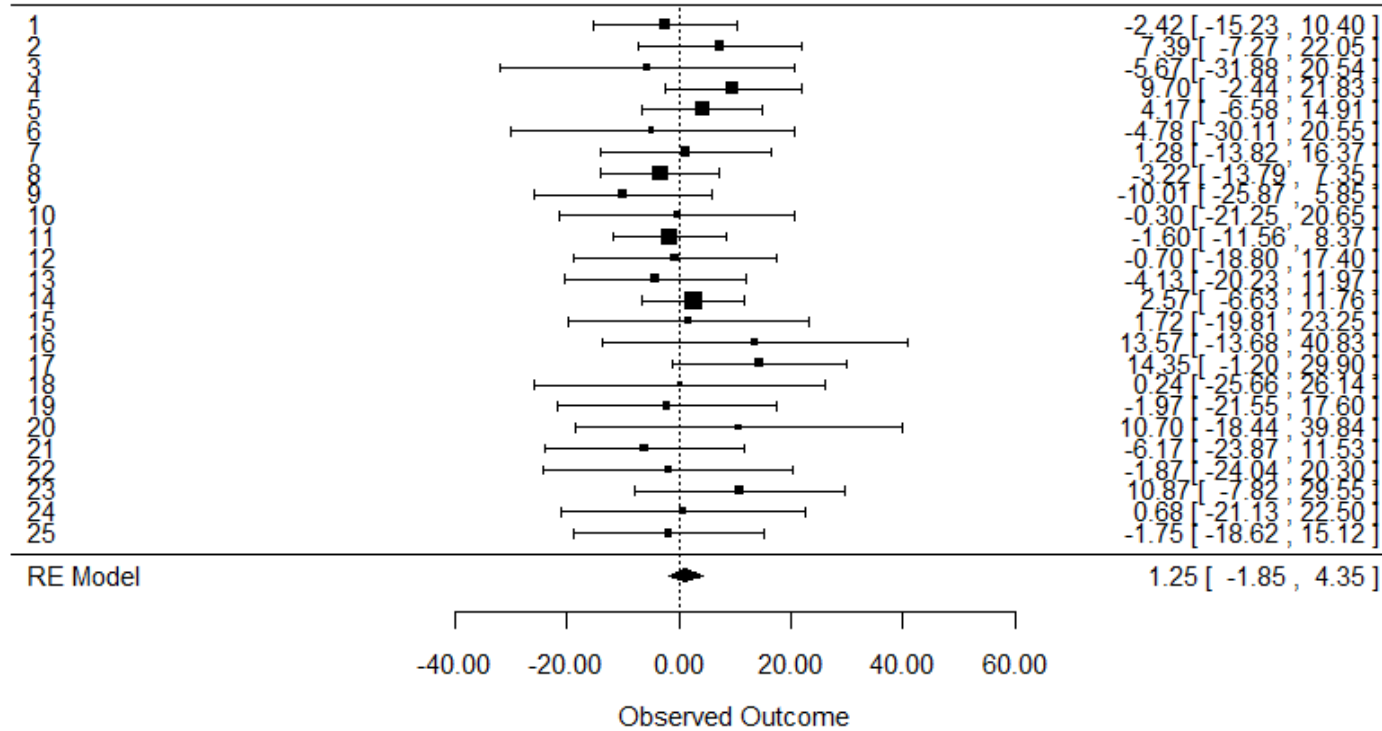


Figure S2a. Posterior summaries of relative intervention effect (in %) and 95% credible intervals **alcohol-related hospital admissions** for 25 randomly selected control areas (i.e. where alcohol licensing policies were not introduced)

(Years 2011 – 2015)

(Years 2011 – 2013)

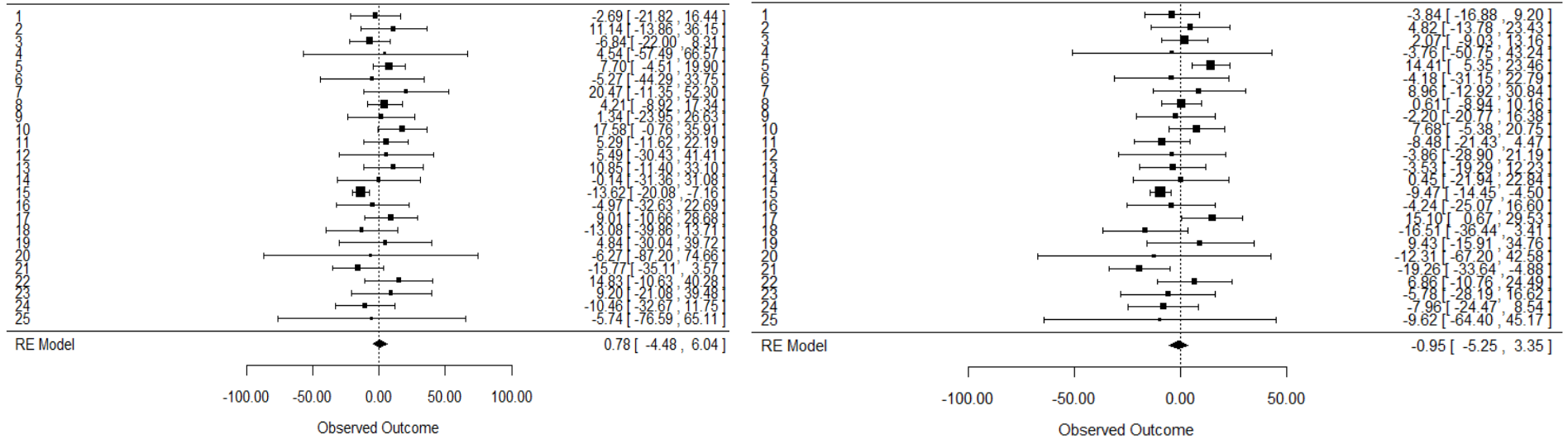
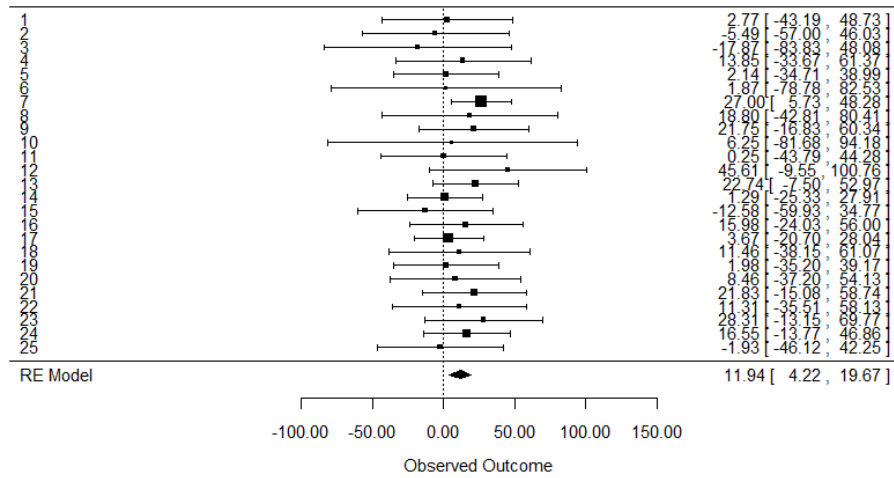


Figure S2b. Posterior summaries of relative intervention effect (in %) and 95% credible intervals alcohol-related violent crimes for 25 randomly selected control areas (i.e. where alcohol licensing policies were not introduced)

(Years 2011 – 2015)



(Years 2011 – 2013)

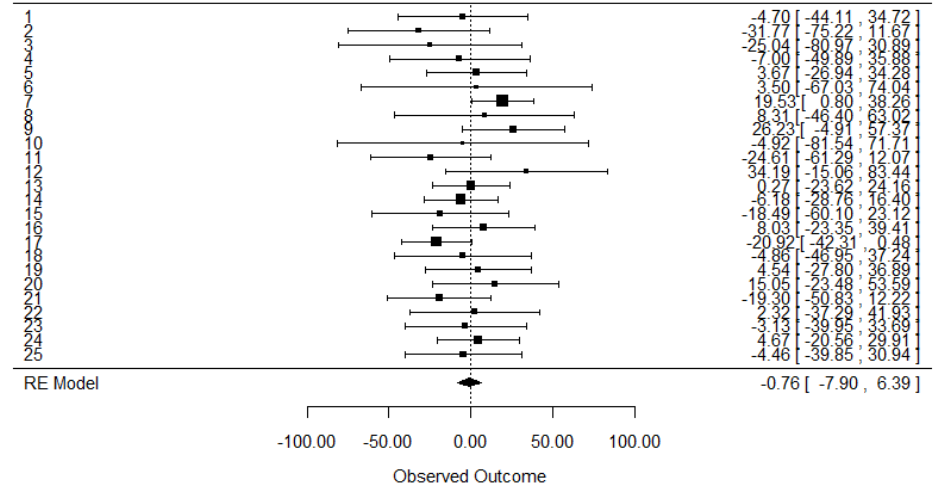
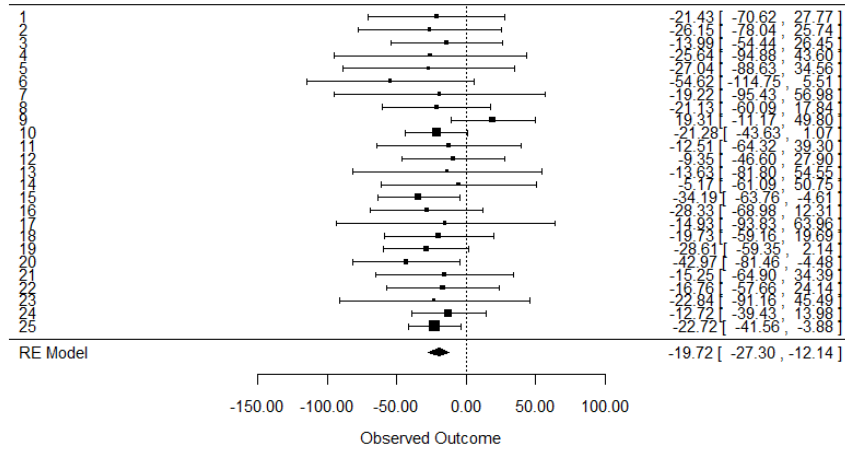


Figure S2c. Posterior summaries of relative intervention effect (in %) and 95% credible intervals **alcohol-related sex crimes** for 25 randomly selected control areas (i.e. where alcohol licensing policies were not introduced)

(Years 2011 – 2015)



(Years 2011 – 2013)

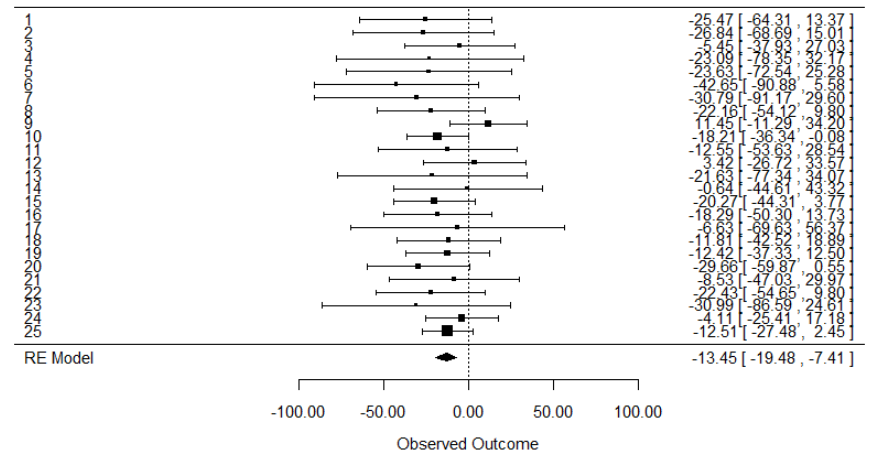


Figure S2d. Posterior summaries of relative intervention effect (in %) and 95% credible intervals **anti-social behaviour** for 10 randomly selected control areas (i.e. where alcohol licensing policies were not introduced)