STATISTICAL MODELS FOR QUANTITATIVE SYNTHESIS OF CLIMATE CHANGE IMPACT STUDIES

David Makowski

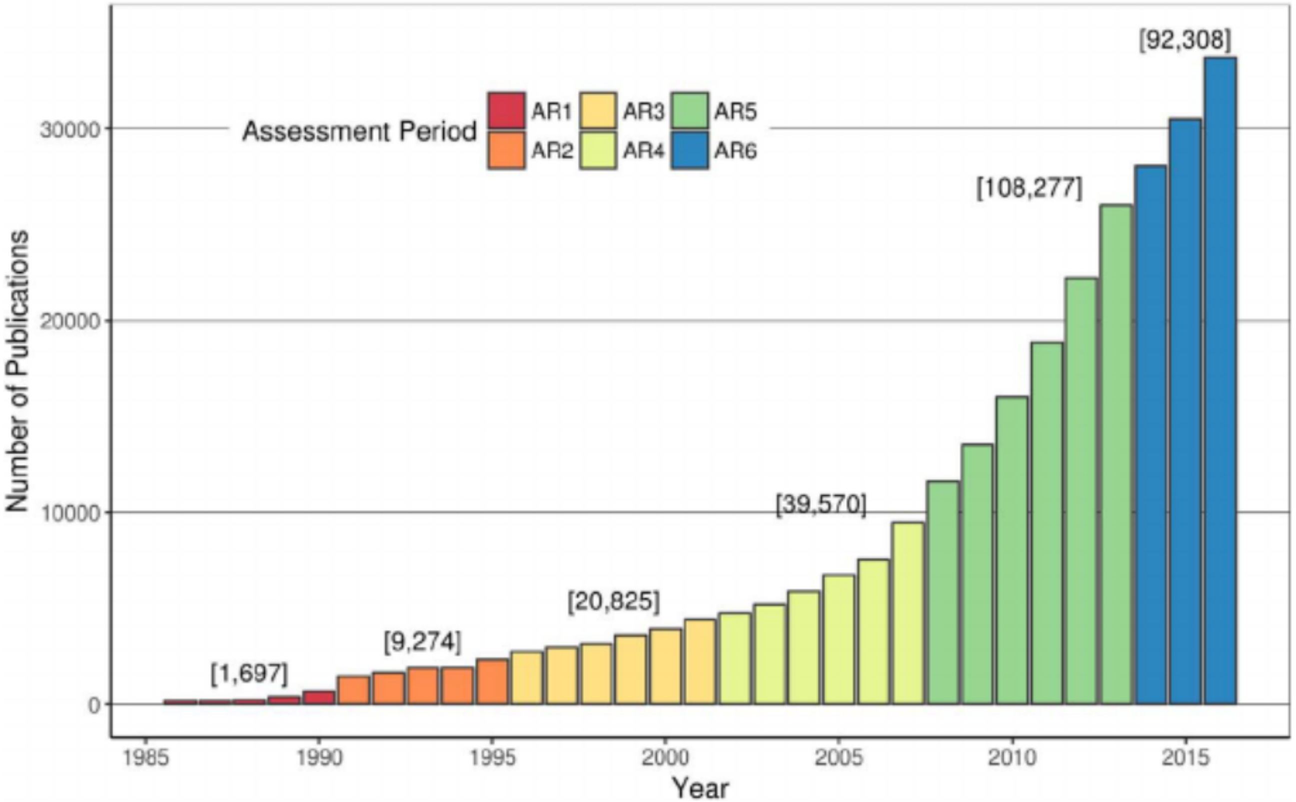
INRA, France

david.makowski@inra.fr

The ‘data synthesis challenge’

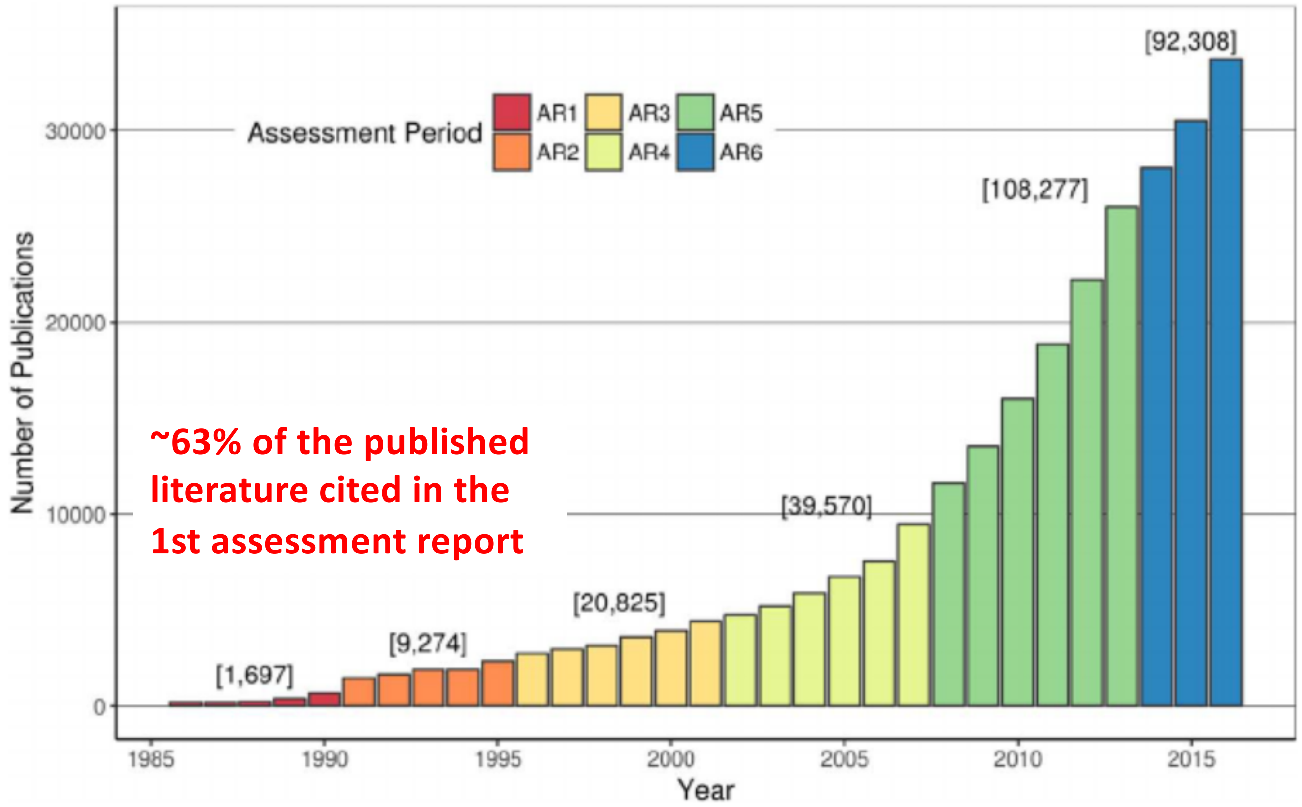
As more and more data become available, how to conduct rigorous and comprehensive assessments on climate change?

The growth of the literature on climate change was much faster than the growth in other areas of research (16% vs. 4%)



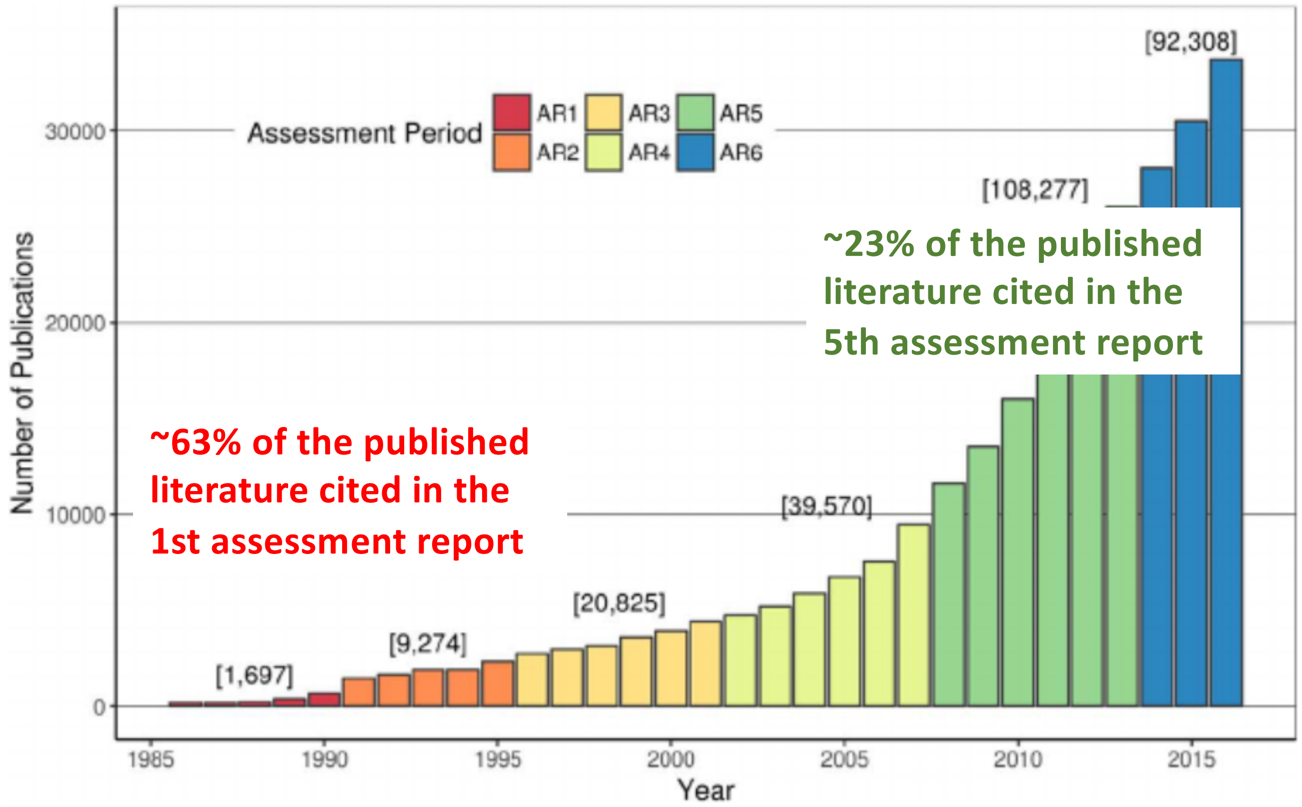
Minx J.C., Callaghan M., Lamb W.F., Garard J., Edenhofer O. 2017. Learning about climate change solutions in the IPCC and beyond. Environmental Science and Policy 77, 252-259

The growth of the literature on climate change was much faster than the growth in other areas of research (16% vs. 4%)



Minx J.C., Callaghan M., Lamb W.F., Garard J., Edenhofer O. 2017. Learning about climate change solutions in the IPCC and beyond. Environmental Science and Policy 77, 252-259

The growth of the literature on climate change was much faster than the growth in other areas of research (16% vs. 4%)



Minx J.C., Callaghan M., Lamb W.F., Garard J., Edenhofer O. 2017. Learning about climate change solutions in the IPCC and beyond. Environmental Science and Policy 77, 252-259

Formal methods are needed to help researchers to conduct rigorous and comprehensive literature synthesis

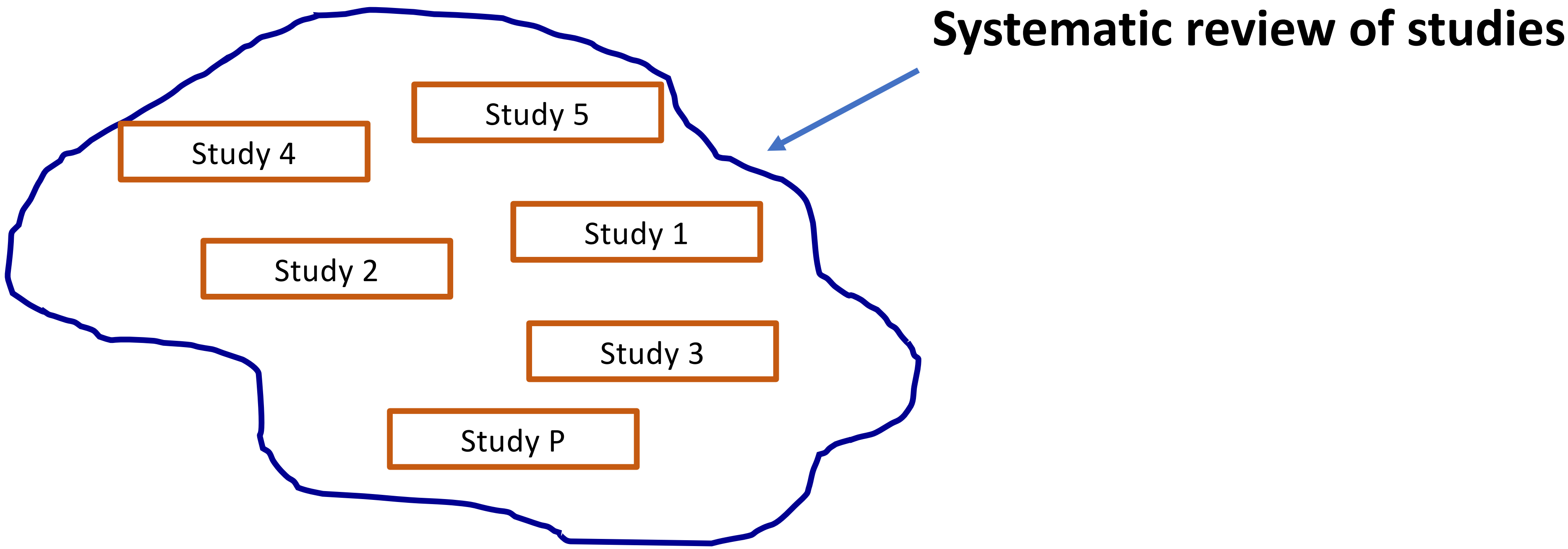
Meta-analysis: a statistical approach for quantitative synthesis

« The analysis of analyses »

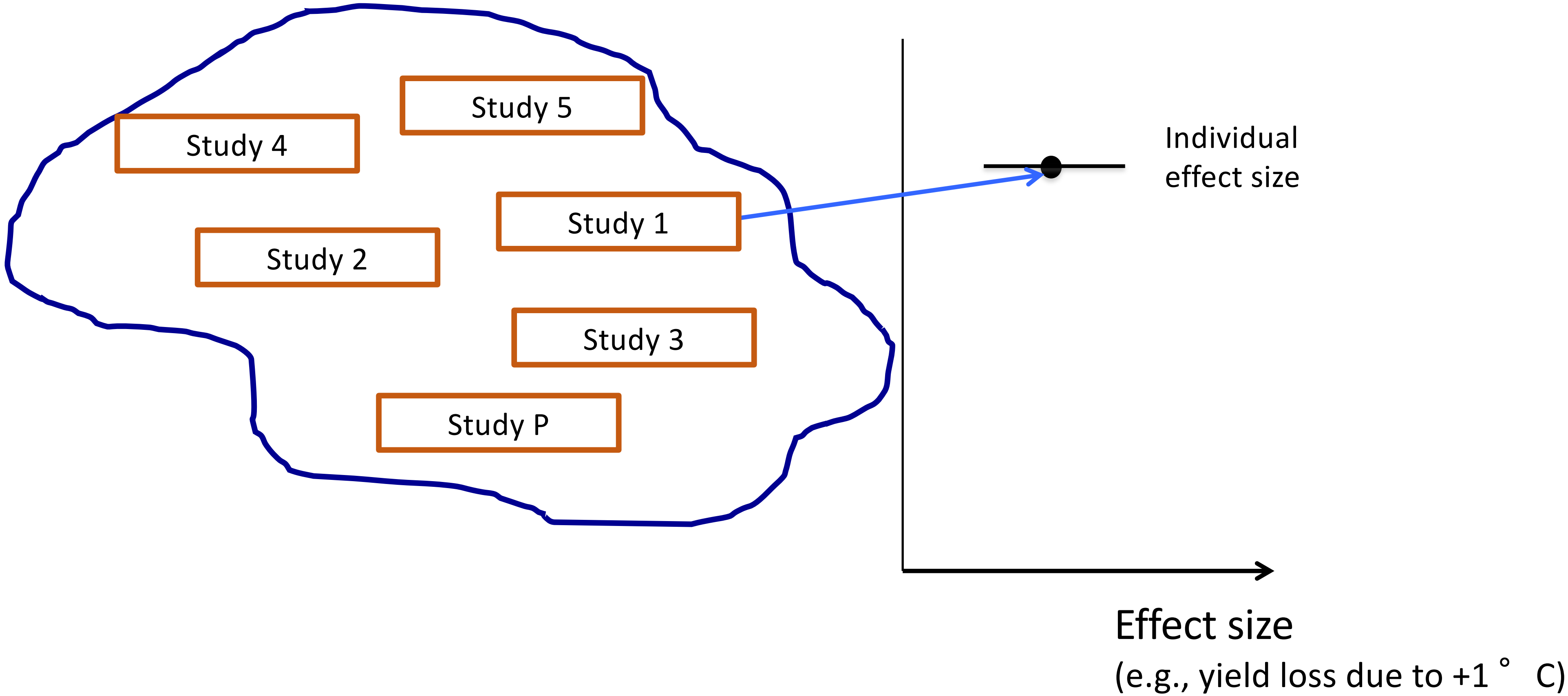
« The statistical analysis of a large collection of results from individual studies for the purpose of integrating the findings »

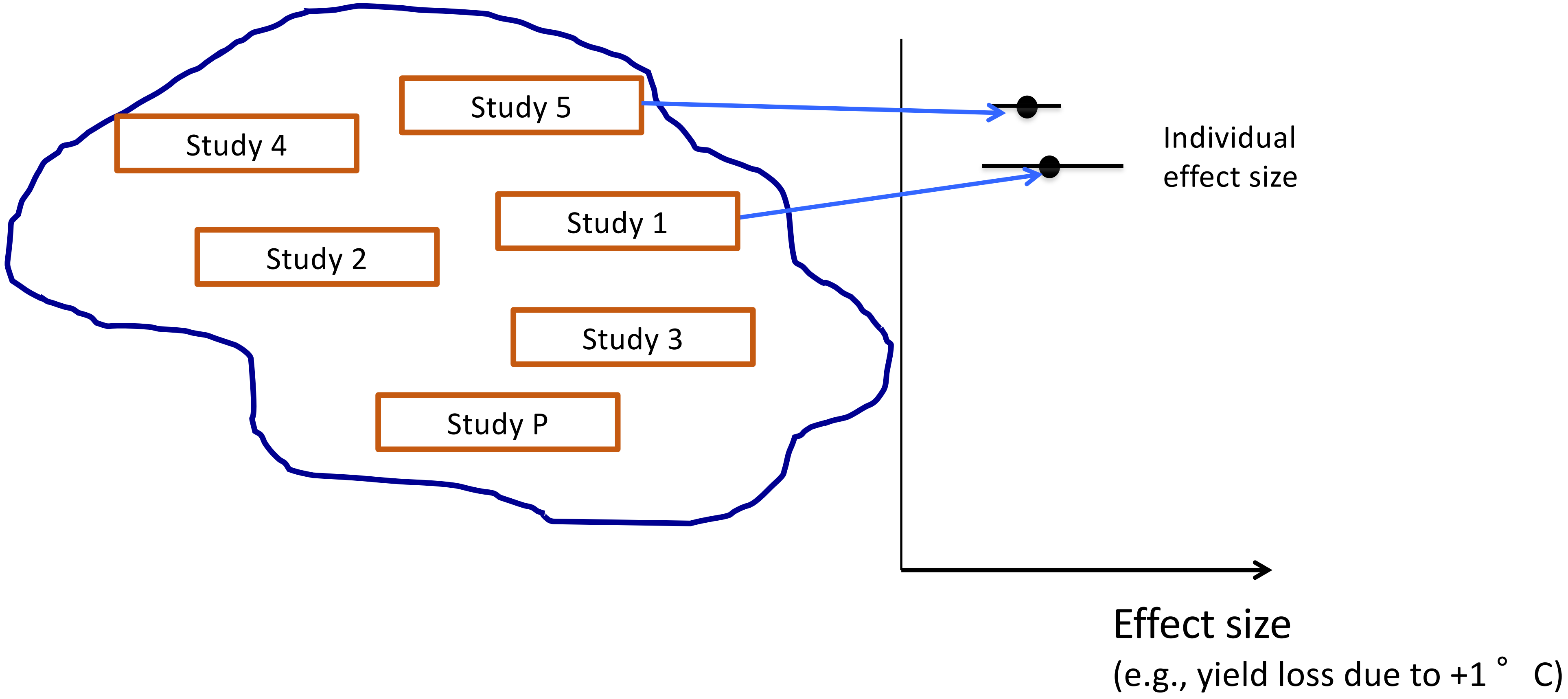
« Systematic review + statistical analysis »

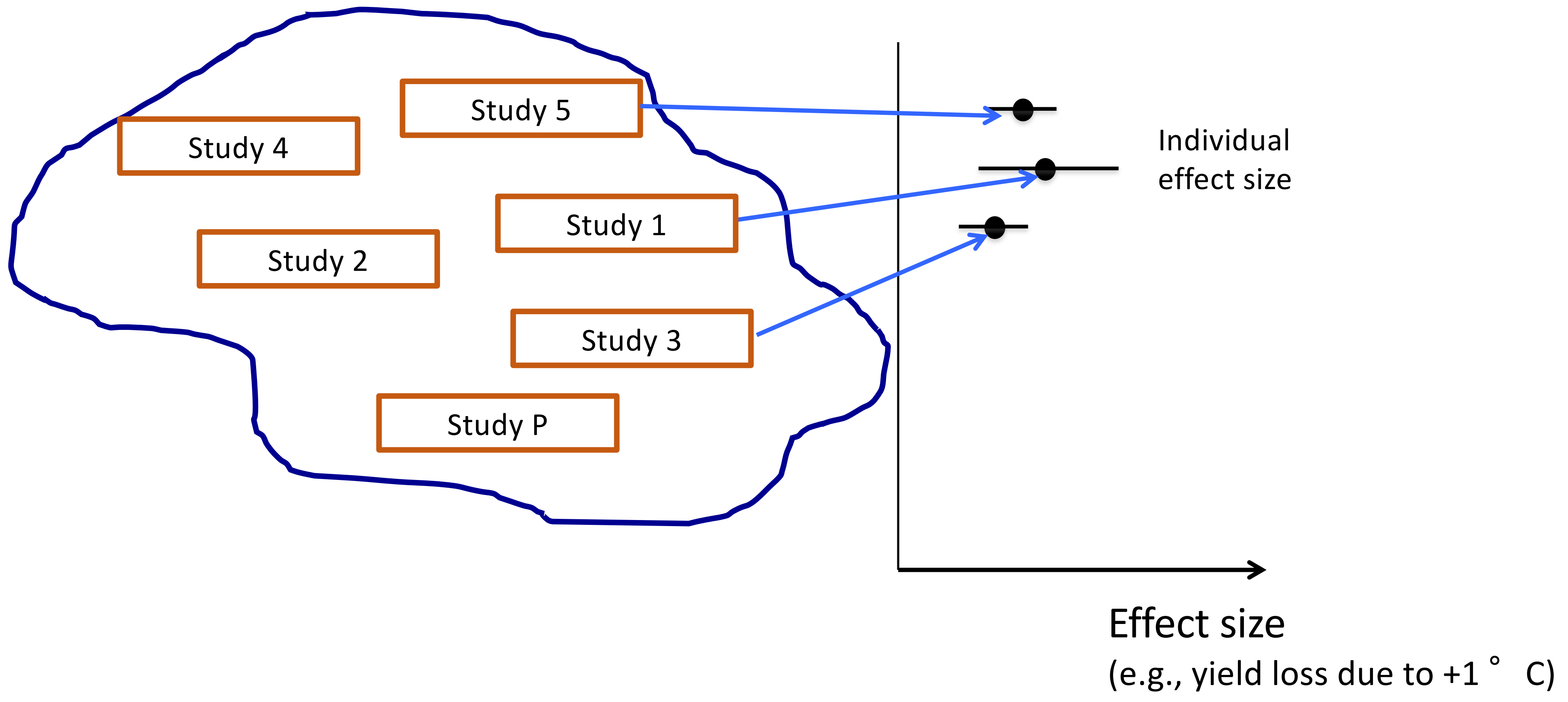
Dictionary of epidemiology, 2001; Chalmers et al., 2002; Glass, 1976; Koricheva et al., 2013

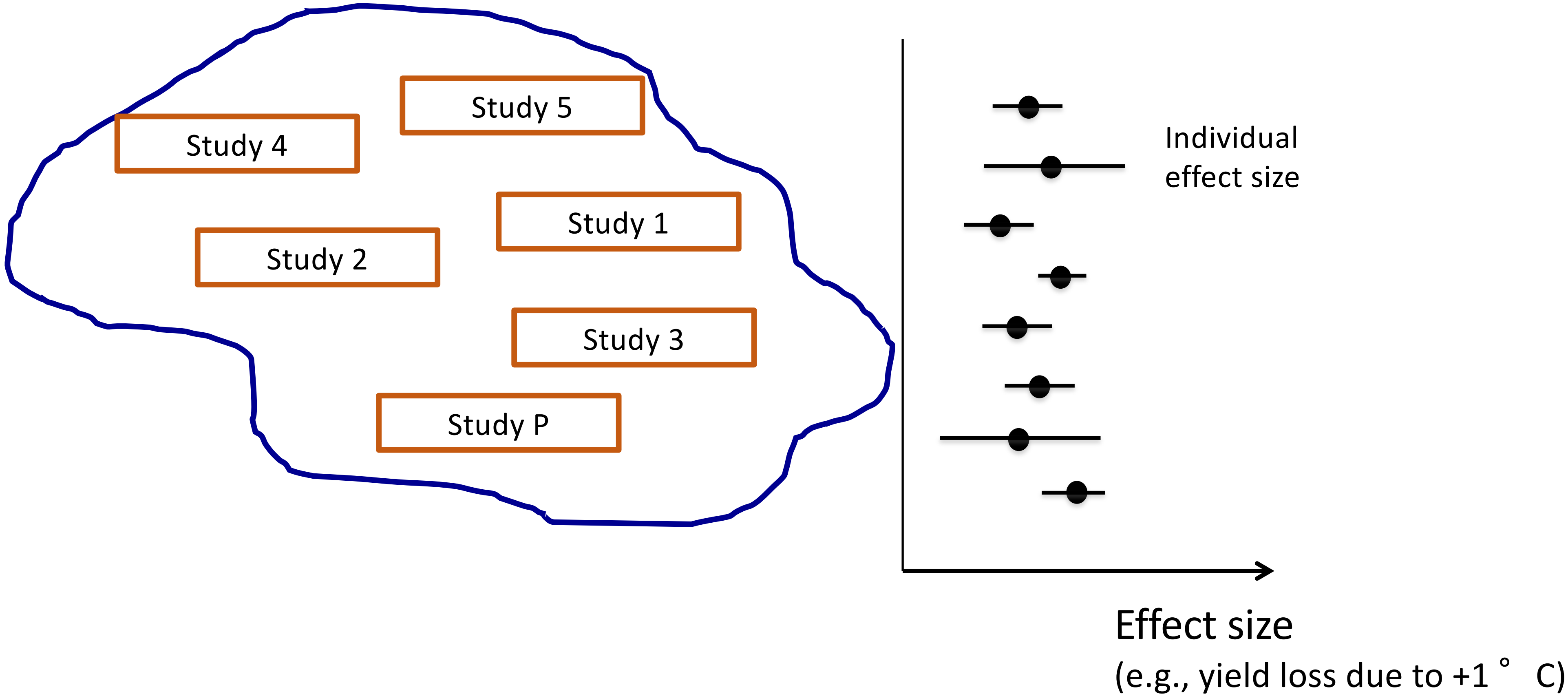


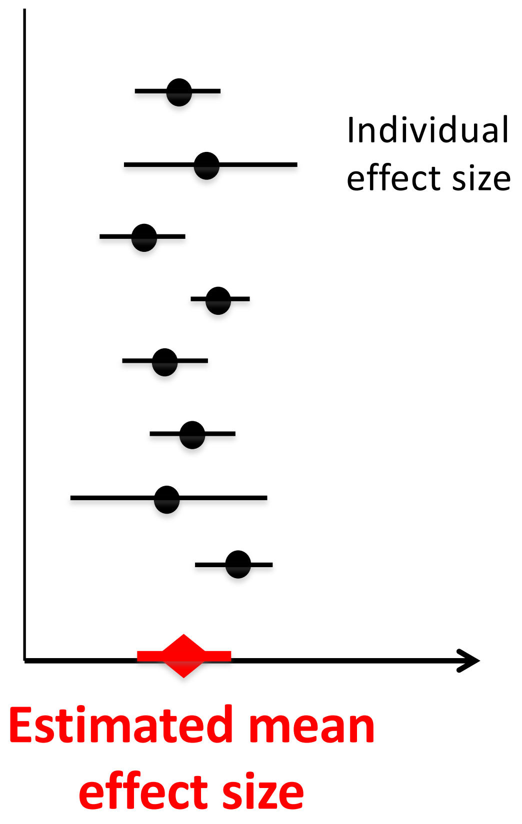
Set of studies dealing with a specific topic (e.g., %yield loss due to +1°C)

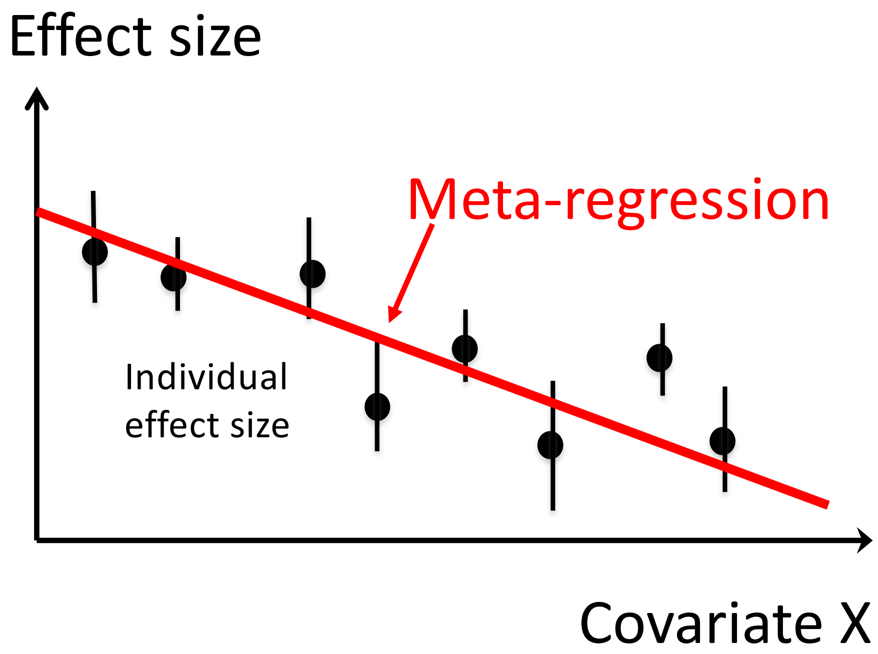

Study 5
Study 4
Study 1
Study 2
Study 3
Study P
Individual
effect size
Effect size
(e.g., yield loss due to +1 ° C)

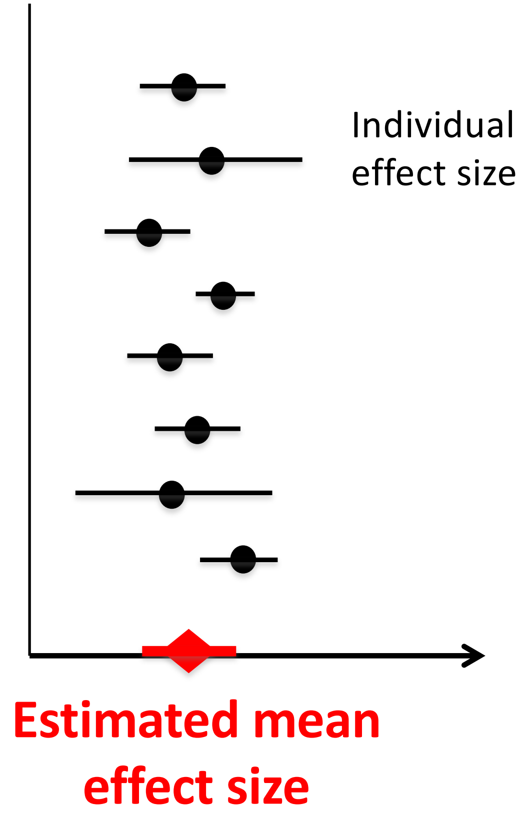

Study 5
Study 4
Study 1
Study 2
Study 3
Study P
Individual
effect size
Effect size
(e.g., yield loss due to +1 ° C)


Study 5
Study 4
Study 1
Study 2
Study 3
Study P
Individual effect size
Effect size
(e.g., yield loss due to +1 ° C)


Study 5
Study 4
Study 1
Study 2
Study 3
Study P
Individual effect size
Effect size
(e.g., yield loss due to +1 ° C)


Individual
effect size
Estimated mean
effect size


Effect size
Meta-regression
Individual
effect size
Covariate X


Individual
effect size
Estimated mean
effect size

Example: Assessment of the impact of temperature increase on crop yield

Two sources of information:

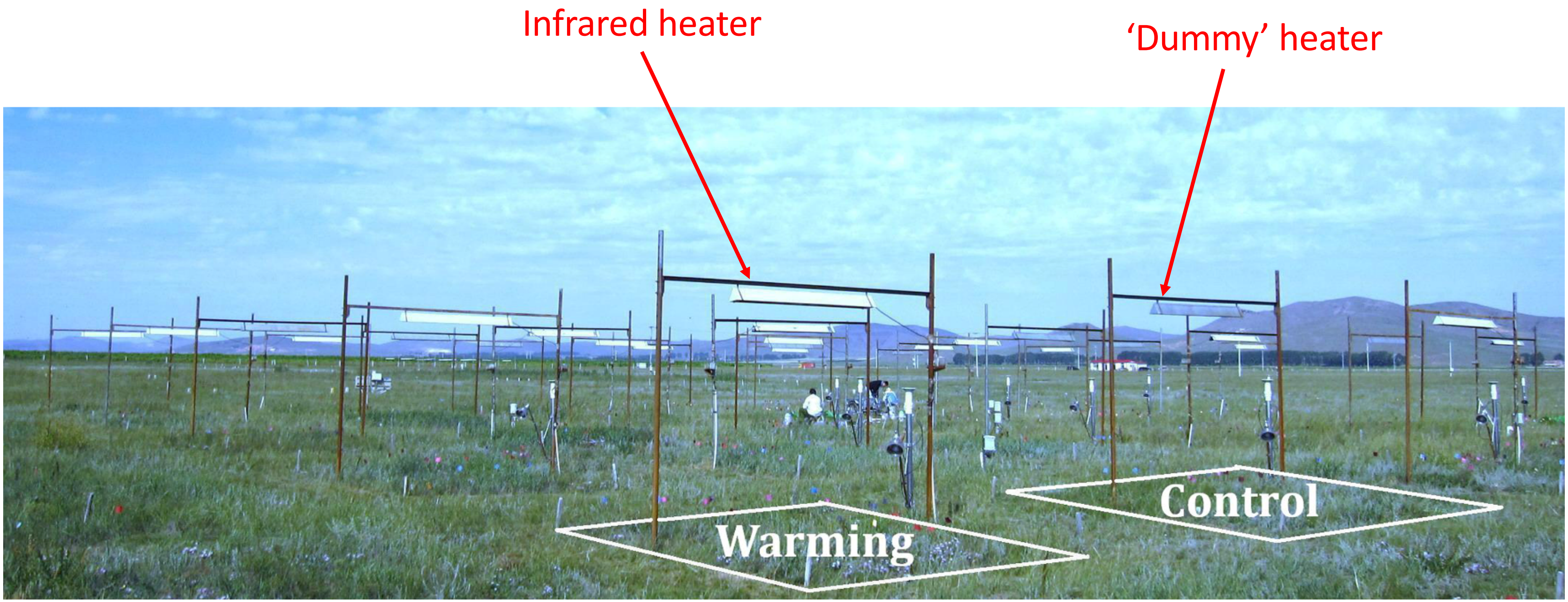
- Experiments
- Crop model simulations

Example: Assessment of the impact of temperature increase on crop yield

Two sources of information:

- **Experiments**
- Crop model simulations

Field warming experiment



from Chi et al. 2013 doi.org/10.1371/journal.pone.0056482

$$\Delta Y = (Yield_{warm} \text{-} Yield_{control})/Yield_{control}$$

$$Sensitivity = Yield\ \%\ change\ per\ {}^{\circ}\mathrm{C} = 100\,\frac{\Delta Y}{\Delta T}$$

nature COMMUNICATIONS

Article | OPEN | Published: 17 November 2016

Field warming experiments shed light on the wheat yield response to temperature in China

Chuang Zhao, Shilong Piao, Yao Huang, Xuhui Wang, Philippe Ciais, Mengtian Huang, Zhenzhong Zeng & Shushi Peng

Compilation of 46 results of field warming experiments located in 11 sites in China

Field experiment
Ambient CO_2

Objectives

- Estimate the mean yield sensitivity to +1°C
- Estimate the effect of the mean local temperature on the sensitivities
- Analyse uncertainties

Site_name	Lat	Long	Design	Temp_increase	Irrigtion_mm	Nitrogen_kgha	TGS	PGS	DGS	Sensitivity	Ref
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.3	393	8	11.1	1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.6	476	7.6	10.5	1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	11.6	341	8.3	14.5	1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.0	387	7.9	6.7	1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.5	325	8.1	11.8	1
Tongwei County	35.22	105.23	Heating cable	1.4	0	NA	5.7	288	6.6	2.21	2
Tongwei County	35.22	105.23	Heating cable	2.2	0	NA	5.7	288	6.6	1.18	2
Lulu Mountain	35.29	105.26	Heating cable	0.6	0	NA	5.7	288	6.6	0.83	2
Lulu Mountain	35.29	105.26	Heating cable	1.4	0	NA	5.7	288	6.6	2.57	2
Lulu Mountain	35.29	105.26	Heating cable	2.2	0	NA	5.7	288	6.6	2.73	2
Guyuan	36.03	106.46	Greenhouse	0.5	0	NA	12.4	97	11.2	-9.33	3
Guyuan	36.03	106.46	Greenhouse	1.2	0	NA	12.4	97	11.2	-11.03	3
Guyuan	36.03	106.46	Greenhouse	2.0	0	NA	12.4	97	11.2	-7.4	3
Guyuan	36.03	106.46	Greenhouse	0.5	60	NA	12.4	97	11.2	-11.84	3
Guyuan	36.03	106.46	Greenhouse	1.2	60	NA	12.4	97	11.2	-10.65	3
Guyuan	36.03	106.46	Greenhouse	2.0	60	NA	12.4	97	11.2	-6.78	3
Dingxing	39.13	115.66	Infrared heaters	2.9	500	210	8.9	77	9.3	-3.1	4
Dingxing	39.13	115.66	Infrared heaters	2.9	500	210	6.4	113	8.2	8.25	4
Xidatan	38.80	106.30	Infrared heaters	0.5	NA	136	14.3	23	12.2	-1.0	5
Xidatan	38.80	106.30	Infrared heaters	1.0	NA	136	14.3	23	12.2	-0.8	5
Xidatan	38.80	106.30	Infrared heaters	1.5	NA	136	14.3	23	12.2	-3.33	5
Xidatan	38.80	106.30	Infrared heaters	2.0	NA	136	14.3	23	12.2	-8.25	5
Xidatan	38.80	106.30	Infrared heaters	2.5	NA	136	14.3	23	12.2	-7.4	5
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	11.0	433	6.1	3.46	6
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	11.4	343	6.6	3.33	6
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	10.2	476	5.7	3.45	6
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.6	118	10	1.23	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.6	118	10	-2.54	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.8	160	8.8	-1.15	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.8	160	8.8	-4.69	7
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	0	7.9	372	7.3	12.92	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	150	7.9	372	7.3	6.31	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	225	7.9	372	7.3	2.95	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	300	7.9	372	7.3	5.82	8
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	9.6	131	9.5	-13.0	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	8.9	65	9.8	-13.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	8.8	153	8.6	-6.0	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	9.6	131	9.5	-12.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	8.9	65	9.8	-3.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	8.8	153	8.6	-4.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	7.3	167	8.5	15.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	7.3	167	8.5	0.5	9
Dingxi	35.58	104.62	Infrared heaters	1.0	0	NA	13.6	171	8.6	-8.37	10
Dingxi	35.58	104.62	Infrared heaters	2.0	0	NA	13.6	171	8.6	-7.55	10
Dingxi	35.58	104.62	Infrared heaters	3.0	0	NA	13.6	171	8.6	-7.27	10

Site_name	Lat	Long	Design	Temp_increase	Irrigtion_mm	Nitrogen_kgha	TGS	PGS	DGS	Sensitivity	Ref
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.3	393	8	11.1	1
Study 1											1
											1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.0	387	7.9	6.7	1
Nanjing	32.03	118.86	Infrared heaters	1.5	0	225	10.5	325	8.1	11.8	1
Study 2											2
											2
Lulu Mountain	35.29	105.26	Heating cable	[illegible]	0	NA	5.7	288	6.6	[illegible]	2
Lulu Mountain	35.29	105.26	Heating cable	1.4	0	NA	5.7	288	6.6	2.57	2
Lulu Mountain	35.29	105.26	Heating cable	2.2	0	NA	5.7	288	6.6	2.73	2
Guyuan	36.03	106.46	Greenhouse	0.5	0	NA	12.4	97	11.2	-9.33	3
Guyuan	36.03	106.46	Greenhouse	1.2	0	NA	12.4	97	11.2	-11.03	3
Guyuan	36.03	106.46	Greenhouse	2.0	0	NA	12.4	97	11.2	-7.4	3
Guyuan	36.03	106.46	Greenhouse	0.5	60	NA	12.4	97	11.2	-11.84	3
Guyuan	36.03	106.46	Greenhouse	1.2	60	NA	12.4	97	11.2	-10.65	3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3
...											4
											4
Xidatan	38.80	106.30	Infrared heaters	0.5	NA	136	14.3	23	12.2	-1.0	5
Xidatan	38.80	106.30	Infrared heaters	1.0	NA	136	14.3	23	12.2	-0.8	5
Xidatan	38.80	106.30	Infrared heaters	1.5	NA	136	14.3	23	12.2	-3.33	5
Xidatan	38.80	106.30	Infrared heaters	2.0	NA	136	14.3	23	12.2	-8.25	5
Xidatan	38.80	106.30	Infrared heaters	2.5	NA	136	14.3	23	12.2	-7.4	5
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	11.0	433	6.1	3.46	6
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	11.4	343	6.6	3.33	6
Shanghai	31.21	121.13	Infrared heaters	1.5	NA	NA	10.2	476	5.7	3.45	6
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.6	118	10	1.23	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.6	118	10	-2.54	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.8	160	8.8	-1.15	7
Yucheng	36.83	116.57	Infrared heaters	1.3	150	285	8.8	160	8.8	-4.69	7
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	0	7.9	372	7.3	12.92	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	150	7.9	372	7.3	6.31	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	225	7.9	372	7.3	2.95	8
Lianyungang	34.55	119.39	Infrared heaters	2.2	0	300	7.9	372	7.3	5.82	8
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	9.6	131	9.5	-13.0	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	8.9	65	9.8	-13.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	8.8	153	8.6	-6.0	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	9.6	131	9.5	-12.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	8.9	65	9.8	-3.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	8.8	153	8.6	-4.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	240	7.3	167	8.5	15.5	9
Luancheng	37.88	114.68	Infrared heaters	2.0	160	0	7.3	167	8.5	0.5	9
Dingxi	35.58	104.62	Infrared heaters	1.0	0	NA	13.6	171	8.6	-8.37	10
Dingxi	35.58	104.62	Infrared heaters	2.0	0	NA	13.6	171	8.6	-7.55	10
Dingxi	35.58	104.62	Infrared heaters	3.0	0	NA	13.6	171	8.6	-7.27	10

Steps

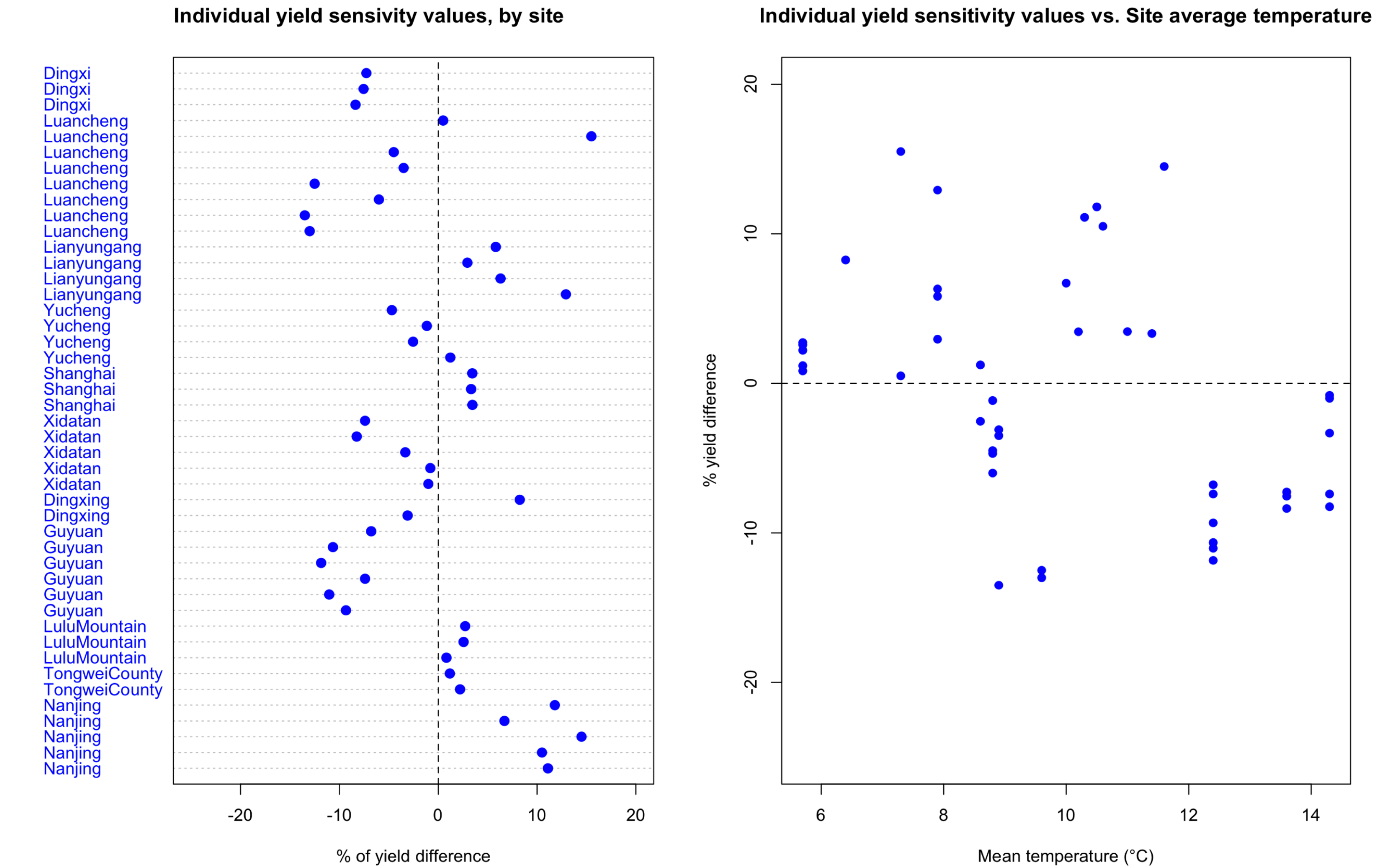
- Explore the dataset
- Define and fit Bayesian models
- Conclude

Steps

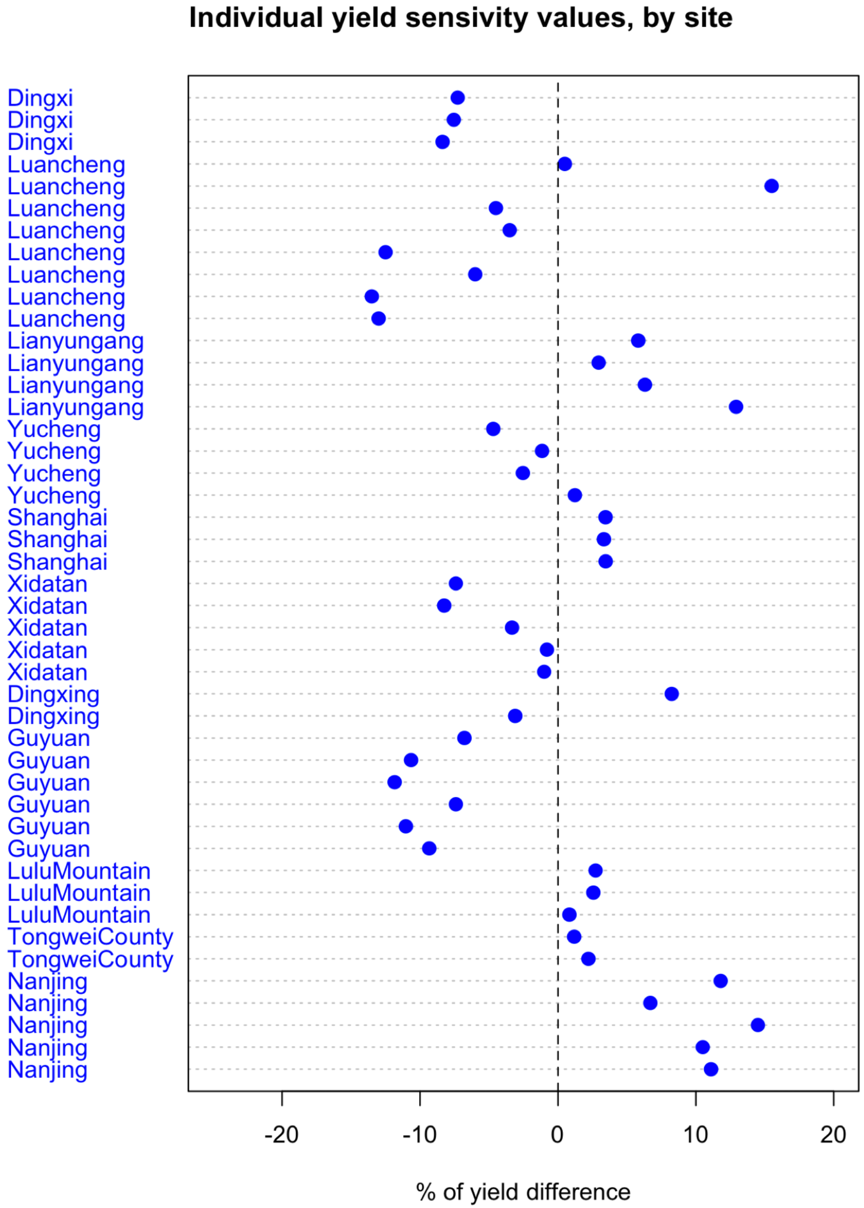
- Explore the dataset
- Define and fit Bayesian models
- Conclude

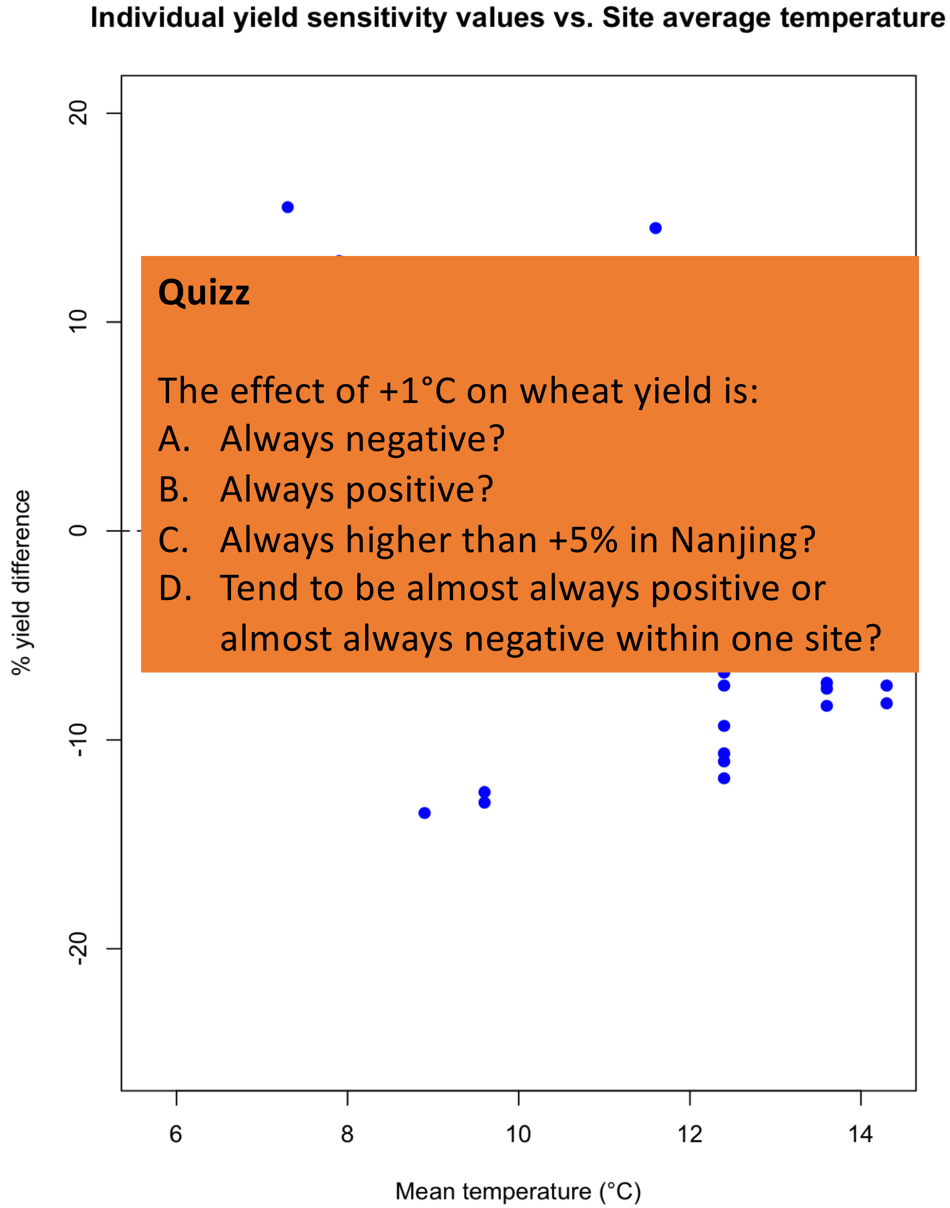
Open and run **Atelier2020_1.R**

```
      Wheat_type          Site_name          Lat              Long                      Design     Temp_increase  Irrigtion_mm    Nitrogen_kgha        TGS              PGS     
 Springwheat:14   Luancheng  : 8   Min.   :31.21   Min.   :104.6   Greenhouse     : 6   Min.   :0.5   Min.   :  0.0   Min.   :  0.0   Min.   : 5.70   Min.   : 23  
 Winterwheat:31   Guyuan     : 6   1st Qu.:34.55   1st Qu.:106.3   Heatingcable   : 5   1st Qu.:1.3   1st Qu.:  0.0   1st Qu.:136.0   1st Qu.: 7.90   1st Qu.: 97  
                  Nanjing    : 5   Median :36.03   Median :114.7   Infraredheaters:34   Median :1.5   Median :  0.0   Median :225.0   Median : 9.60   Median :160  
                  Xidatan    : 5   Mean   :35.86   Mean   :112.5                        Mean   :1.7   Mean   : 82.7   Mean   :178.6   Mean   :10.04   Mean   :202  
                  Lianyungang: 4   3rd Qu.:37.88   3rd Qu.:118.9                        3rd Qu.:2.0   3rd Qu.:160.0   3rd Qu.:240.0   3rd Qu.:12.40   3rd Qu.:325  
                  Yucheng    : 4   Max.   :39.13   Max.   :121.1                        Max.   :3.0   Max.   :500.0   Max.   :300.0   Max.   :14.30   Max.   :476  
                  (Other)    :13                                                                      NA's   :8       NA's   :17                                     
      DGS          Sensitivity            Ref        
 Min.   : 5.700   Min.   :-13.5000   Min.   : 1.000  
 1st Qu.: 7.300   1st Qu.: -7.4000   1st Qu.: 3.000  
 Median : 8.600   Median : -1.0000   Median : 5.000  
 Mean   : 8.942   Mean   : -0.8364   Mean   : 5.467  
 3rd Qu.:10.000   3rd Qu.:  3.4500   3rd Qu.: 8.000  
 Max.   :12.200   Max.   : 15.5000   Max.   :10.000  
```



Individual yield sensivity values, by site
Dingxi
Dingxi
Dingxi
Luancheng
Luancheng
Luancheng
Luancheng
Luancheng
Luancheng
Luancheng
Luancheng
Lianyungang
Lianyungang
Lianyungang
Lianyungang
Yucheng
Yucheng
Yucheng
Yucheng
Shanghai
Shanghai
Shanghai
Xidatan
Xidatan
Xidatan
Xidatan
Xidatan
Dingxing
Dingxing
Guyuan
Guyuan
Guyuan
Guyuan
Guyuan
Guyuan
LuluMountain
LuluMountain
LuluMountain
TongweiCounty
TongweiCounty
Nanjing
Nanjing
Nanjing
Nanjing
Nanjing
-20
-10
0
10
20
% of yield difference
Individual yield sensitivity values vs. Site average temperature
20
10
0
-10
-20
% yield difference
6
8
10
12
14
Mean temperature (°C)

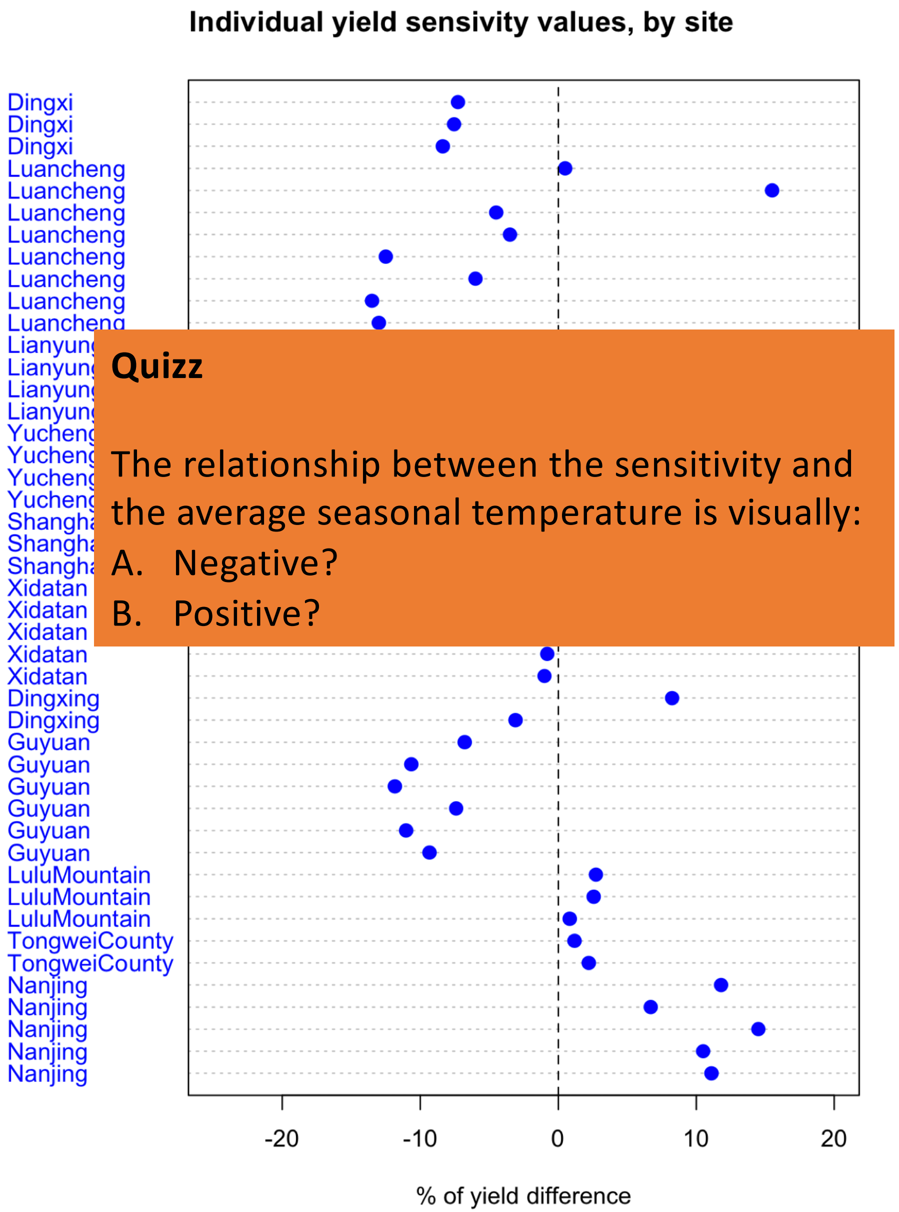




Quizz

The effect of +1°C on wheat yield is:

A. Always negative?
B. Always positive?
C. Always higher than +5% in Nanjing?
D. Tend to be almost always positive or almost always negative within one site?

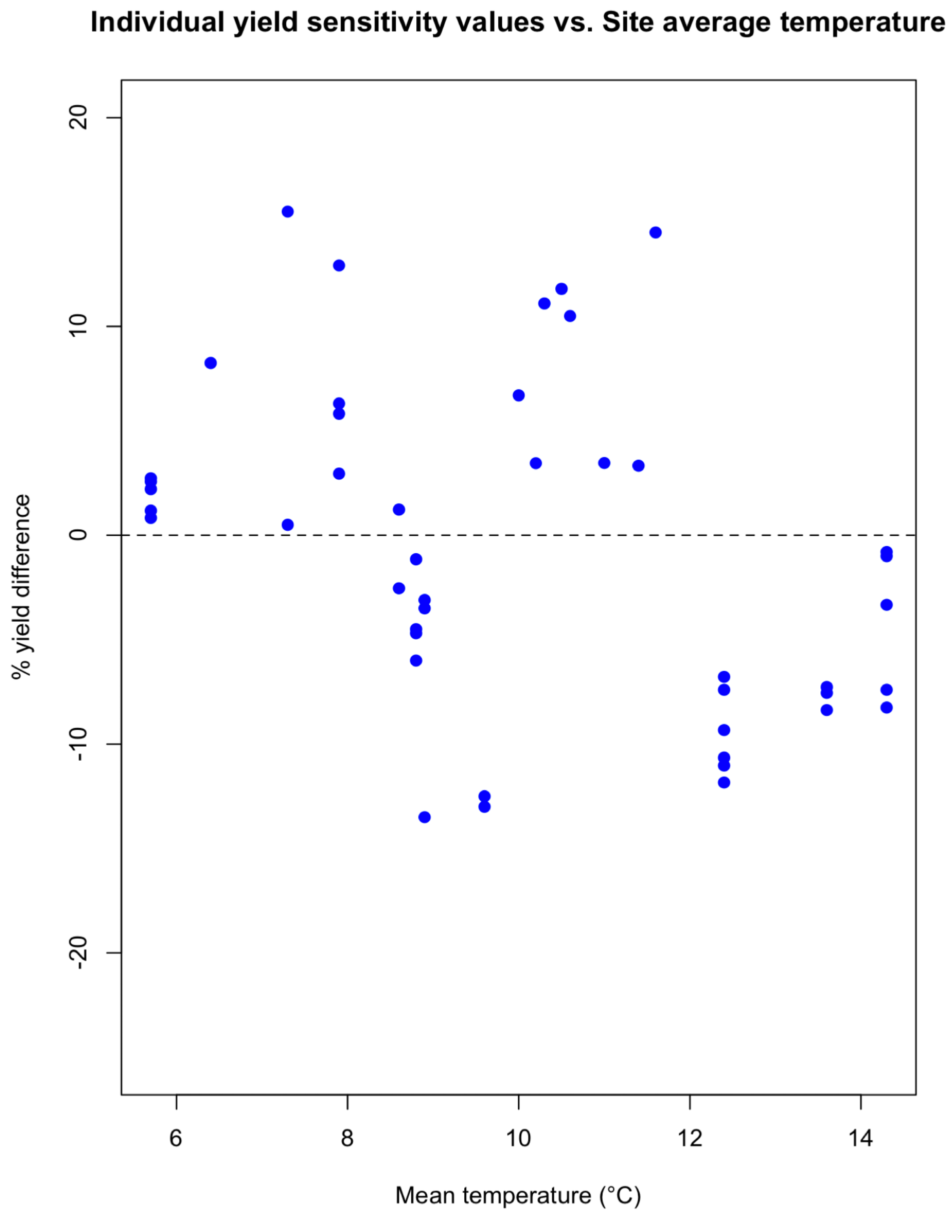


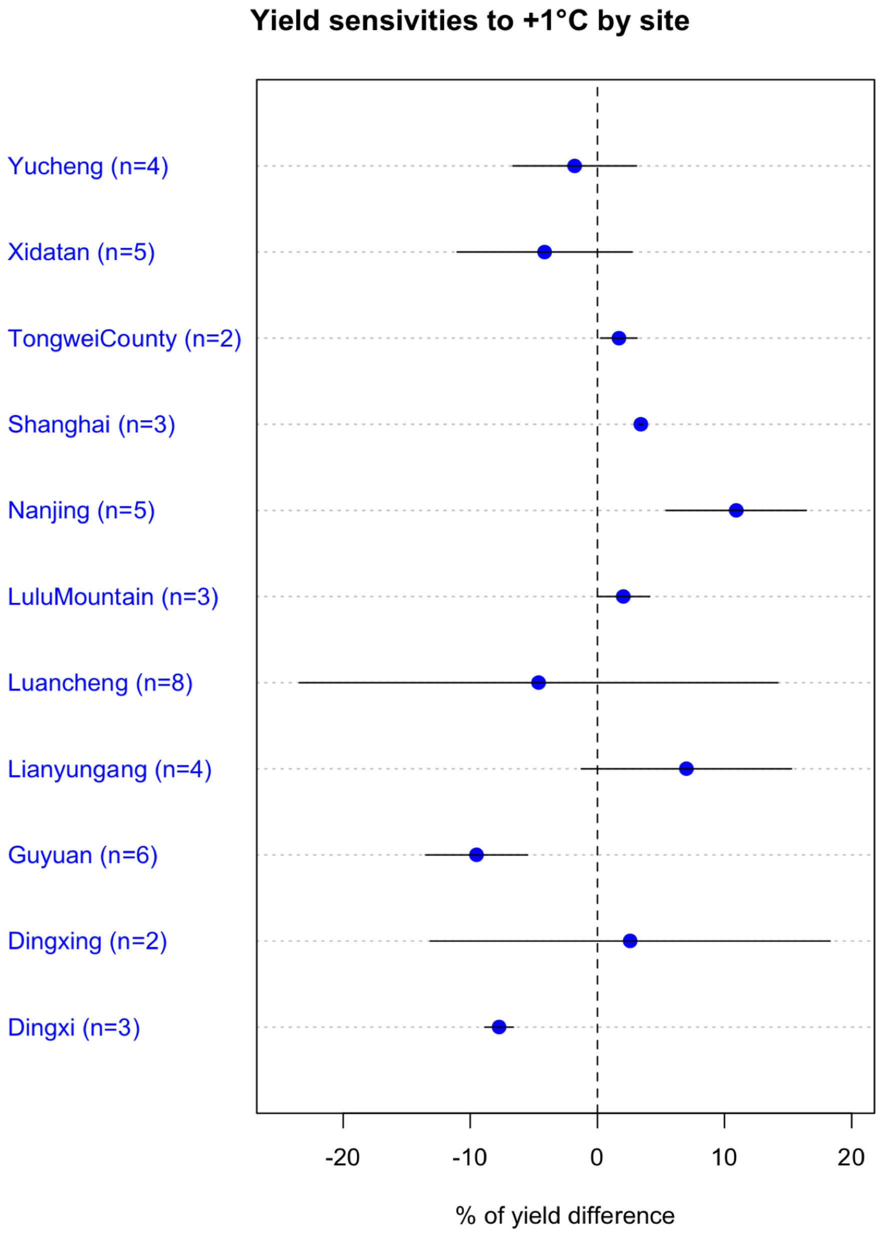
Quizz

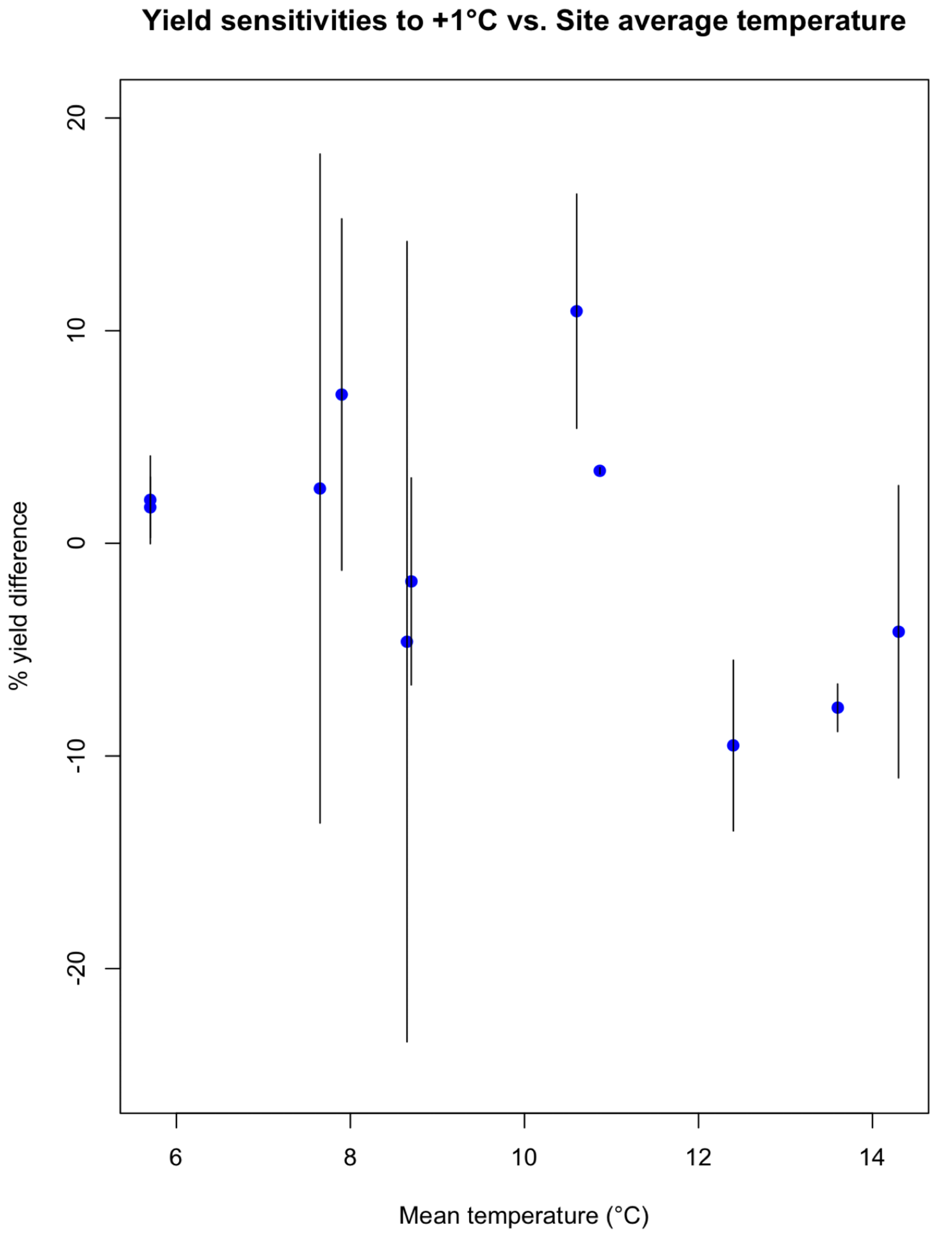
The relationship between the sensitivity and the average seasonal temperature is visually:

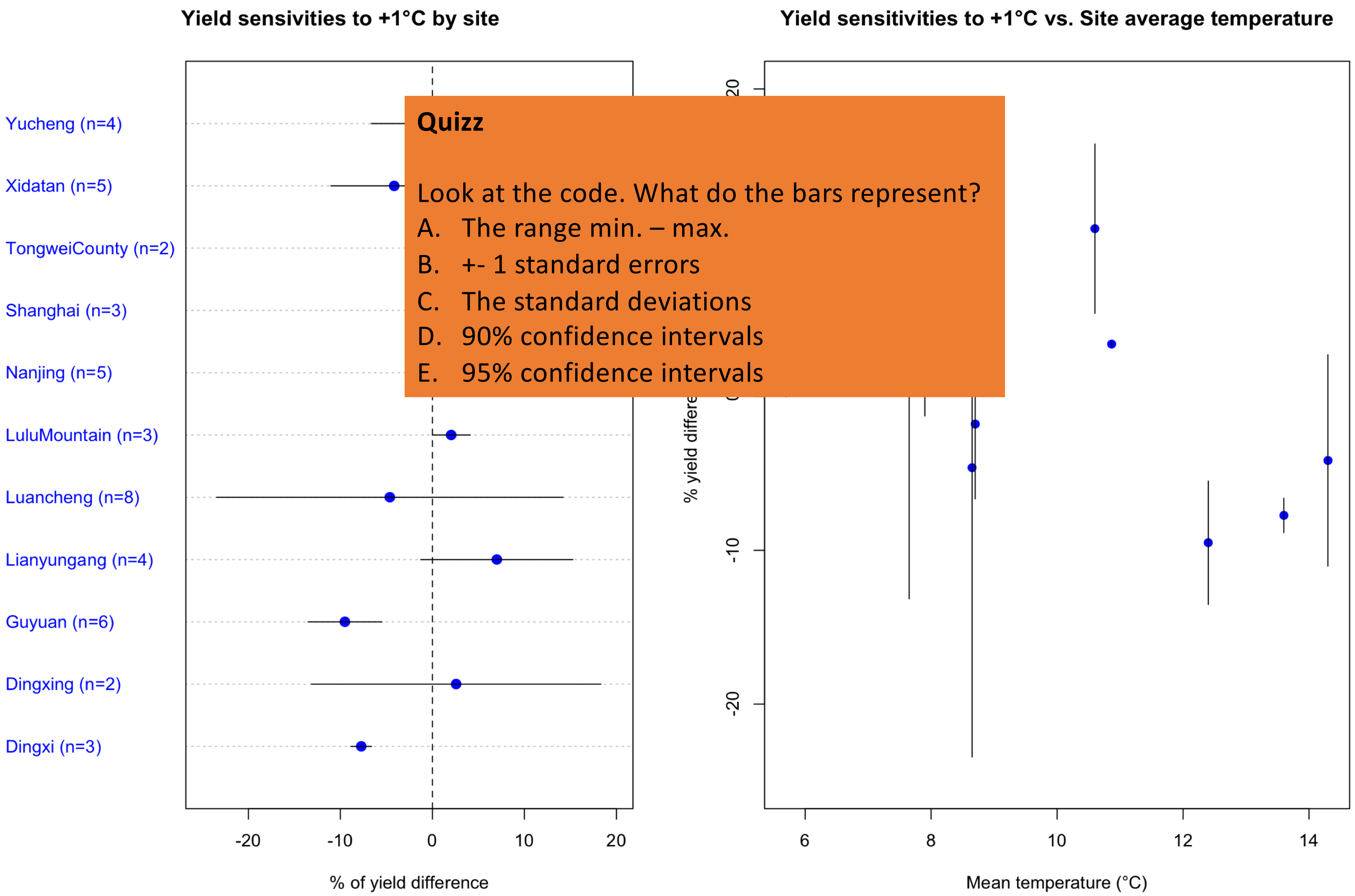
A. Negative?

B. Positive?




Yield sensitivities to +1°C by site
Yucheng (n=4)
Xidatan (n=5)
TongweiCounty (n=2)
Shanghai (n=3)
Nanjing (n=5)
LuluMountain (n=3)
Luancheng (n=8)
Lianyungang (n=4)
Guyuan (n=6)
Dingxing (n=2)
Dingxi (n=3)
-20
-10
0
10
20
% of yield difference

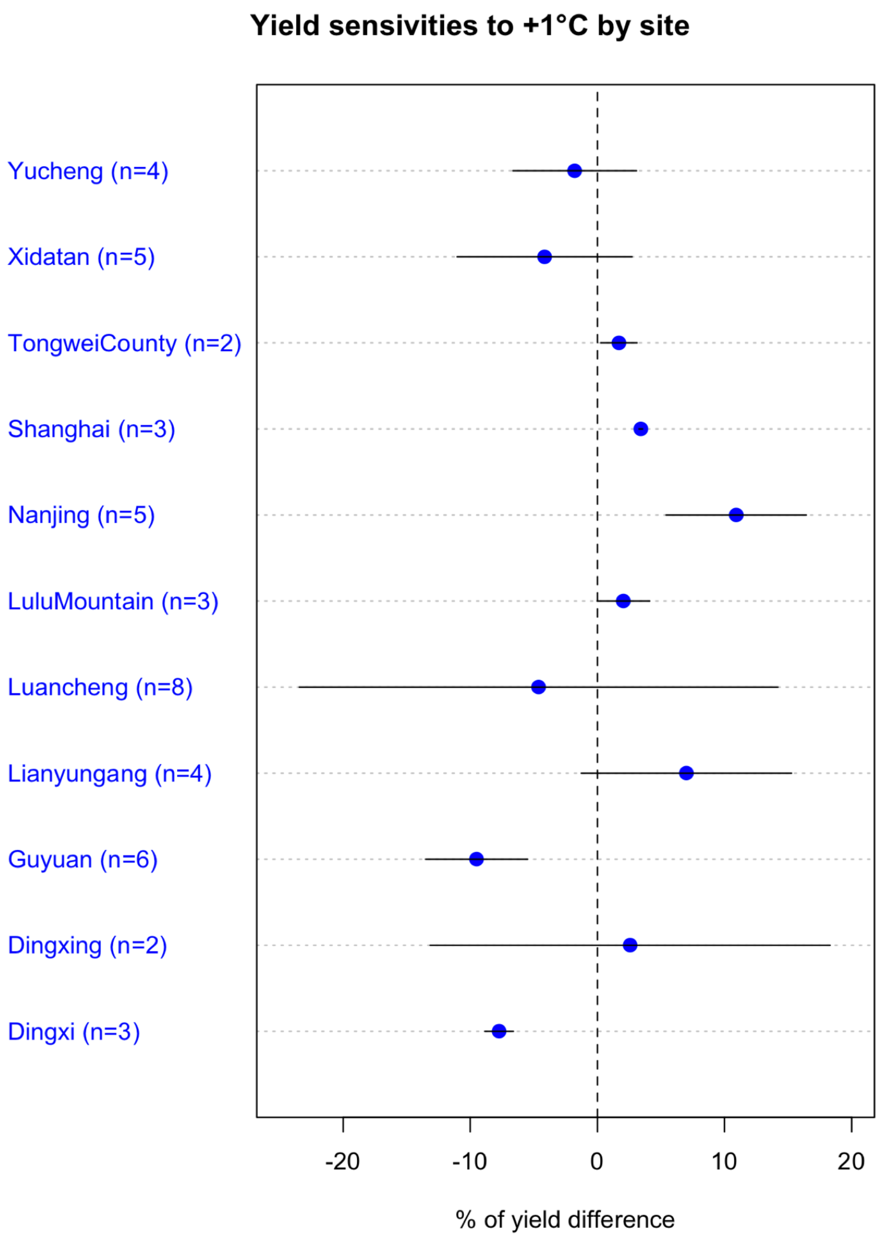

Yield sensitivities to +1°C vs. Site average temperature
20
10
0
-10
-20
% yield difference
6
8
10
12
14
Mean temperature (°C)

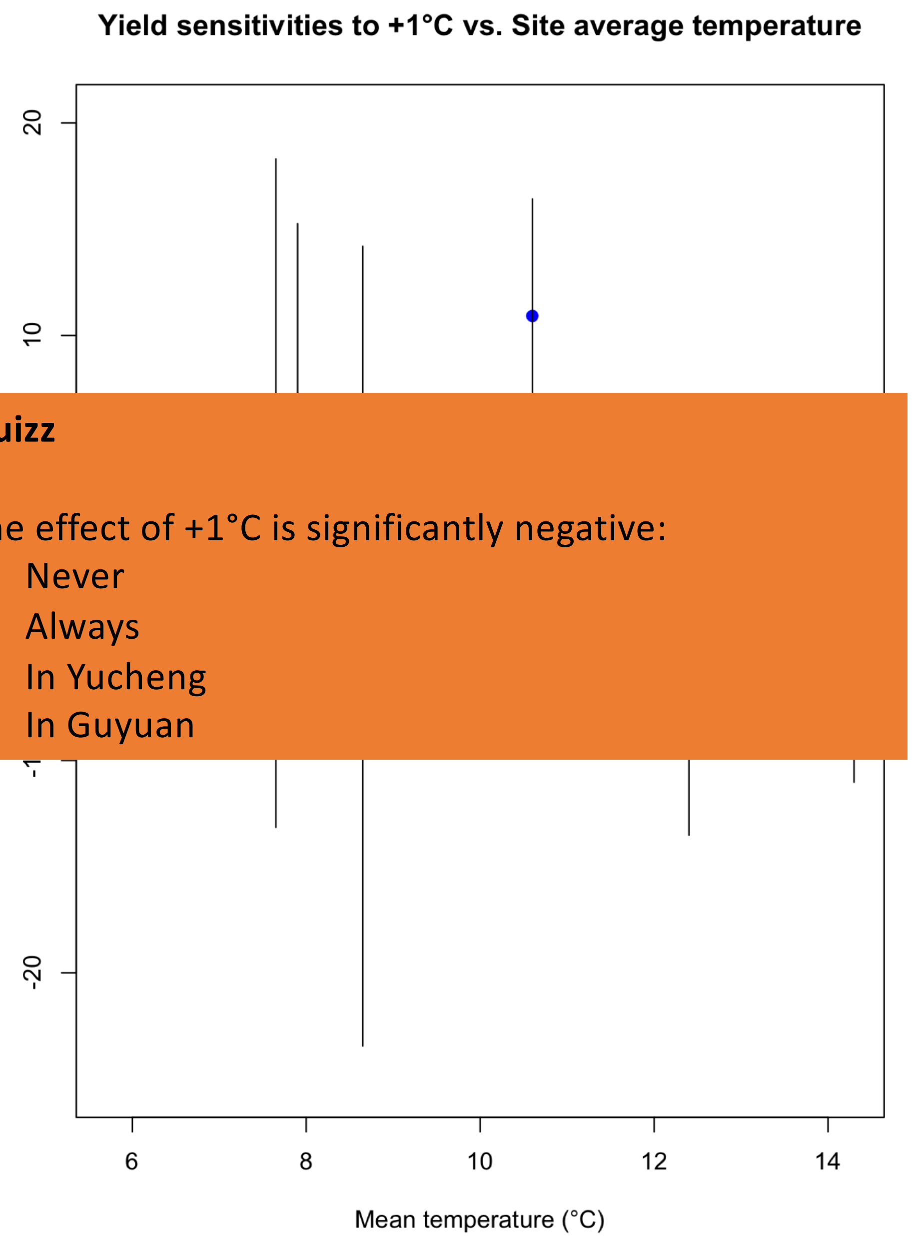


Quizz

Look at the code. What do the bars represent?

A. The range min. – max.
B. +- 1 standard errors
C. The standard deviations
D. 90% confidence intervals
E. 95% confidence intervals

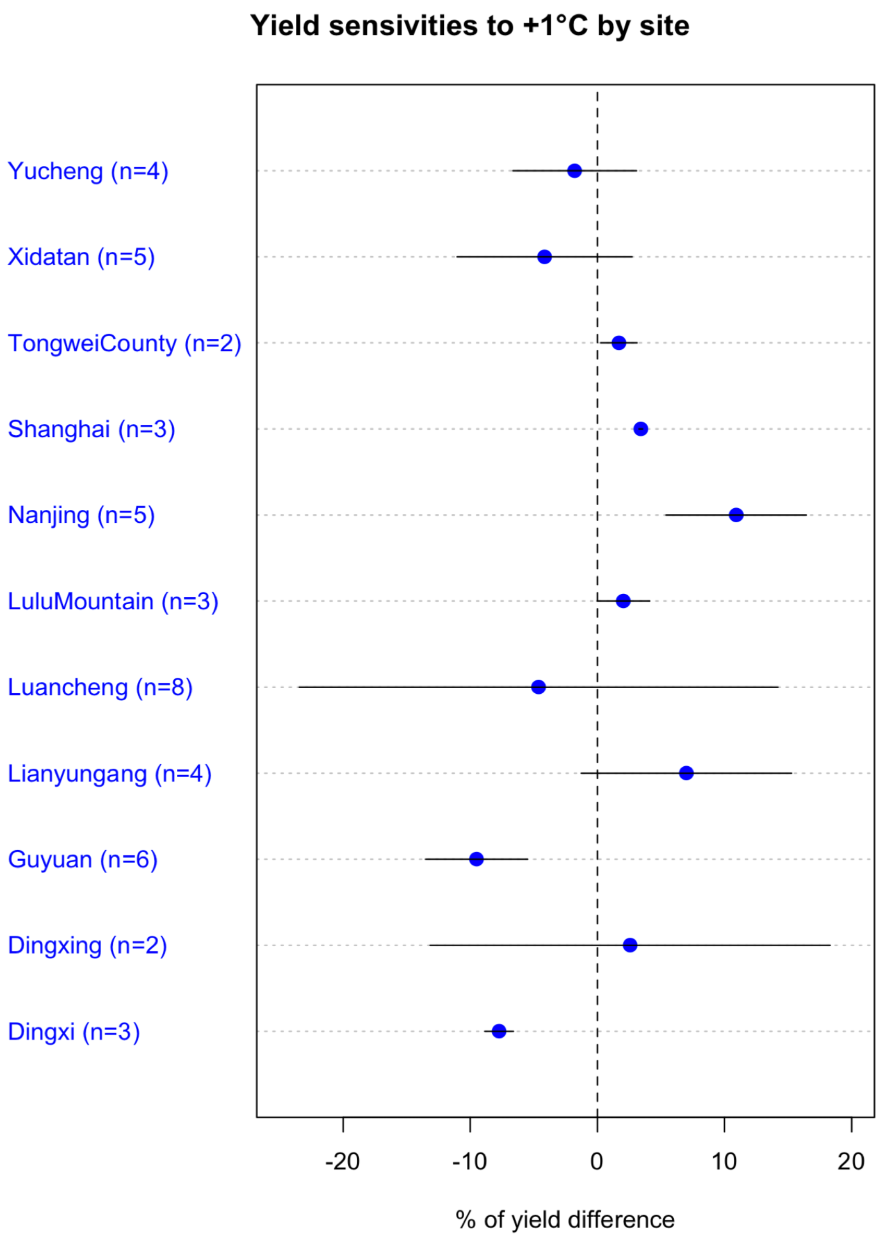


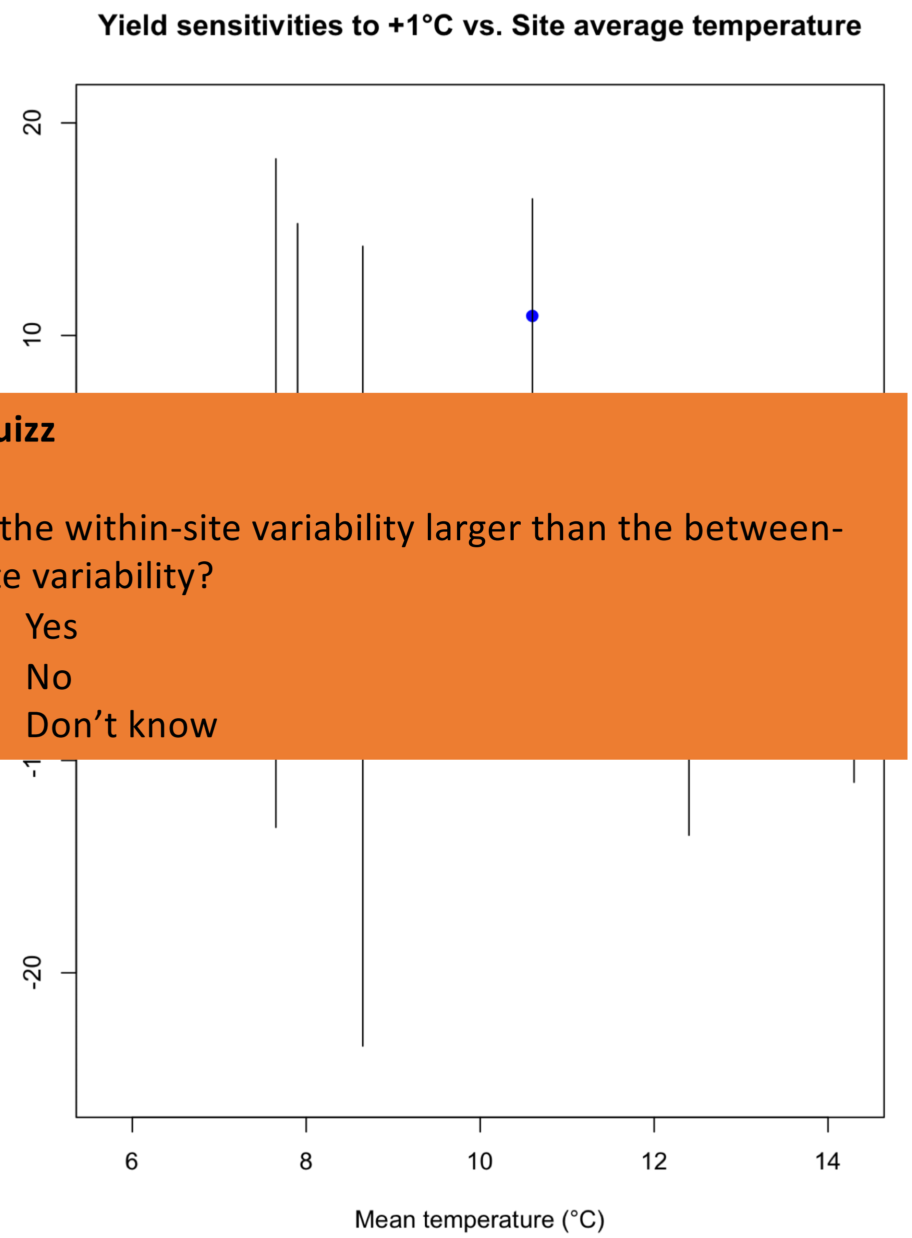


Quizz

The effect of +1°C is significantly negative:

A. Never
B. Always
C. In Yucheng
D. In Guyuan

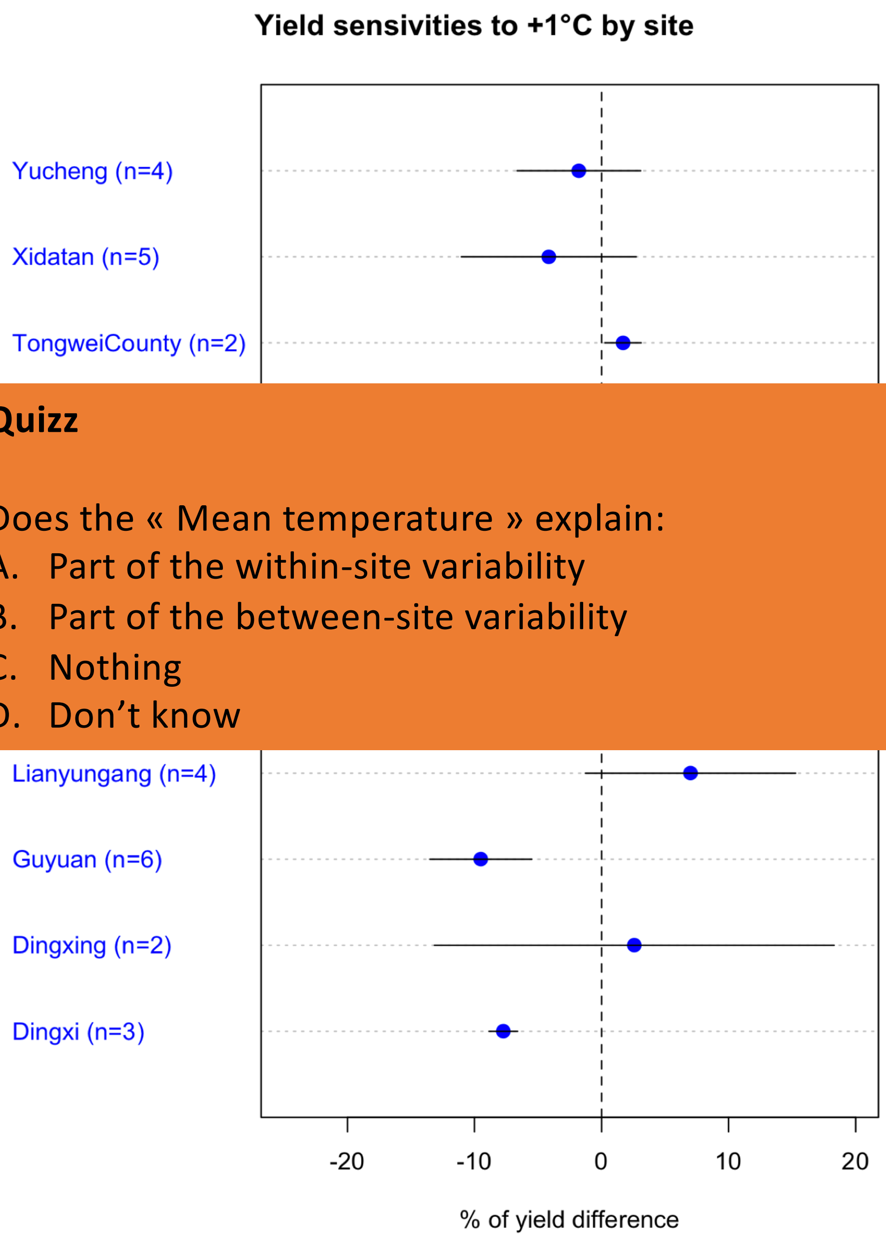




Quizz

Is the within-site variability larger than the between-site variability?

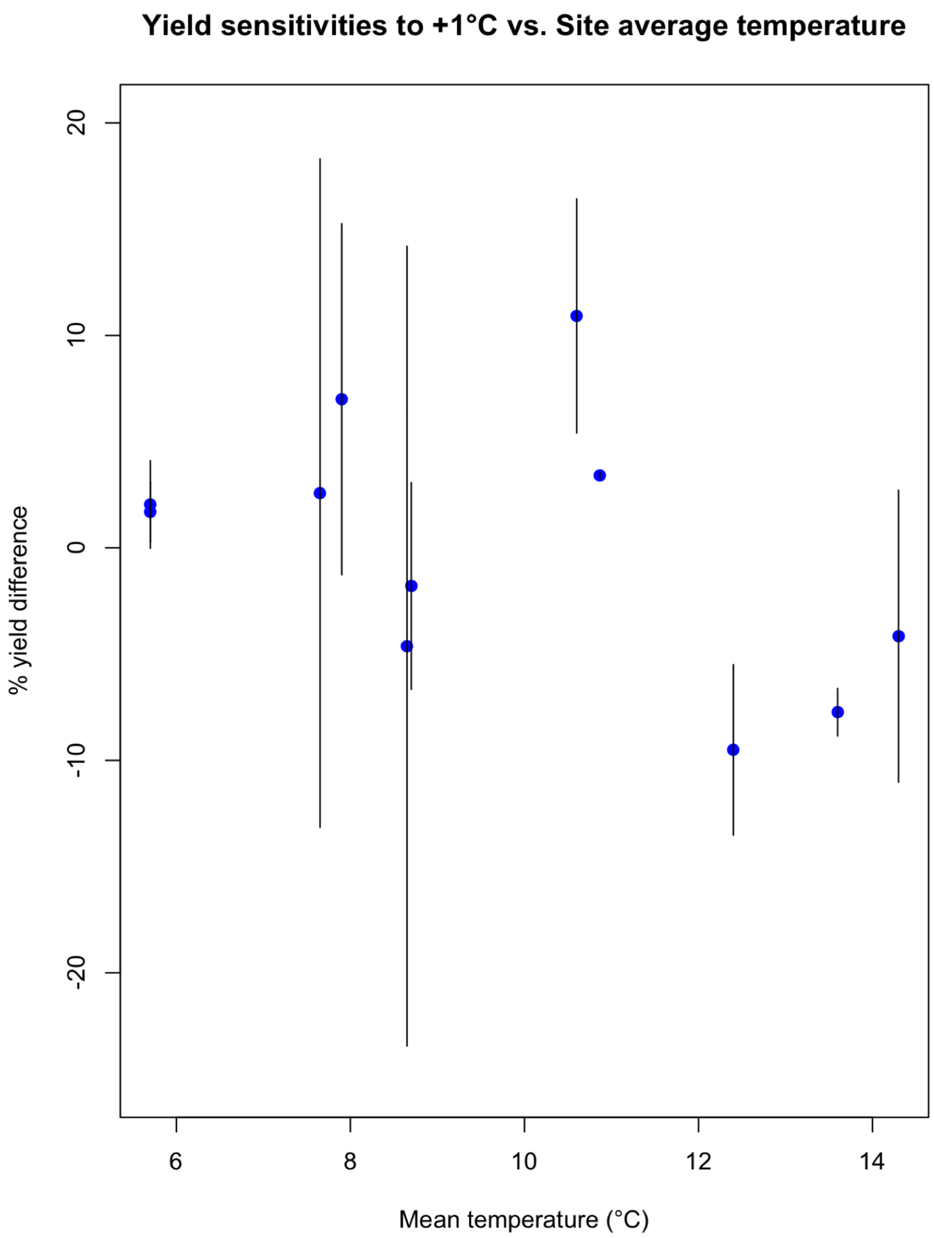
A. Yes
B. No
C. Don't know



Quizz

Does the « Mean temperature » explain:

A. Part of the within-site variability
B. Part of the between-site variability
C. Nothing
D. Don't know



Steps

- Explore the dataset
- Define and fit Bayesian models
- Conclude

Hierarchical statistical model
« Random-effect model »

Overall mean

Effect of study i

Within-study level: $S_{ij} = \mu + b_i + \varepsilon_{ij}$ $\varepsilon_{ij} \sim N\left(0, \sigma_{\varepsilon i}^2\right)$

Yield sensitivity in study i, replicate j

Residual for jth data in study i

Hierarchical statistical model
« Random-effect model »

Overall mean

Effect of study i

Within-study level: $S_{ij} = \mu + b_i + \varepsilon_{ij}$ $\varepsilon_{ij} \sim N\left(0, \sigma_{\varepsilon i}^2\right)$

Yield sensitivity in study i, replicate j

Residual for jth data in study i

Between-study level: $b_i \sim N\left(0, \sigma_b^2\right)$

Prior: Gaussian and Uniform

Hierarchical statistical model « Random-effect model »

Overall mean

Effect of study i

Within-study level: $S_{ij} = \mu + b_i + \varepsilon_{ij}$ $\qquad \varepsilon_{ij} \sim N\left(0, \sigma_{\varepsilon i}^2\right)$

Yield sensitivity in study i, replicate j

Residual for jth data in study i

Between-study level: $b_i \sim N\left(0, \sigma_b^2\right)$

Prior: Gaussian and Uniform

Fitting algorithm: MCMC

Hierarchical statistical model (with covariate)
« Random-effect model »

Covariate value for study i replicate j

Within-study level: $S_{ij} = \mu + \alpha X_{ij} + b_i + \varepsilon_{ij}$ $\varepsilon_{ij} \sim N\left(0, \sigma^2_{\varepsilon i}\right)$

Yield sensitivity in
study i, replicate j

Between-study level: $b_i \sim N\left(0, \sigma^2_b\right)$

Prior: Gaussian and Uniform

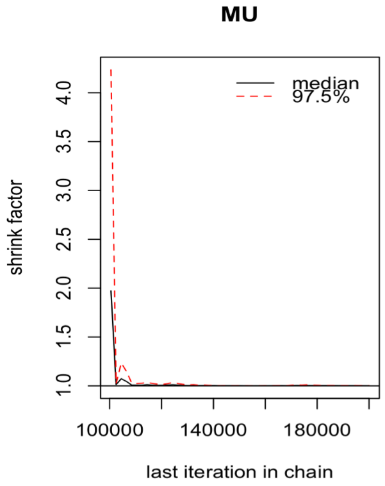
Fitting algorithm: MCMC

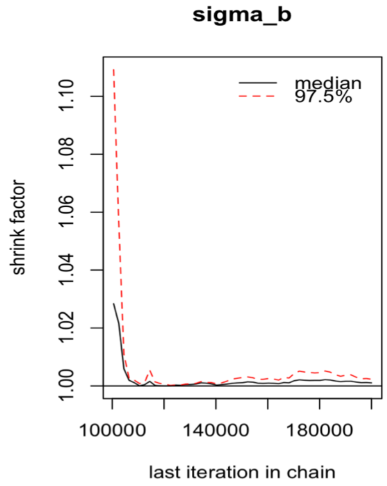
Open **Atelier2020_2.R**

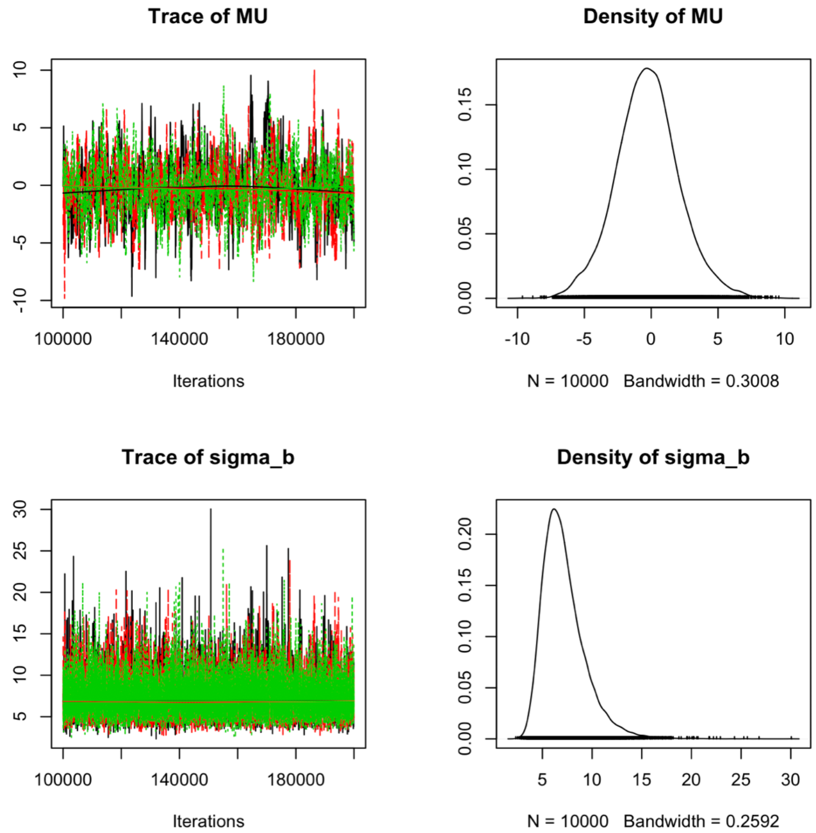
This file includes four Bayesian models coded with rjags.

- What are the differences between these models?
- Which one is the simplest?
- Which one is the most complex?

Run model 1



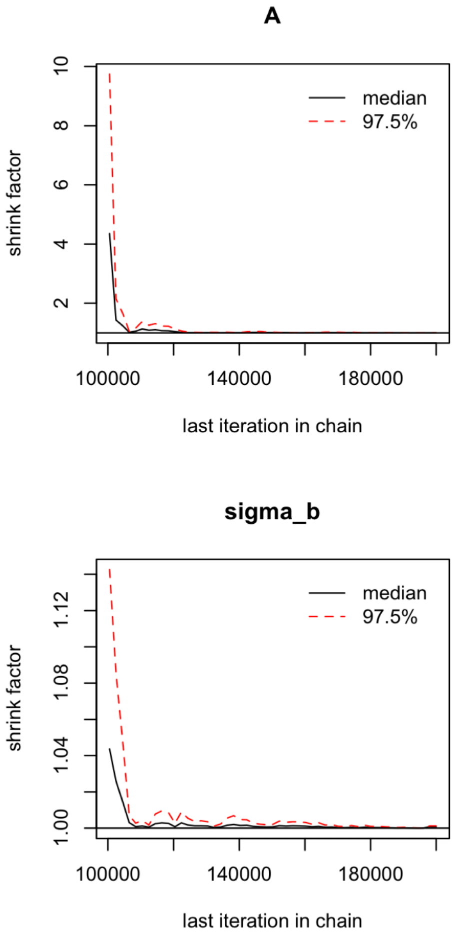


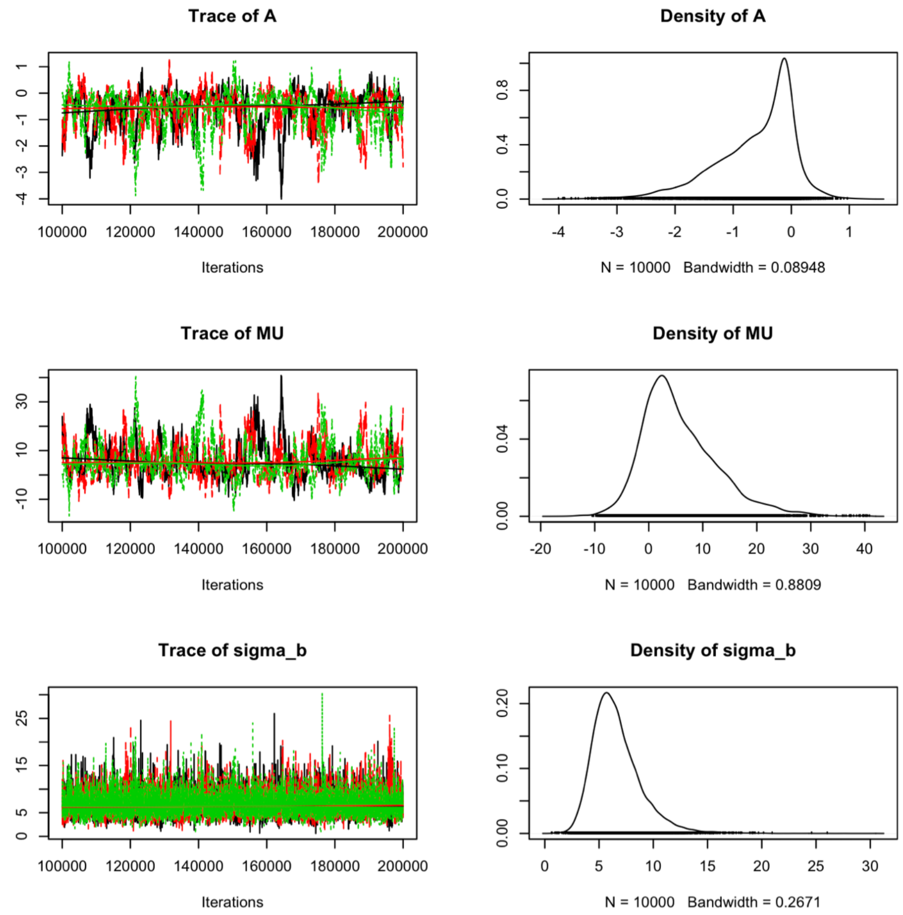



```
Iterations = 100010:2e+05
Thinning interval = 10
Number of chains = 3
Sample size per chain = 10000

1. Empirical mean and standard deviation for each variable,
   plus standard error of the mean:

           Mean    SD Naive SE Time-series SE
MU      -0.2577 2.362  0.01364        0.09475
sigma_b  7.1907 2.205  0.01273        0.02351

2. Quantiles for each variable:

          2.5%    25%    50%   75%  97.5%
MU      -4.985 -1.784 -0.286 1.205  4.668
sigma_b  4.086  5.677  6.798 8.252 12.614

> dic.samples(model, 10000)
  |**************************************************| 100%
Mean deviance:  236.2
penalty 437.3
Penalized deviance: 673.5
```

- What is the posterior mean of the yield sensitivity?
- What is the 95% credibility interval?
- Practical conclusion?

Run model 2

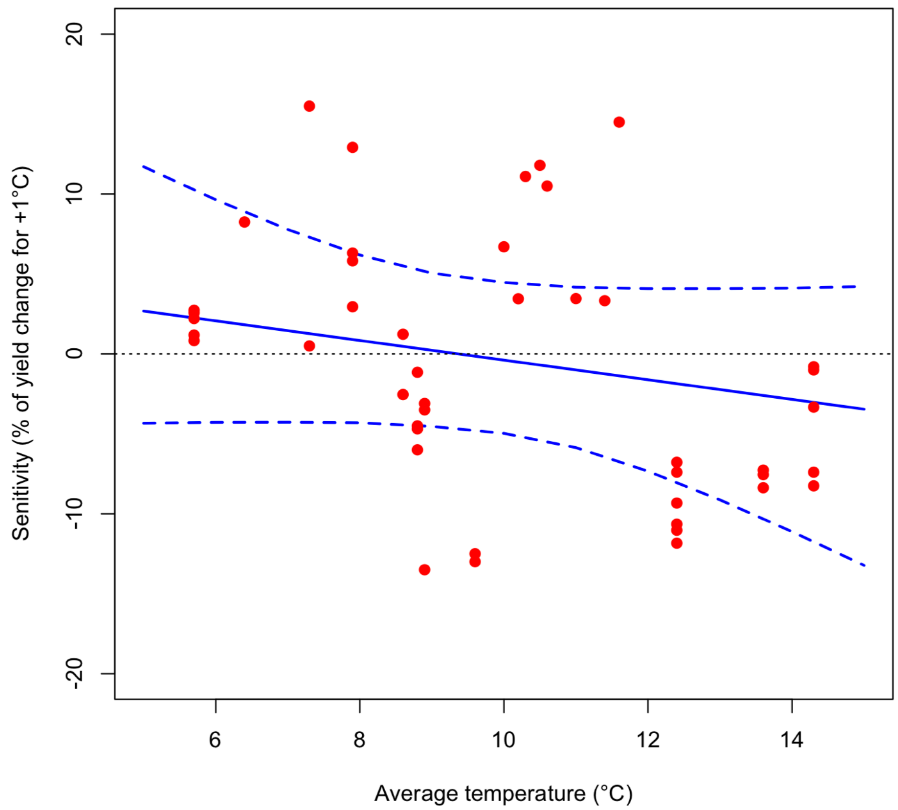




- What are the meanings of A, MU, sigma_b?
- Does the model includes other parameters?

Run model 2

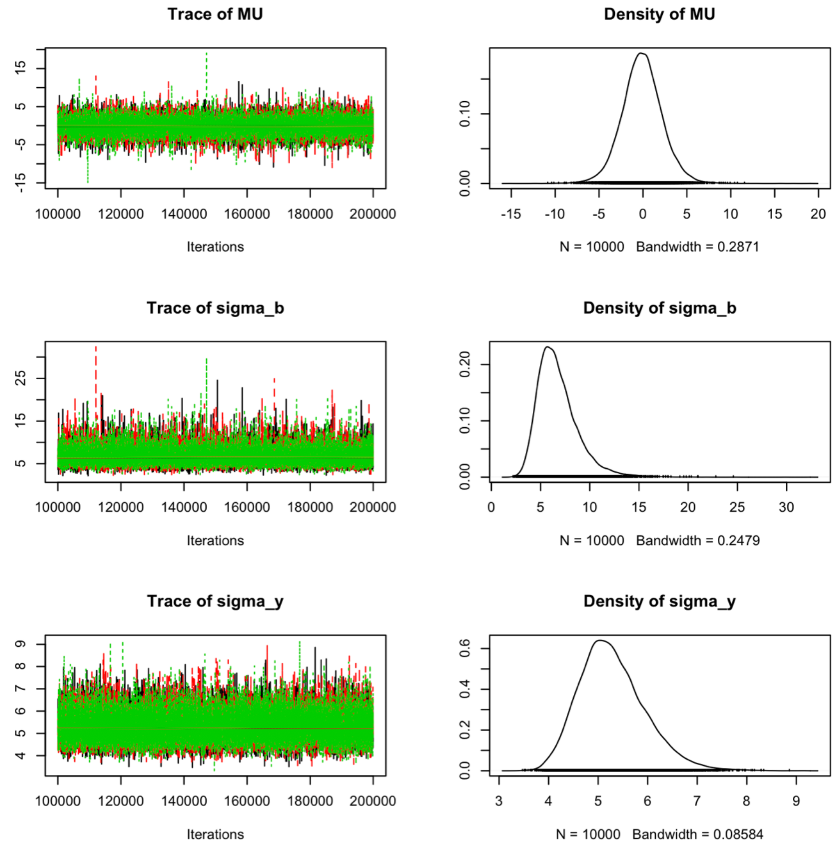
```
> summary(samples)

Iterations = 100010:2e+05
Thinning interval = 10
Number of chains = 3
Sample size per chain = 10000

1. Empirical mean and standard deviation for each variable,
   plus standard error of the mean:

           Mean    SD Naive SE Time-series SE
A       -0.6139 0.689 0.003978        0.04979
MU       5.7506 7.015 0.040500        0.49460
sigma_b  6.6276 2.280 0.013165        0.04103

2. Quantiles for each variable:

          2.5%     25%     50%     75%   97.5%
A       -2.293 -1.0024 -0.4249 -0.1132  0.3409
MU      -4.960  0.8774  4.3804  9.6299 22.8198
sigma_b  3.276  5.0932  6.2541  7.7468 12.1035

> dic.samples(model, 10000)
  |**************************************************| 100%
Mean deviance:  243.4
penalty 1146
Penalized deviance: 1389
```



- What is the effect of the average temperature?
- Was this variable able to explain a big part of the between-site variability?

Run model 1bis

```
> summary(samples)

Iterations = 100010:2e+05
Thinning interval = 10
Number of chains = 3
Sample size per chain = 10000

1. Empirical mean and standard deviation for each variable,
   plus standard error of the mean:

            Mean     SD Naive SE Time-series SE
MU      -0.09876 2.2985 0.013270        0.01889
sigma_b  6.76543 2.1056 0.012157        0.01323
sigma_y  5.28503 0.6643 0.003836        0.00380

2. Quantiles for each variable:

          2.5%    25%     50%   75%  97.5%
MU      -4.593 -1.536 -0.1248 1.317  4.528
sigma_b  3.751  5.320  6.4026 7.783 11.902
sigma_y  4.173  4.823  5.2160 5.676  6.772

> dic.samples(model, 10000)
  |**************************************************| 100%
Mean deviance:  275.9
penalty 11.3
Penalized deviance: 287.2
```

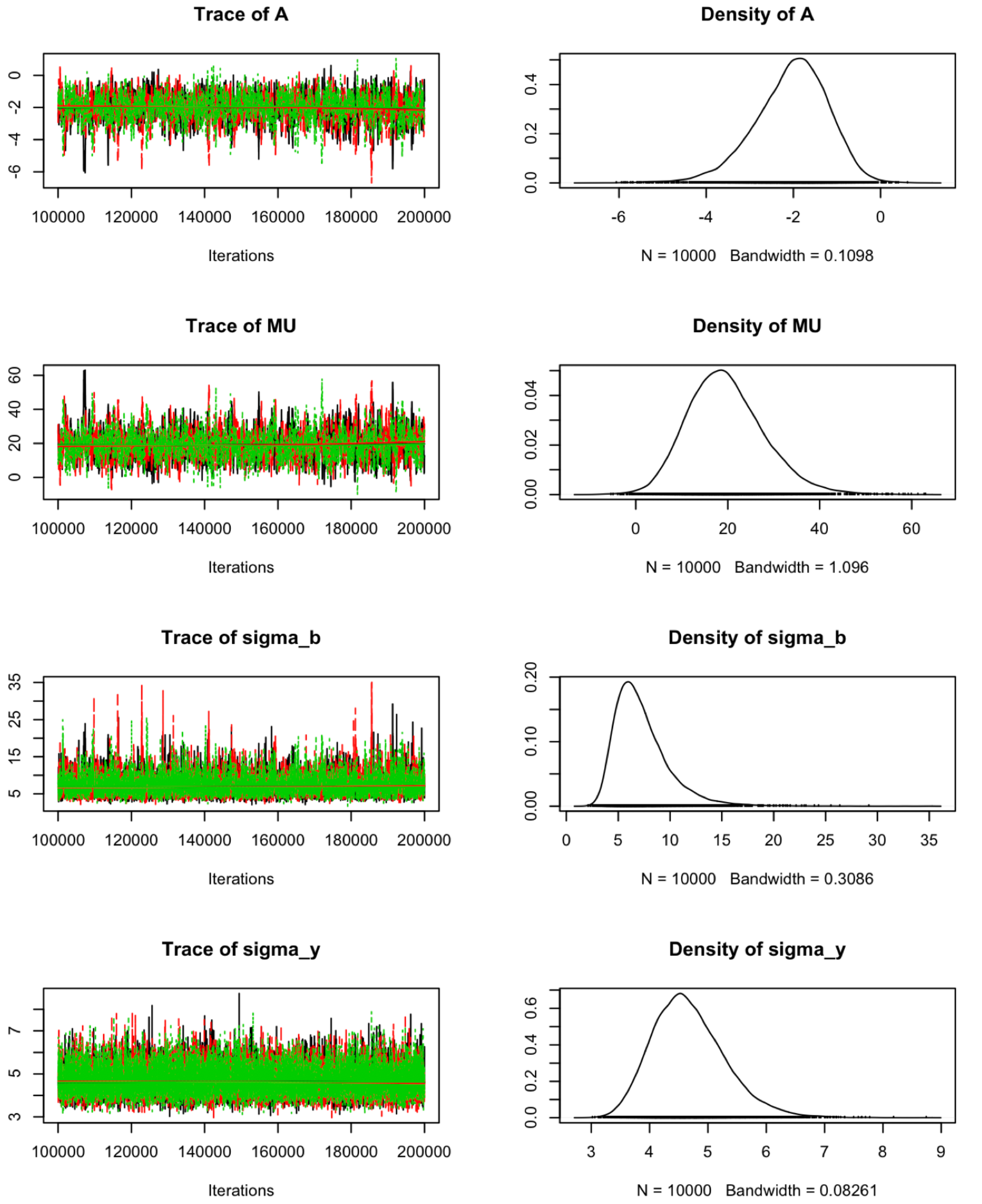


- How does this model compare with model 1?
- Is it relevant to consider different within-site variances?

Run model 2bis

```
> summary(samples)

Iterations = 100010:2e+05
Thinning interval = 10
Number of chains = 3
Sample size per chain = 10000

1. Empirical mean and standard deviation for each variable,
   plus standard error of the mean:

          Mean     SD Naive SE Time-series SE
A       -2.045 0.8503 0.004909       0.027451
MU      19.581 8.3981 0.048487       0.266484
sigma_b  7.273 2.6770 0.015456       0.054430
sigma_y  4.679 0.6271 0.003621       0.006523

2. Quantiles for each variable:

          2.5%    25%    50%    75%   97.5%
A       -3.917 -2.552 -1.974 -1.461 -0.5895
MU       5.001 13.773 18.979 24.668 37.8528
sigma_b  3.719  5.435  6.748  8.501 13.8902
sigma_y  3.632  4.234  4.614  5.055  6.0909

> dic.samples(model, 10000)
  |**************************************************| 100%
Mean deviance:  264.7
penalty 12.43
Penalized deviance: 277.2
```

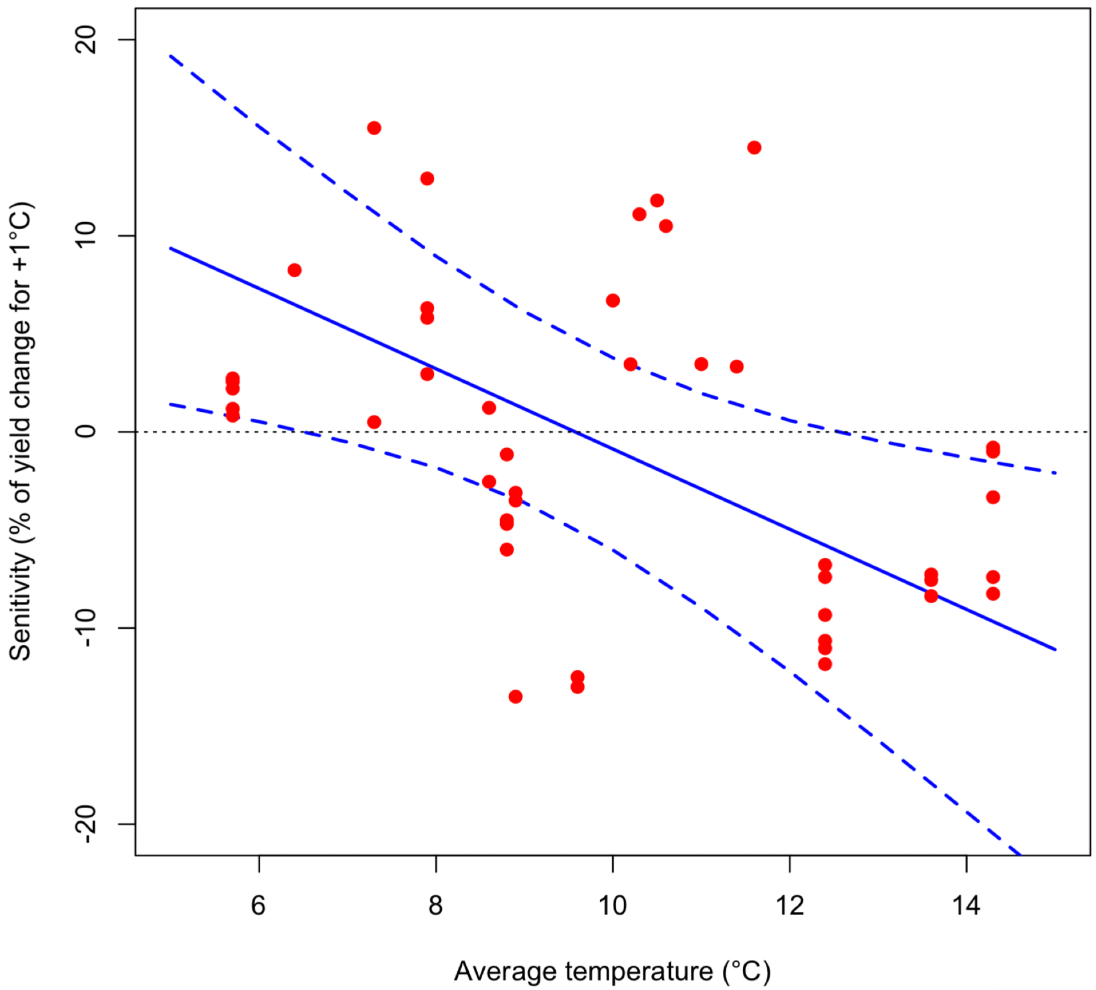
- How does this model compare with the other models?
- What is the effect of the average temperature?



Run model 2bis

- What is the yield sensitivity when the average temperature is of 6°C or of 14°C?

- Can you anticipate a shift of the wheat growing area due to climate change based on this model?



If you had 2 days available, how will you improve this model?