Design and Analysis of BACI Experiments.

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Abstract

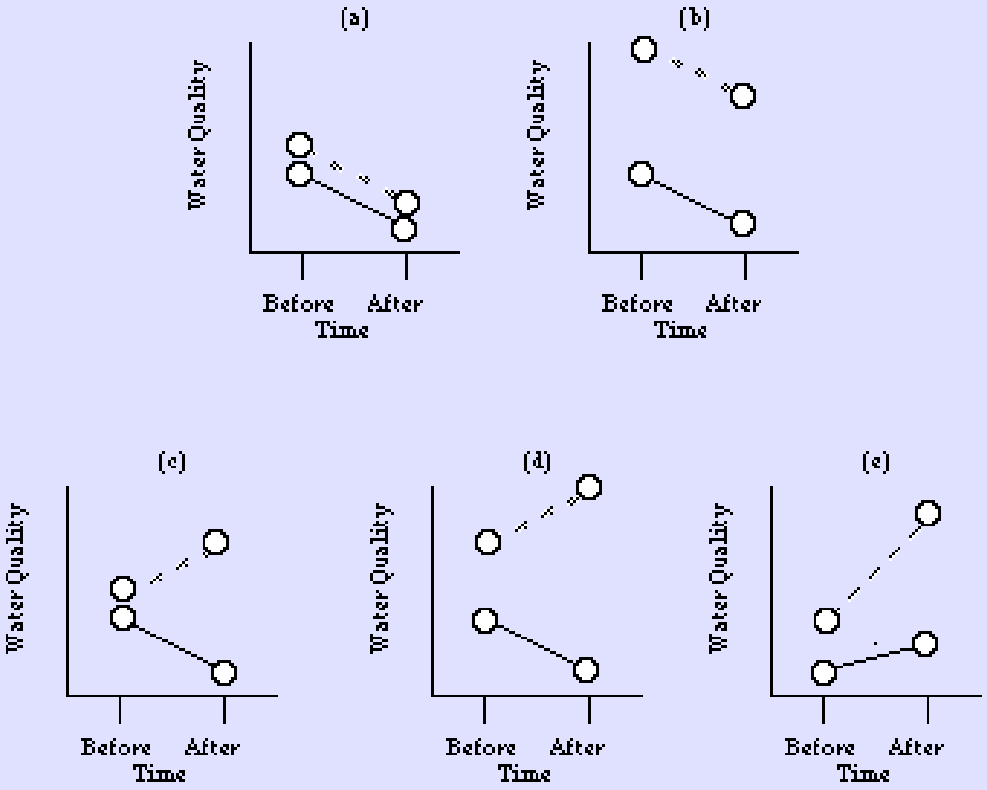
Before-After-Control-Impact (BACI) designs are commonly used to monitor for potential environmental impacts. We will review the four most common BACI designs highlighting the proper analyses of these designs, their limitations in the interpretation of the results (and alternatives), and what information is required for planning purposes. Finally, we will review alternatives to BACI designs, especially when control information is limited or lacking.

Additional information is available at:

- `http://www.stat.sfu.ca/~cschwarz/CourseNotes`
- Follow link on above page to *Sample Program Library* for *SAS*, *JMP*, and *R* code.

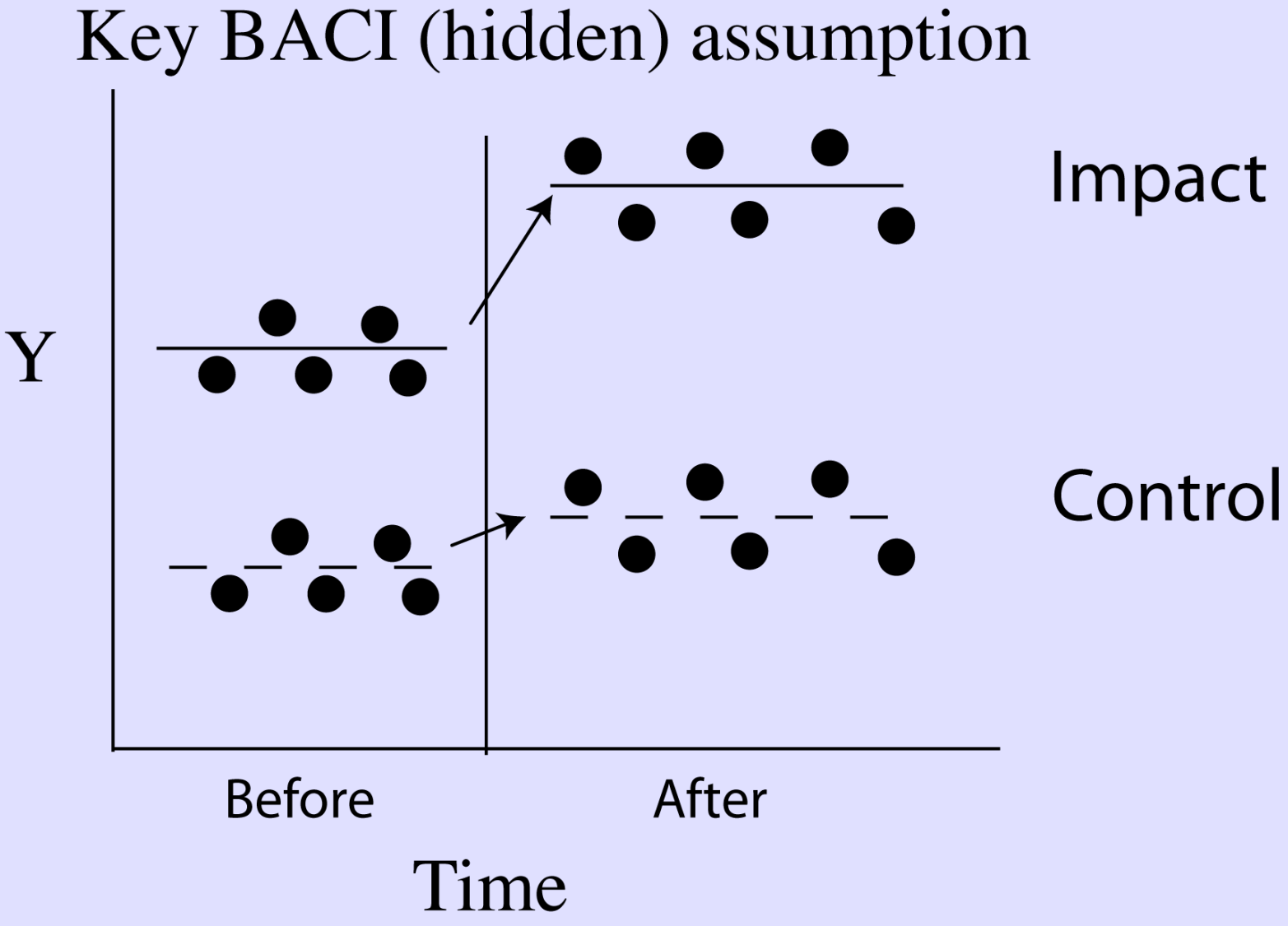
Why BACI?

- Temporal changes may be confounded with environmental impact.
- Site-differences may be unrelated to environmental impact.



Non-parallelism in response = Environmental Impact

Key BACI (hidden) assumption



Step change between Before and After Impact!

When is BACI best?

BACI designs are good for:

- Large potential changes after impact
- Changes are permanent after impact
- Monitoring to protect against disasters
- Monitoring for changes in the MEAN

BACI designs are poor for:

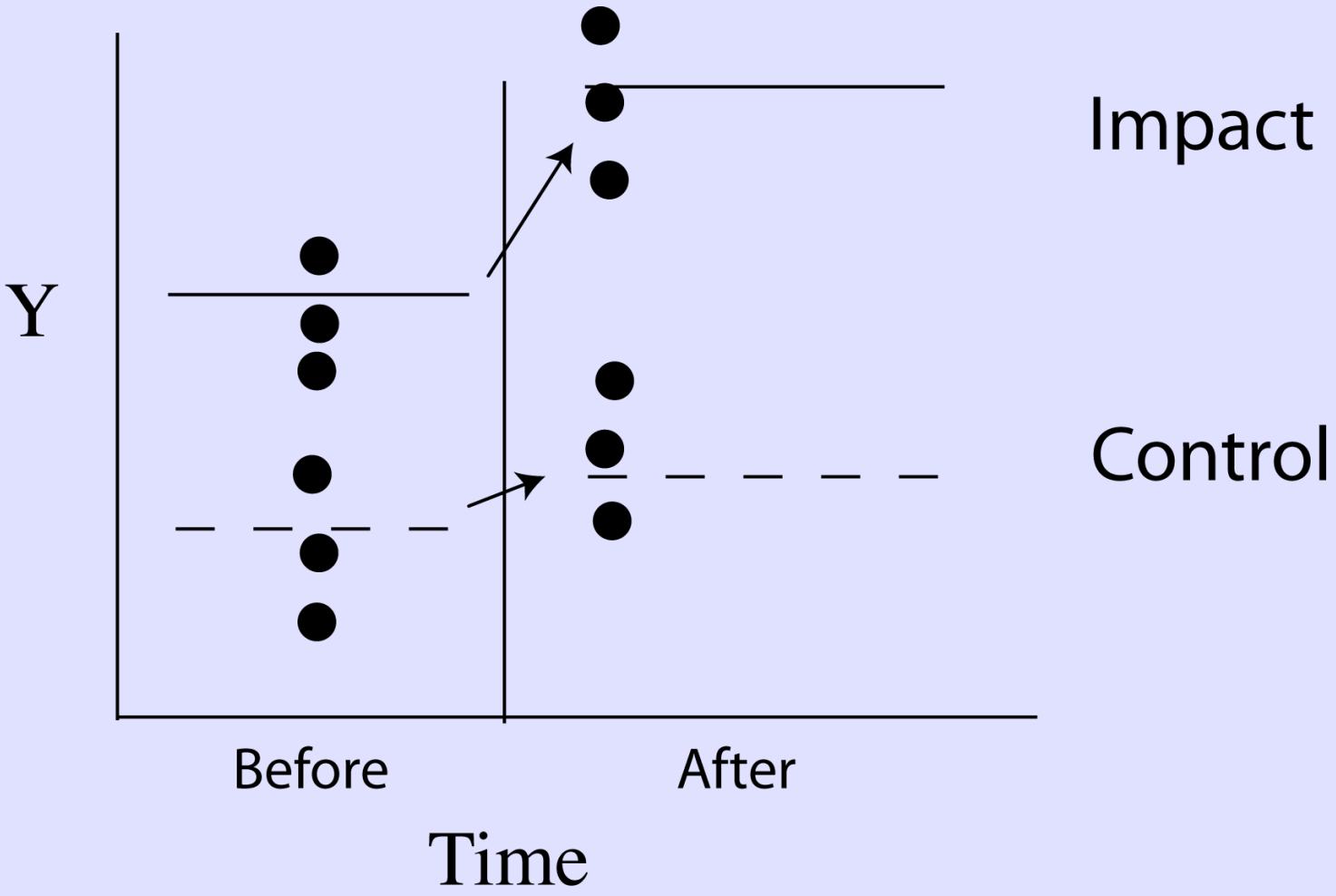
- Small potential changes after impact
- Gradual changes after impact (i.e. not a step change)
- Long term monitoring
- Monitoring for changes in VARIABILITY

Four standard BACI Designs

Four standard BACI designs:

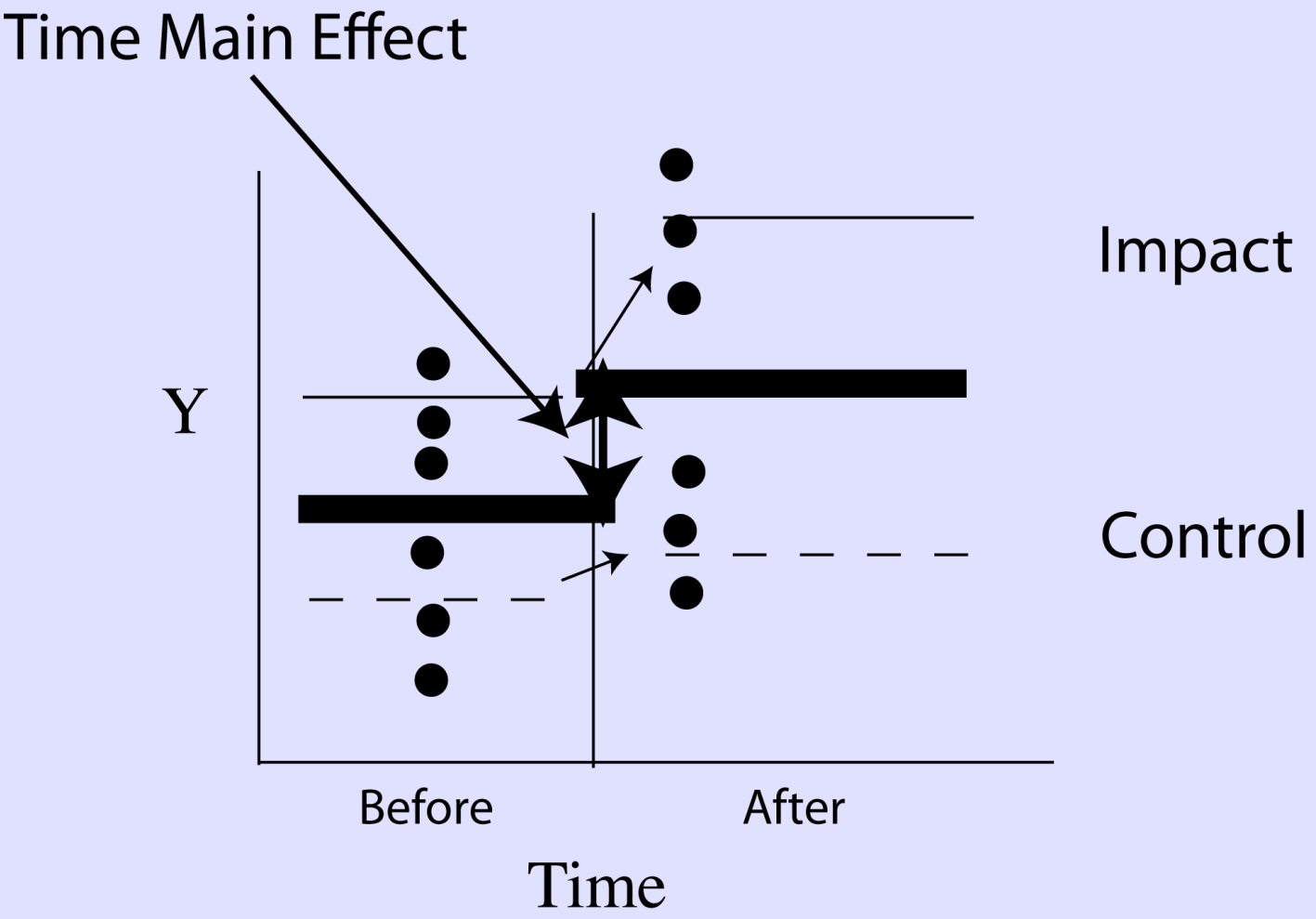
1. Single impact site; single control site; one year before; one year after.
2. Single/multiple impact site; multiple control sites; one year before; one year after.
3. Single impact site; single control site; multiple years before; multiple years after.
4. Single impact site; multiple control sites; multiple years before; multiple years after.

BACI Design 1

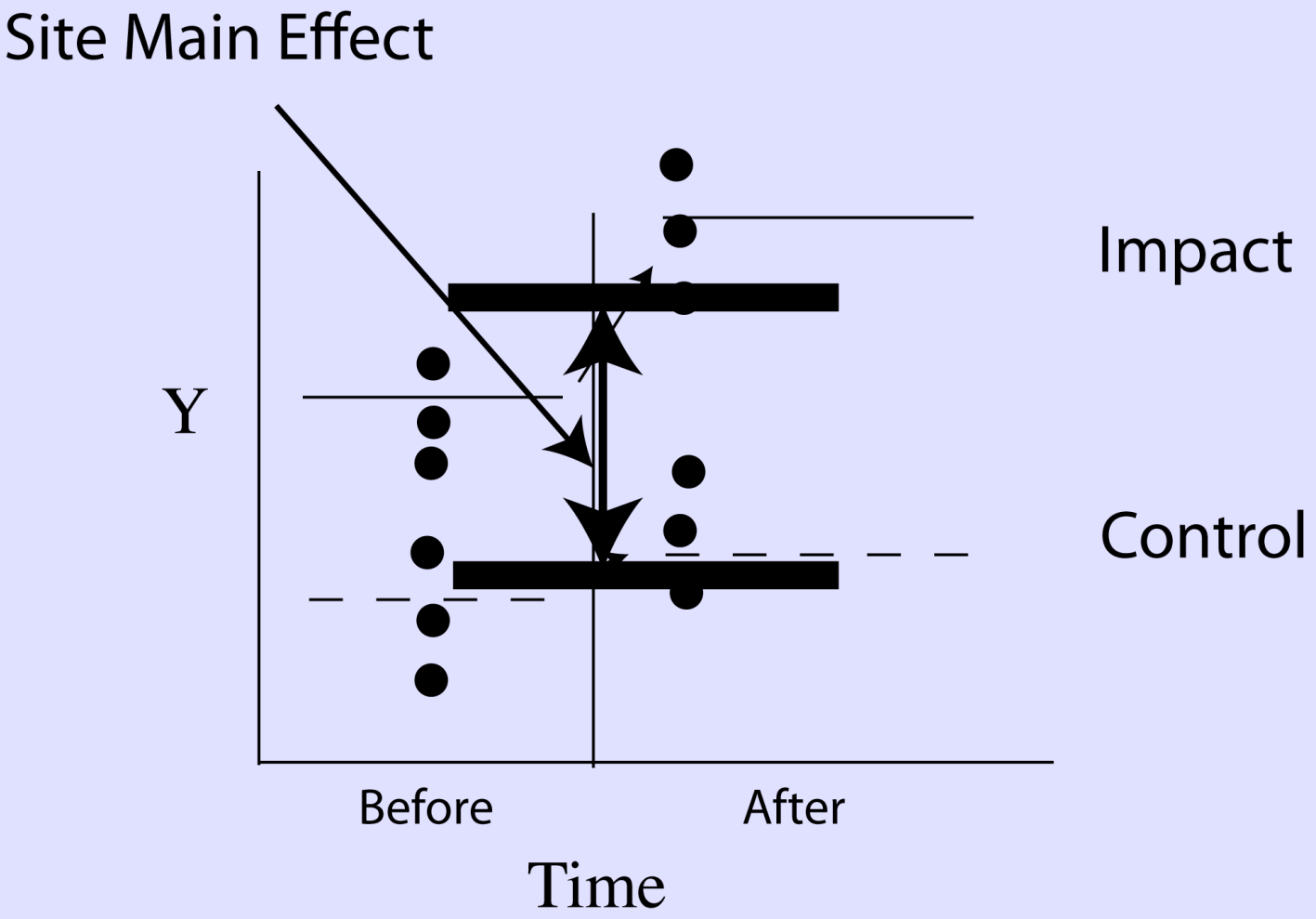


E.g. Number of shore crabs on beaches affected by cooling water of power plant measured using independent quadrats each year.

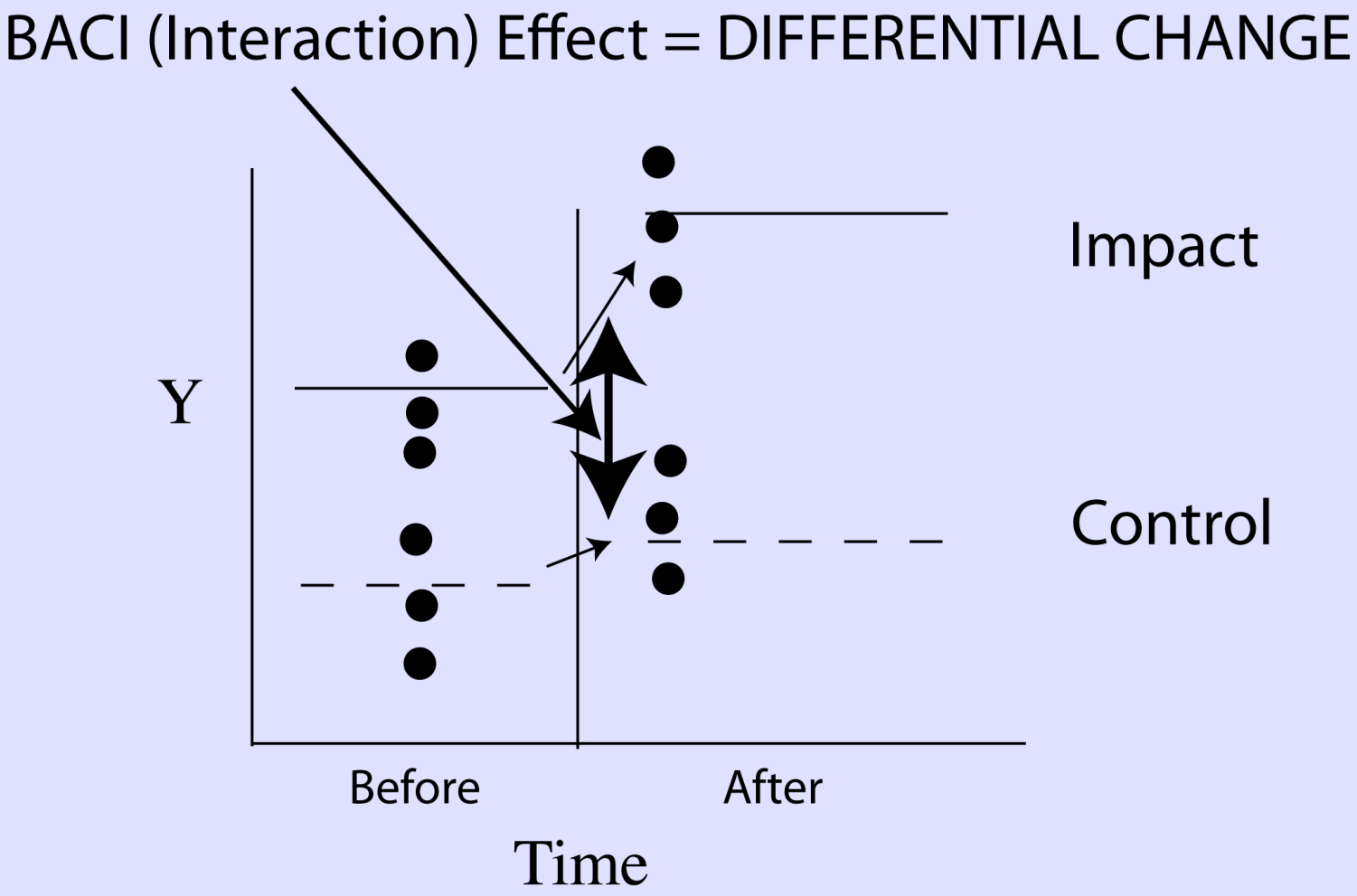
BACI Design 1 - Decomposition of Effects



BACI Design 1 - Decomposition of Effects



BACI Design 1 - Decomposition of Effects



BACI Design 1

Two-factor completely-randomized design ANOVA.

SAS Analysis:

```
PROC Mixed data=blah;
CLASS Period Siteclass;
MODEL Y = Period   Siteclass   Period*Siteclass;
ESTIMATE 'BACI Effect' Period*Siteclass 1 -1 -1 1;
```

The test of no impact is the test for no interaction, i.e. test of *Period* $*$ *Siteclass* interaction.
Estimate BACI effect as DIFFERENTIAL change in means between two sites, i.e.

$$BACI = (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$$

BACI Design 1

Two-factor completely-randomized design ANOVA.

SAS results (with 4/5/6/4 replicates at site-year combinations):

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
SiteClass	1	15	13.90	0.0020
Period	1	15	8.54	0.0105
SiteClass*Period	1	15	0.97	0.3404

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**
BACI effect	3.0500	3.0974	15	0.98	0.3404	0.05

BACI Design 1

Two-factor completely-randomized design ANOVA.

R Analysis: (Be sure that Period and Siteclass are FACTORS).

```
    results<-lm(Y~Period+ Siteclass+Period:Siteclass,
data=blah)
    anova(results)
    summary(results)
```

CAUTION: In *R*, you must put the interaction term last if design is unbalanced otherwise the test for interaction is NOT correct.

BACI Design 1

Two-factor completely-randomized design ANOVA.

R results:

```
Response: Density
                 Df  Sum Sq Mean Sq F value    Pr(>
SiteClass         1 194.695 194.695 17.5877 0.00078
Period            1  92.205  92.205  8.3293 0.01131
SiteClass:Period  1  10.734  10.734  0.9696 0.34039
Residuals        15 166.050  11.070
```

Note that tests for *SiteClass* and *Period* are MISLEADING and don't test what you think they do!

Estimate of BACI effect is:

```
  Estimate Std. Error    t value   Pr(>|t|)
3.0500000  3.0974183  0.9846910  0.3403935
```

BACI Design 1

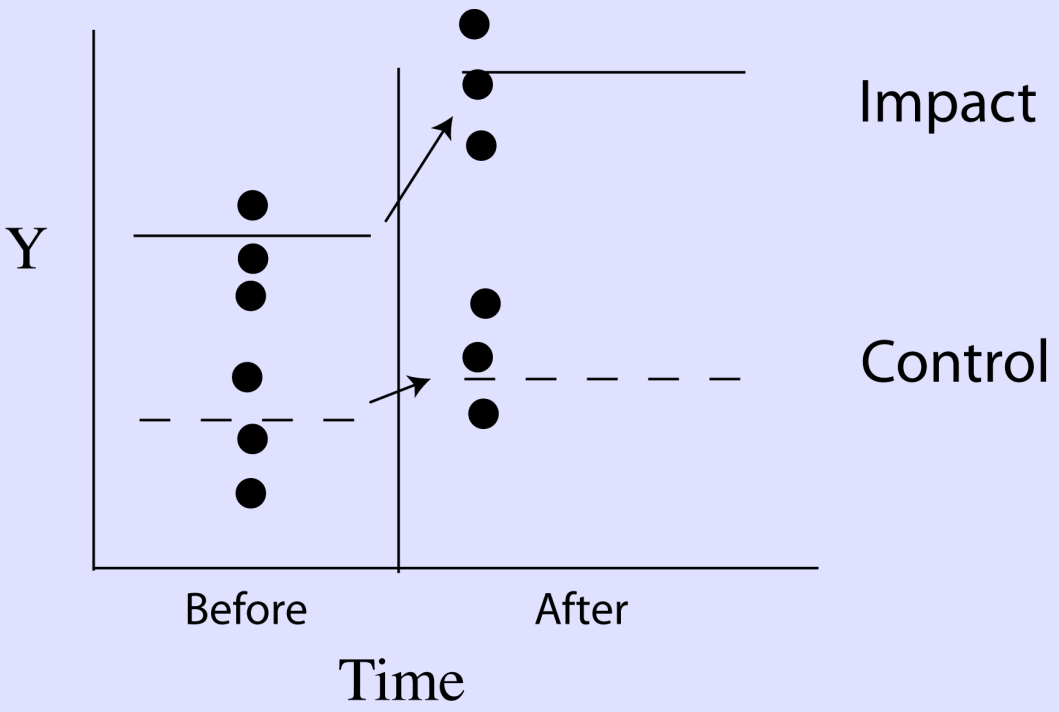
Assumptions:

- Not necessary for design to be balanced, i.e. number of replicates can vary across site-time.
- All measurements within and across years at a site are INDEPENDENT of each other
- Normality of residuals (but fairly robust IF....)
- Equality of variation each each Site $\times$ Period

Key Limitations:

- Effect may be an artifact of sites chosen or years chosen.
- Inference is LIMITED to those particular sites and years chosen.

BACI Design 1



Power (see web site for programs) depends on:

- Size of BACI effect $= (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$
- Std DEV (σ) of replicates at each site-year combination
- Number of replicates at each site-year combination

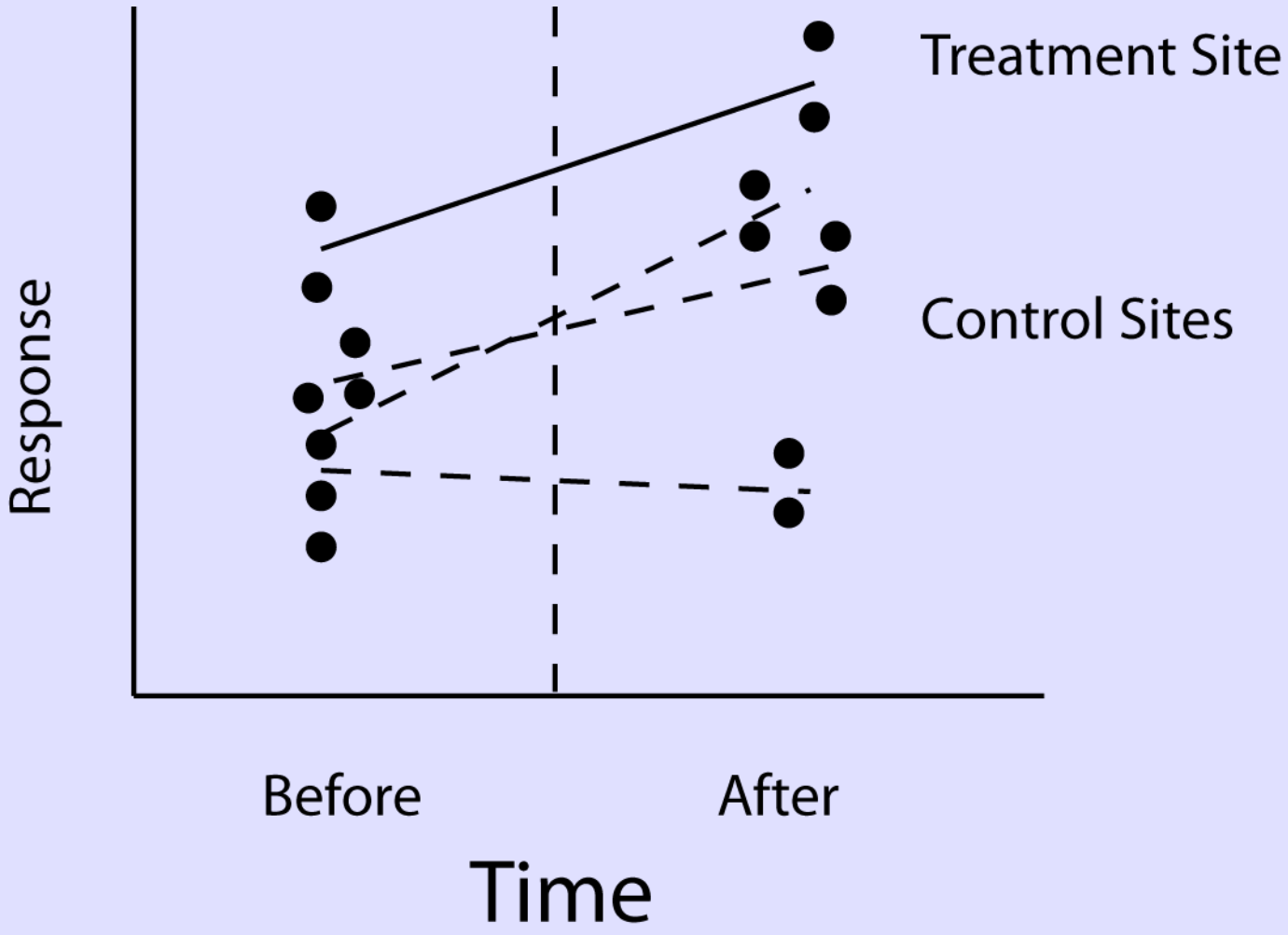
BACI Design 1

Crabs example: $BACI = -5$, $\sigma = 3.32$

```
     alpha n_TA n_TB n_CA n_CB baci power
[1,] 0.05  5    5    5    5    -5   0.3533207
[2,] 0.05  10   10   10   10   -5   0.6396126
[3,] 0.05  15   15   15   15   -5   0.8175554
[4,] 0.05  20   20   20   20   -5   0.9138353
```

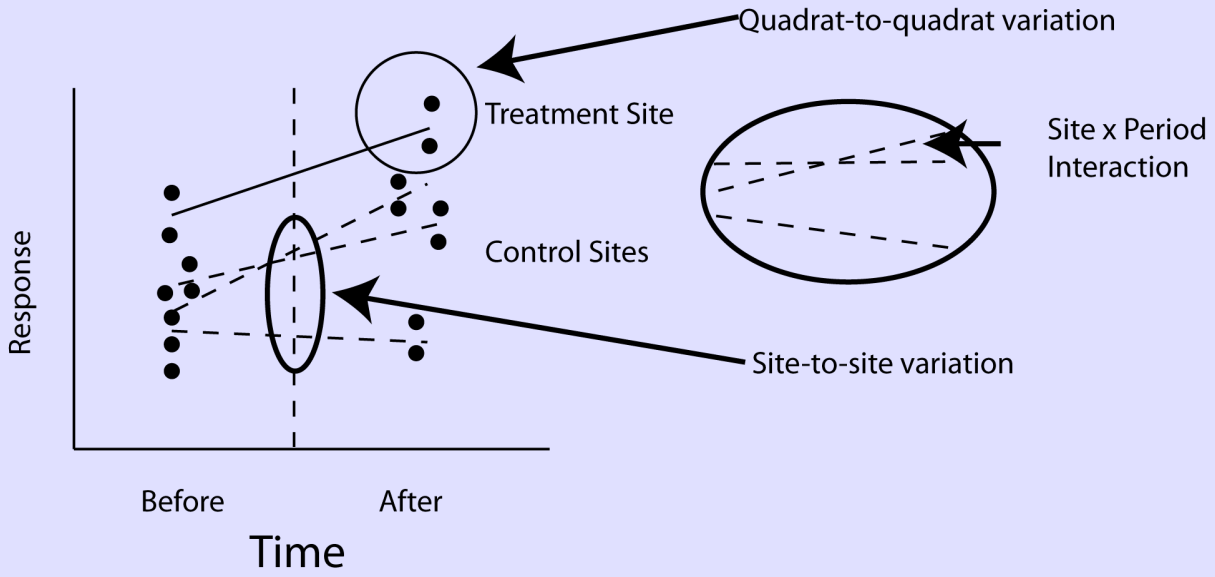
Aim for about 80% power at $\alpha = 0.05$.

BACI Design 2



E.g. Number of shore crabs on beaches affected by cooling water of power plant measured using independent quadrats each year with multiple beaches for controls.

BACI Design 2

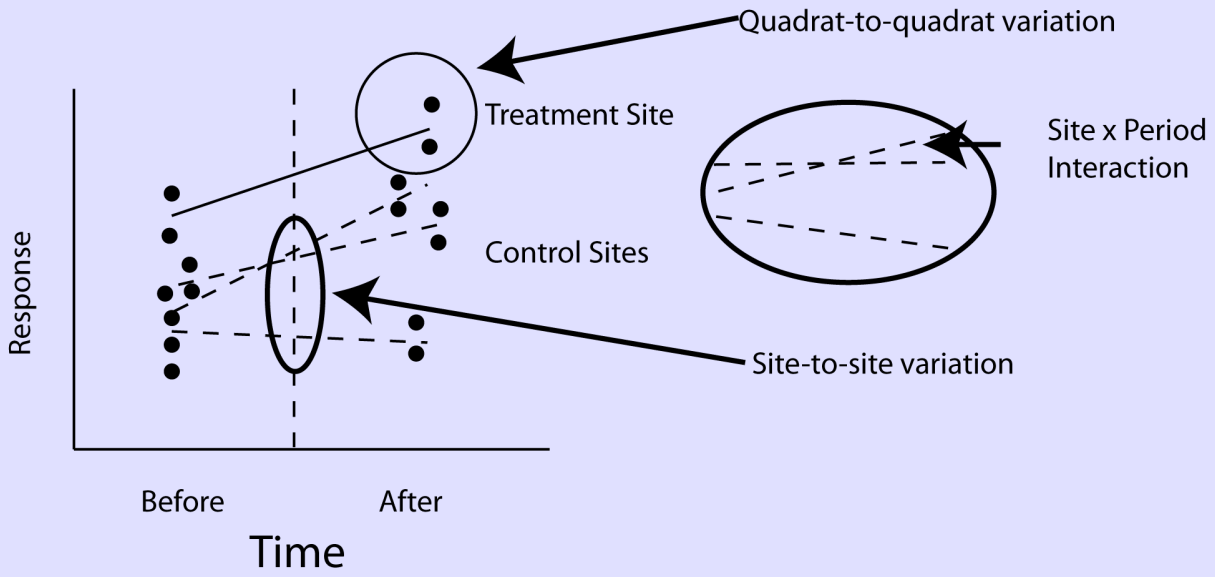


Three levels of variation:

- quadrats-within-a-beach; These are pseudo-replicates. Variability can be reduced by increasing the size of the quadrats.
- site-to-site. Site serve a “blocks” so main effect site-differences are NOT important.
- Site-Year. This represents the inconsistent temporal effects over sites.

Note that if you only have one quadrat, then quadrat and site*year variation is confounded and cannot be separated.

BACI Design 2



What can you control via modifications to the sampling design?

- Quadrat variation can be controlled by choosing larger quadrats.
- Site variation cannot be controlled, but by measuring all sites in all years, site effects “cancel”.
- Site-Year variation cannot be controlled by modifying design. This is the limiting variation for the design.

BACI Design 2

Multiple (equivalent) ways to analyze this data:

- Find difference of means for EACH site; analyze the differences in means using *t*-test to see if the mean difference among the controls = mean difference for impact site. [Only approximate analysis if design is unbalanced.]
- Mixed Effects ANOVA on the means of each site-year combination.
- Mixed Effects ANOVA on the raw data. This is the most general and provides estimates of ALL variance components needed for power analysis.

BACI Design 2

Two-factor mixed-effect ANOVA.
SAS Analysis:

```
PROC Mixed data=blah;
CLASS Period Siteclass Site;
MODEL Y = Period   Siteclass   Period*Siteclass / ddfm=kr;
RANDOM site(SiteClass) site(Siteclass)*Period;
ESTIMATE 'BACI Effect' Period*Siteclass 1 -1 -1 1;
```

The test of no impact is the test for no interaction, i.e. test of *Period* $*$ *Siteclass* interaction.
Estimate BACI effect as DIFFERENTIAL change in means between two sites, i.e.

$$BACI = (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$$

BACI Design 2

Two-factor mixed-effect ANOVA.

SAS results (2C, 1I site; 30 quadrats in total):

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
SiteClass	1	1.01	2.92	0.3351
Period	1	1.11	9.99	0.1746
SiteClass*Period	1	1.11	0.10	0.8002

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**
BACI effect	1.1038	3.4794	1.11	0.32	0.8002	0.05

BACI Design 2

Two-factor mixed-effect ANOVA.

SAS results (continued):

Cov Parm	Estimate
Site	14.6854
Period*Site	1.6775
Residual	10.9274

BACI Design 2

R Analysis: (Be sure that Period, Site, and Siteclass are FACTORS).

```
result <- lme(Density ~ SiteClass+Period+SiteClass:Period,
        data=blah,
        random=~ 1 | Site / Period)
anova(result) # Get the ANOVA Table
summary(result) # Get the BACI Effect
VarCorr(result) # Get the variance components
```

CAUTION: *R* does NOT have a KR adjustment so results may differ from *SAS*.
CAUTION: *R lmer()* function can also be used, but doesn't give p-values directly.

BACI Design 2

R results:

```
                  numDF denDF    F-value p-value
(Intercept)           1    24 151.84378  <.0001
SiteClass             1     1   3.20326  0.3244
Period                1     1  10.73376  0.1886
SiteClass:Period      1     1   0.10075  0.8043
```

Note that test results differ (slightly) from *SAS*

Estimate of BACI effect is:

```
    Value Std.Error        DF   t-value   p-value
1.1038098 3.4774971 1.0000000 0.3174150 0.8043309
```

BACI Design 2

R results (continued):

Estimate of Variance Components

```
                Variance      StdDev
Site =          pdLogChol(1)
(Intercept) 14.683328     3.831883
Period =        pdLogChol(1)
(Intercept)  1.680436     1.296316
Residual    10.927019     3.305604
```

CAUTION: *R* labels the results poorly!

BACI Design 2

Assumptions:

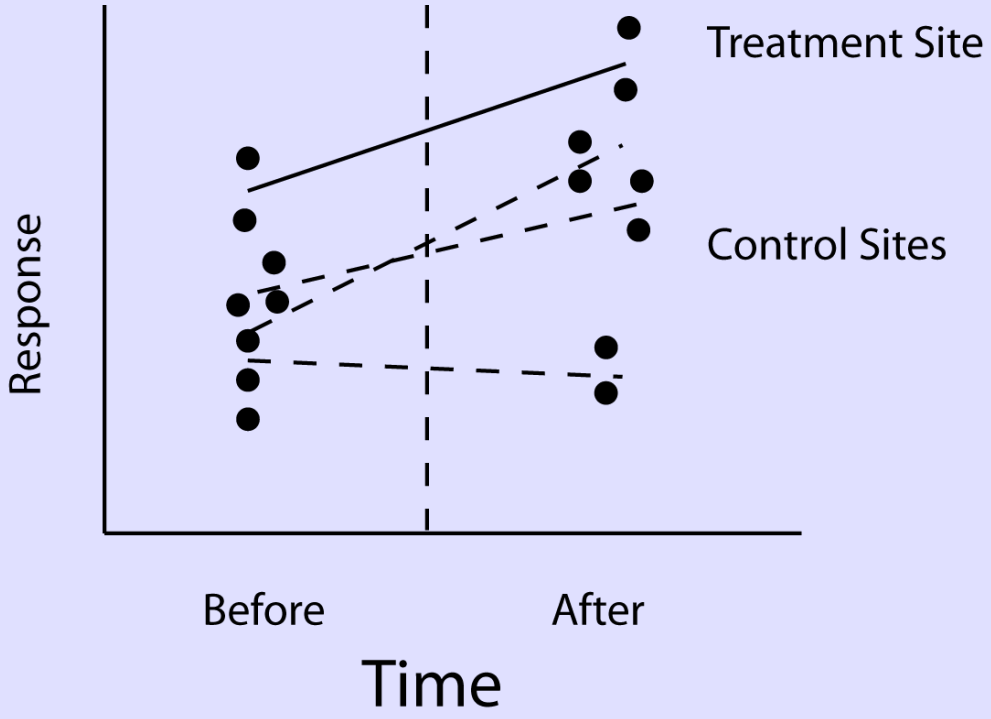
- Not necessary for design to be balanced, i.e. number of quadrats can vary among sites and years; not all sites need both before and after information.
- All measurements within and across sites and years at a site are INDEPENDENT of each other.
- All sites are independent of each other.
- Normality of residuals (but fairly robust IF....)
- Equality of variation each each Site $\times$ Period
- Normality of site effects; normality of *site*period* interactions. Difficult to assess because typically have a few sites.

BACI Design 2

Key Limitations and Difference from Design 1:

- Inference is now more general to all SITES, not just the 2 particular sites chosen in Design 1. Consequently, there can be “loss of power” but you are comparing two different inferences!
- Limiting feature is the *site*period* variance component as you cannot influence by more sampling! Consequently, there is benefit to sampling more site and/or more quadrats but you need to look at tradeoffs.

BACI Design 2



Power (see web site for programs) depends on:

- Size of BACI effect $= (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$
- TWO sources of variation important for planning:
  - $\sigma_{quadrat}$ of replicates at each site-year combination
  - $\sigma_{site*year}$

  σ_{site} "cancels' because each site is measured both before and after (A GOOD THING TO DO)!
- Number of quadrats, number of sites.

BACI Design 2

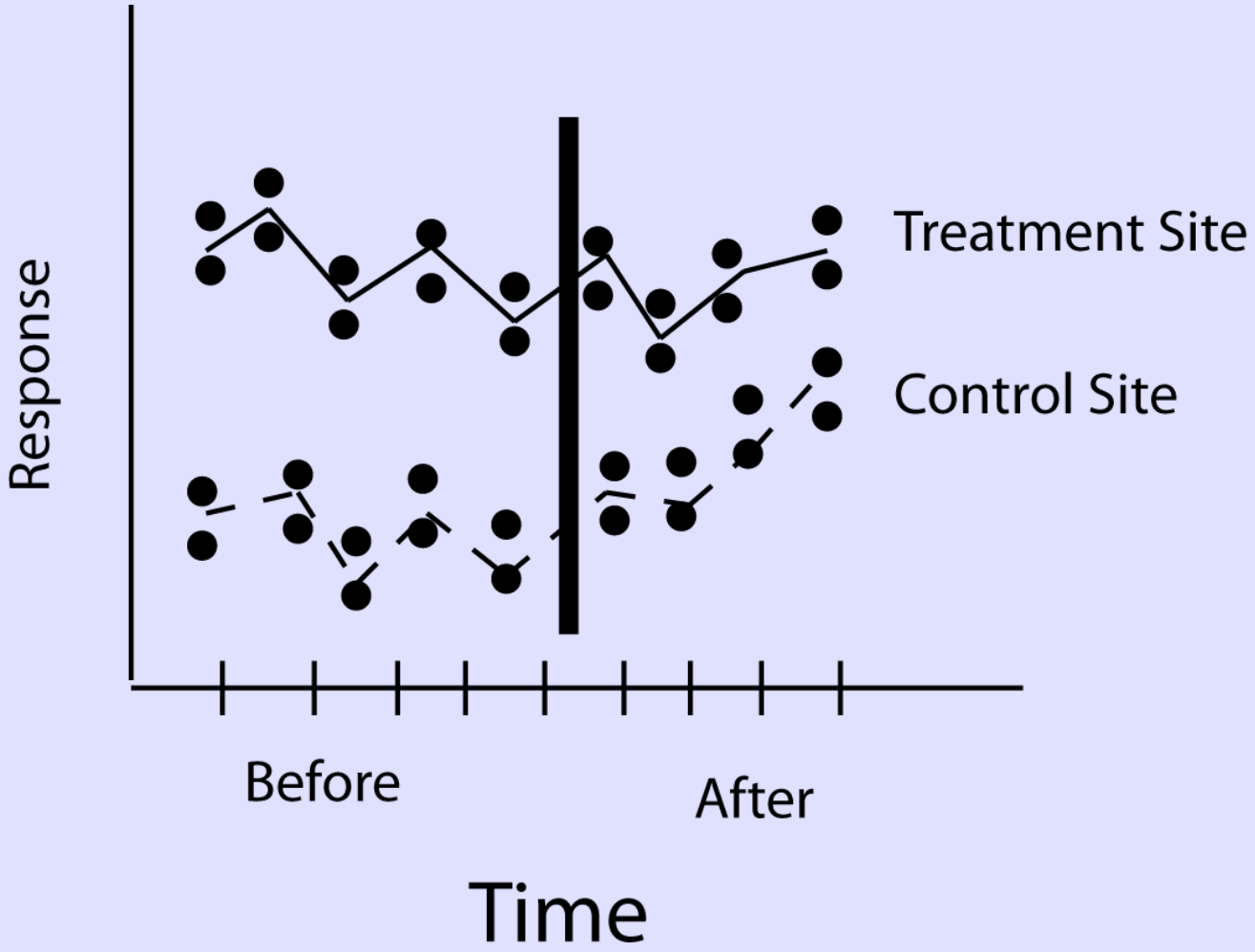
Crabs example: $BACI = -5$, $\sigma_{quadrats} = 3.30$, $\sigma_{site*year} = 1.296$

	alpha	ns_T	ns_C	n_TA	n_TB	n_CA	n_CB	baci	power
[1,]	0.05	1	2	5	5	5	5	-5	0.095
[2,]	0.05	1	2	40	40	40	40	-5	0.129
[3,]	0.05	1	4	5	5	5	5	-5	0.207
[4,]	0.05	1	4	20	20	20	20	-5	0.316
[5,]	0.05	1	4	20	20	5	5	-5	0.284
[6,]	0.05	1	10	5	5	5	5	-5	0.335
[7,]	0.05	2	10	5	5	5	5	-5	0.555
[8,]	0.05	2	10	40	40	40	40	-5	0.836

Aim for about 80% power at $\alpha = 0.05$.

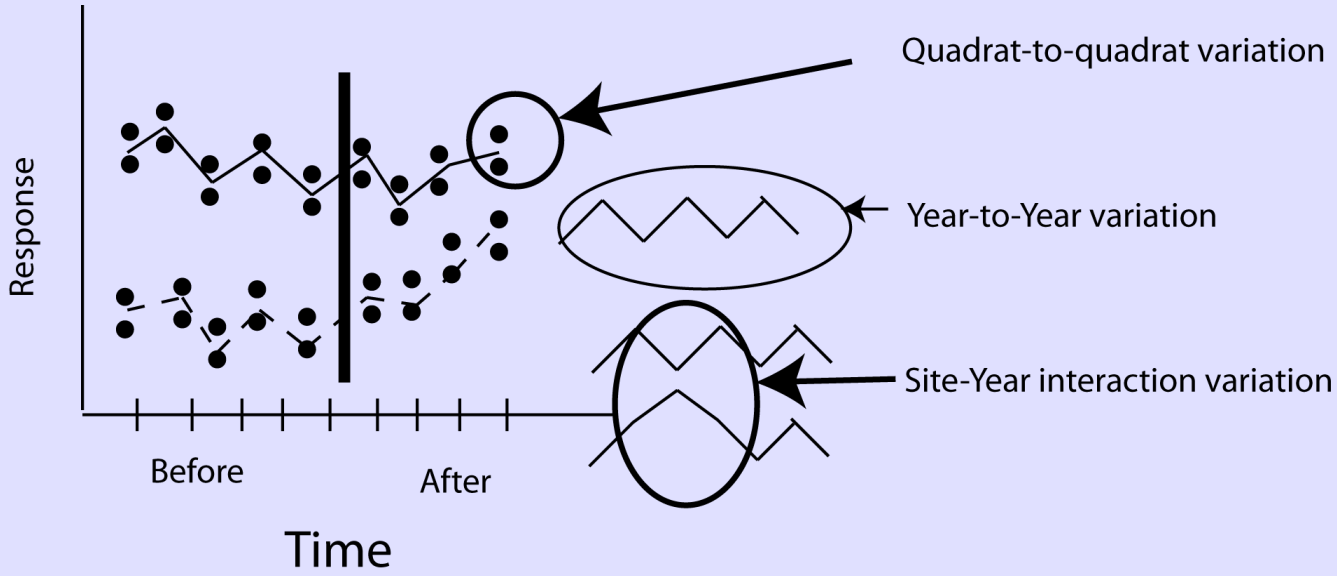
Usually, more sites are preferable to more quadrats/site to improve power.

BACI Design 3



E.g. Fish counts (minnow traps) measured in control and impacted stream several years before and after impact. Only one measurement taken per year per stream (this has implications later).

BACI Design 3

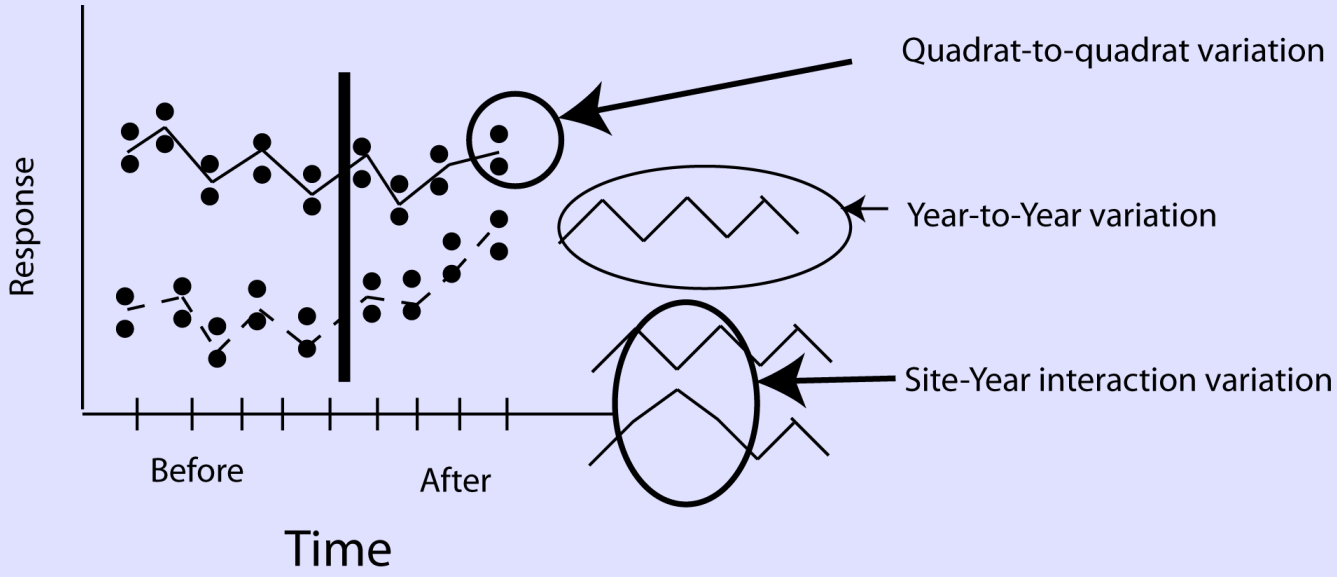


Three levels of variation:

- quadrats-within-a-beach; These are pseudo-replicates
- year-to-year. External factors that affect all sites the same way. Because measurements are paired within years, this variance component will “cancel” in the analysis.
- site*year interaction. Measures the inconsistency of the response of sites to the temporal effects.

Note that if you only have one quadrat, then quadrat and site*year variation is confounded and cannot be separated.

BACI Design 3



What can you control via modifications to the sampling design?

- Quadrat variation can be controlled by choosing larger quadrats.
- Year variation cannot be controlled, but by pairing the effects “cancel”.
- Site-Year variation cannot be controlled by modifying design. This is the limiting variation for the design.

BACI Design 3

Multiple (equivalent) ways to analyze this data:

- Find difference of means for EACH YEAR; analyze the differences in means using *t*-test to see if the mean difference before is the same as the mean difference after.. [Only approximate analysis if design is unbalanced.]
- Mixed Effects ANOVA on the means of each site-year combination.
- Mixed Effects ANOVA on the raw data. This is the most general and provides estimates of ALL variance components needed for power analysis.

BACI Design 3

Two-factor mixed-effect ANOVA.
SAS Analysis:

```
PROC Mixed data=blah;
CLASS Period Siteclass Year Site;
MODEL Y = Period   Siteclass   Period*Siteclass / ddfm=kr;
RANDOM Year(Period) year(Period)*Site;
ESTIMATE 'BACI Effect' Period*Siteclass 1 -1 -1 1;
```

The test of no impact is the test for no interaction, i.e. test of $Period * Siteclass$ interaction.
Estimate BACI effect as DIFFERENTIAL change in means between two sites, i.e.

$$BACI = (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$$

BACI Design 3

Two-factor mixed-effect ANOVA.

SAS results (25 y; one measurement/year-site combination):

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
SiteClass	1	23	2.28	0.1444
Period	1	23	0.93	0.3438
SiteClass*Period	1	23	0.34	0.5631

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**
BACI effect	-8.9936	15.3280	23	-0.59	0.5631	0.05

BACI Design 3

Two-factor mixed-effect ANOVA.

SAS results (continued)

Cov Parm	Estimate
SampleTime	1005.95
Residual	733.04

Note that if you only have one quadrat, then quadrat and site*year variation is confounded and cannot be separated. So the residual variation represents both effects combined.

BACI Design 3

R Analysis: (Be sure that Period, **Year — common error**, and Siteclass are FACTORS).

```
result <- lme(Density ~ SiteClass+Period+SiteClass:Period,
        data=blah,
        random=~ 1 | Year / Site)
anova(result) # Get the ANOVA Table
summary(result) # Get the BACI Effect
VarCorr(result) # Get the variance components
```

CAUTION: *R* does NOT have a KR adjustment so results may differ from *SAS*.
CAUTION: *R lmer()* function can also be used, but doesn't give p-values directly.

BACI Design 3

R results:

```
                   numDF denDF    F-value p-value
(Intercept)            1    23 14.199342  0.0010
SiteClass              1    23  2.358289  0.1383
Period                 1    23  0.934481  0.3438
SiteClass:Period       1    23  0.344265  0.5631
```

Note that test results differ (slightly) from *SAS*

Estimate of BACI effect is:

```
     Value  Std.Error          DF    t-value    p-va
-8.9935897 15.3280369 23.0000000 -0.5867411  0.5630
```

BACI Design 3

R results (continued):

Estimate of Variance Components

```
SamplingTime = pdLogChol(1)
             Variance StdDev
(Intercept) 1005.949 31.71670
Residual     733.040 27.07471
```

CAUTION: *R* labels the results poorly!
Note that if you only have one quadrat, then quadrat and site*year variation is confounded and cannot be separated. So the residual variation represents both effects combined.

BACI Design 3

Assumptions:

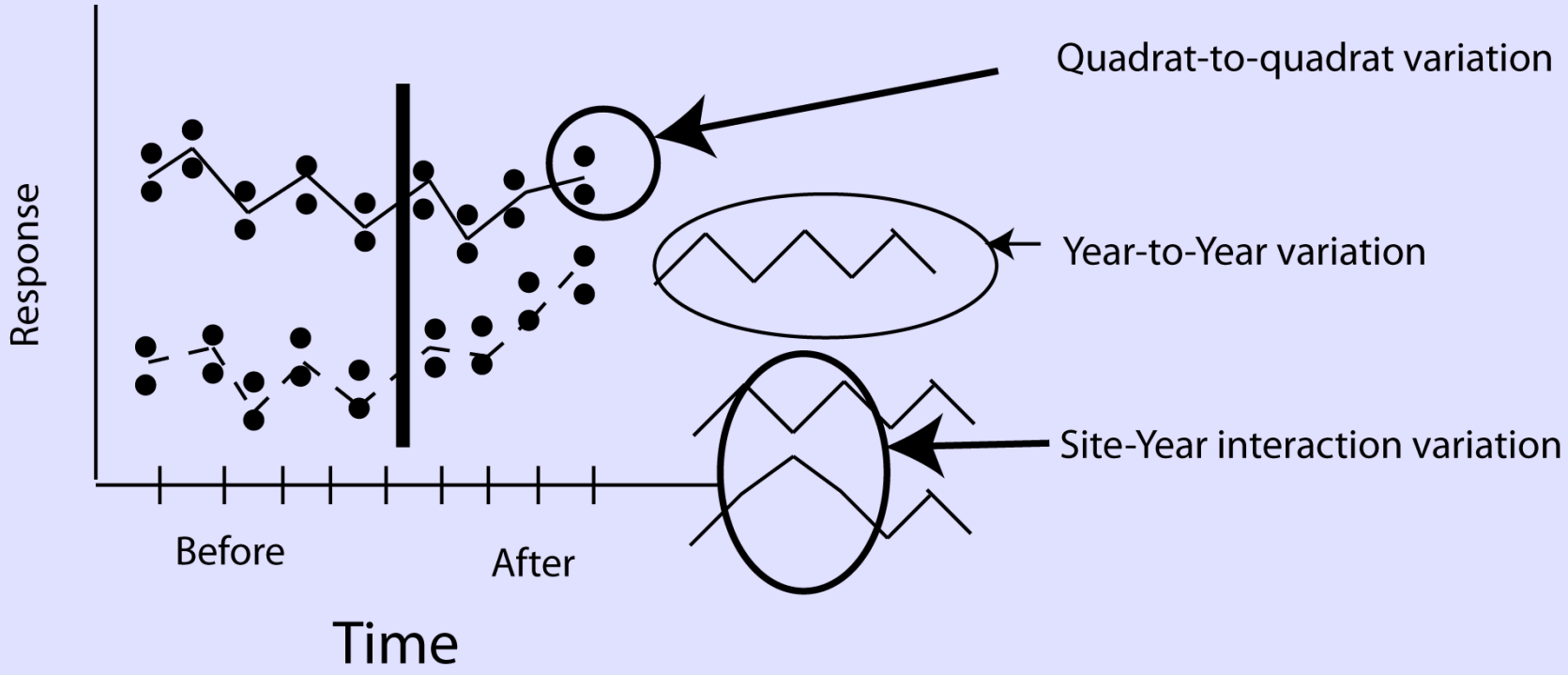
- Not necessary for design to be balanced, i.e. number of quadrats can vary among sites and years; not all sites need be measured in all years.
- All measurements within and across sites and years at a site are INDEPENDENT of each other.
- All sites are independent of each other.
- Normality of residuals (but fairly robust IF....)
- Equality of variation each each Site $\times$ Year
- Normality of year effects; normality of *site*year* interactions. Difficult to assess because typically have a few years.

BACI Design 3

Key Limitations and Difference from Design 1:

- Inference is limited to these two sites, but now over ALL years.
- Note that a STEP CHANGE in the mean is assumed (see previous slides)!
- Limiting feature is the *site*year* variance component as you cannot influence it by better sample design!
- There is benefit to sampling more years and/or more quadrats, but you need to look at tradeoffs.

BACI Design 3



Power (see web site for programs) depends on:

- Size of BACI effect $= (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$
- TWO sources of variation important for planning:
  - $\sigma_{quadrat}$ of replicates at each site-year combination
  - $\sigma_{site*year}$

  σ_{year} "cancels' because each site is measured in all years (A GOOD THING TO DO)!
- Number of quadrats, number of years before and after impact.

BACI Design 3

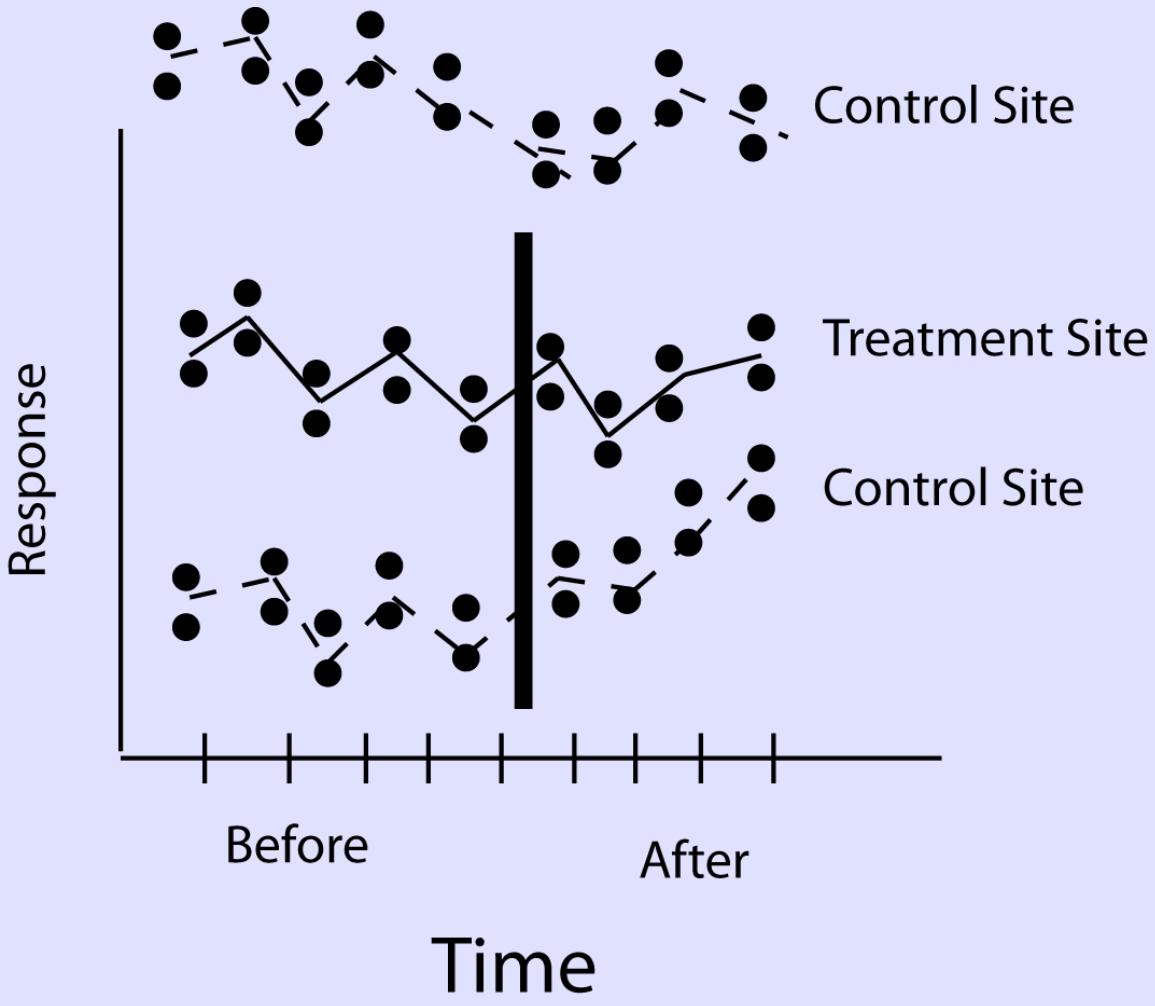
Fish counts example: *BACI* = *various*, $\sigma_{quadrats+site*year} = 27.07$. [With only 1 measurement/year, you cannot separate the two sources of variation.]

```
     alpha ny_B ny_A baci power
[1,] 0.05  12   13   -10  0.09591081
[2,] 0.05  24   26   -10  0.1476783
[3,] 0.05  12   13   40   0.7053772
[4,] 0.05  12   13   50   0.8777241
```

Aim for about 80% power at $\alpha = 0.05$.

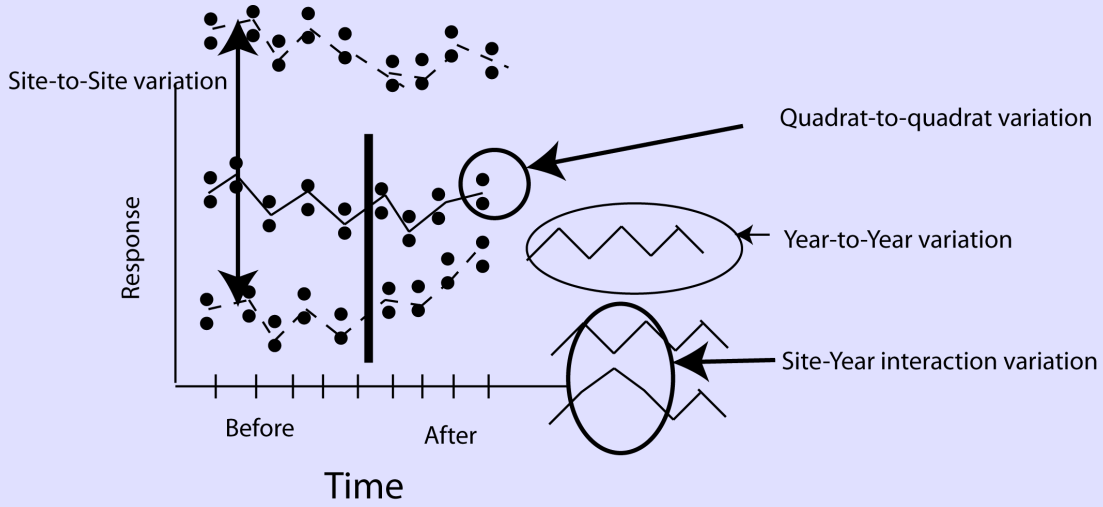
Usually, more years are preferable to more quadrats/site to improve power.

BACI Design 4



E.g. Fry counts (minnow traps) measured in several control and impacted streams several years before and after impact. Multiple traps per site-year combination.

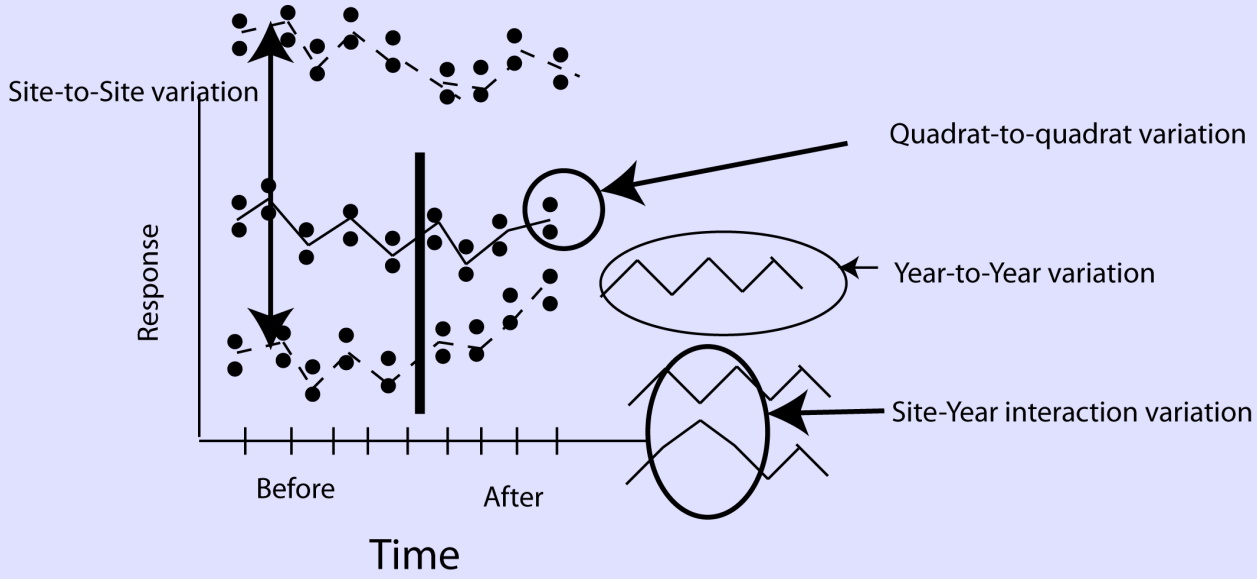
BACI Design 4



Four levels of variation:

- trap-to-trap; These are pseudo-replicates
- year-to-year. External factors that affect all sites the same way. Because measurements are paired within years, this variance component will “cancel” in the analysis.
- site-to-site. Sites are naturally different. Because all sites measured before and after, this variance component will “cancel” in the analysis.
- site*year interaction. Measures the inconsistency of the response of sites to the temporal effects.

BACI Design 4



What can you control via modifications to the sampling design?

- Trap variation can be controlled by soaking longer or using larger traps.
- Year variation cannot be controlled, but by pairing the effects “cancel”.
- Site variation cannot be controlled, but by measuring same site over time, the effect “cancel”.
- Site-Year variation cannot be controlled by modifying design. This is the limiting variation for the design.

BACI Design 4

No simple way to analyze this design except via a fully specified mixed-effects model!

BACI Design 4

Two-factor mixed-effect ANOVA.
SAS Analysis:

```
PROC Mixed data=blah nobound;
CLASS Period Siteclass Site Year;
MODEL Y = Period   Siteclass   Period*Siteclass / ddfm=kr;
RANDOM Year(Period) site(SiteClass)
        year(Period)*site(SiteClass);
ESTIMATE 'BACI Effect' Period*Siteclass 1 -1 -1 1;
```

The test of no impact is the test for no interaction, i.e. test of *Period* $*$ *Siteclass* interaction.
Estimate BACI effect as DIFFERENTIAL change in means between two sites, i.e.

$$BACI = (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb})$$

BACI Design 4

Two-factor mixed-effect ANOVA.

SAS results:

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
SiteClass	1	23	2.28	0.1444
Period	1	23	0.93	0.3438
SiteClass*Period	1	23	0.34	0.5631

Label	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**
baci contrast	1.0512	2.5022	1	0.42	0.7468	0.05

BACI Design 4

Two-factor mixed-effect ANOVA.

SAS results (continued):

Cov Parm	Estimate
Year(Period)	0.1239
Site(SiteClass)	0.2963
Year*Site(Site*Peri)	-4.3630
Residual	4.3331

A negative estimate of variance is possible (and just means that the variance component is small, i.e. close to zero) which is nice for this example.

BACI Design 4

R Analysis: (Be sure that Period, **Year — common error**, Site, and Siteclass are FACTORS).

NOT FOR THE FAINT OF HEART!

SOME R MAGIC - see my website.
anova(result) # Get the ANOVA Table
summary(result) # Get the BACI Effect
VarCorr(result) # Get the variance components

CAUTION: *R* does NOT have a KR adjustment so results may differ from *SAS*.
CAUTION: *R lmer()* function can also be used, but doesn't give p-values directly.

BACI Design 4

R results:

```
                  numDF denDF    F-value p-value
(Intercept)           1    48 218.89032  <.0001
Period                1    48   0.18685  0.6675
SiteClass             1    48   1.78879  0.1874
Period:SiteClass      1    48   0.01295  0.9099
```

Note that test results differ (considerably) from *SAS* but the final conclusion is similar.

Estimate of BACI effect is:

```
      Value   Std.Error           DF     t-value
-0.04760722  0.41841862 48.00000000 -0.11377893  0.
```

BACI Design 4

R results (continued):

Estimate of Variance Components

```
  component          sigma         sigma2
1      Year 2.141448e-01 4.585800e-02
2      Site 7.669657e-01 5.882364e-01
3 Year:Site 2.628037e-05 6.906579e-10
4  Residual 7.234663e-01 5.234035e-01
```

CAUTION: *R* labels the results poorly!

BACI Design 4

Assumptions:

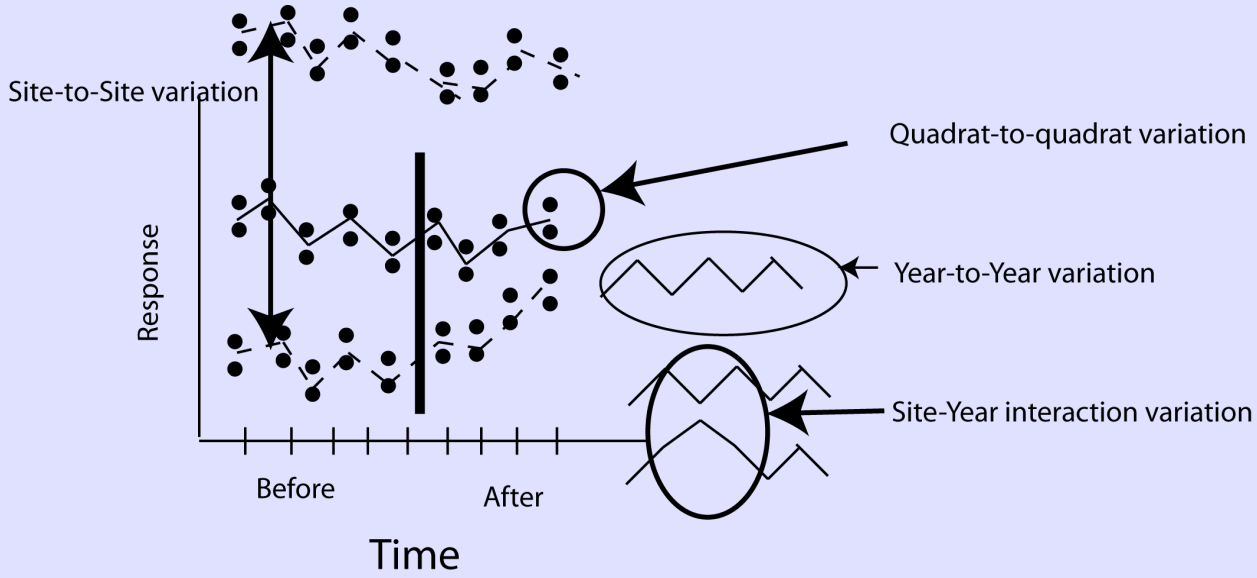
- Not necessary for design to be balanced, i.e. number of traps can vary among sites and years; not all sites need be measured in all years.
- All measurements within and across sites and years at a site are INDEPENDENT of each other.
- All sites are independent of each other.
- Normality of residuals (but fairly robust IF....)
- Equality of variation each each Site $\times$ Year
- Normality of year effects; normality of site effects; normality of *site*year* interactions. Difficult to assess because typically have a few years.

BACI Design 4

Key Limitations and Difference from Design 1:

- Inference generalized to ALL sites and over ALL years.
- Note that a STEP CHANGE in the mean is assumed (see previous slides)!
- Limiting feature is the *site*year* variance component as you cannot influence it by better sample design!
- There is benefit to sampling more years and/or more quadrats, but you need to look at tradeoffs.

BACI Design 4



Power (see web site for programs) depends on:

- Size of BACI effect $= (\mu_{ca} - \mu_{cb}) - (\mu_{ta} - \mu_{tb}) = 5$
- TWO sources of variation important for planning:
  - $\sigma_{quadrat}$ of replicates at each site-year combination
  - $\sigma_{site*year}$

  Other effects (year and site) "cancel" because of pairing and blocking.
- Number of quadrats, number of years before and after impact, number of sites impact and control.

BACI Design 4

Fish counts example: $BACI = 5$, $\sigma_{quadrats} = 0.75$, $\sigma_{site*year} = 0.1$.

```
     alpha n_TA n_TB n_CA n_CB ny_B ny_A ns_T ns_C baci power
[1,] 0.05  3    3    3    3    3    2    3    3    -0.5 0.2996488
[2,] 0.05  6    6    6    6    3    2    3    3    -0.5 0.5068123
[3,] 0.05  9    9    9    9    3    3    3    3    -0.5 0.7619485
[4,] 0.05  6    6    6    6    3    4    3    3    -0.5 0.6722755
```

Aim for about 80% power at $\alpha = 0.05$.

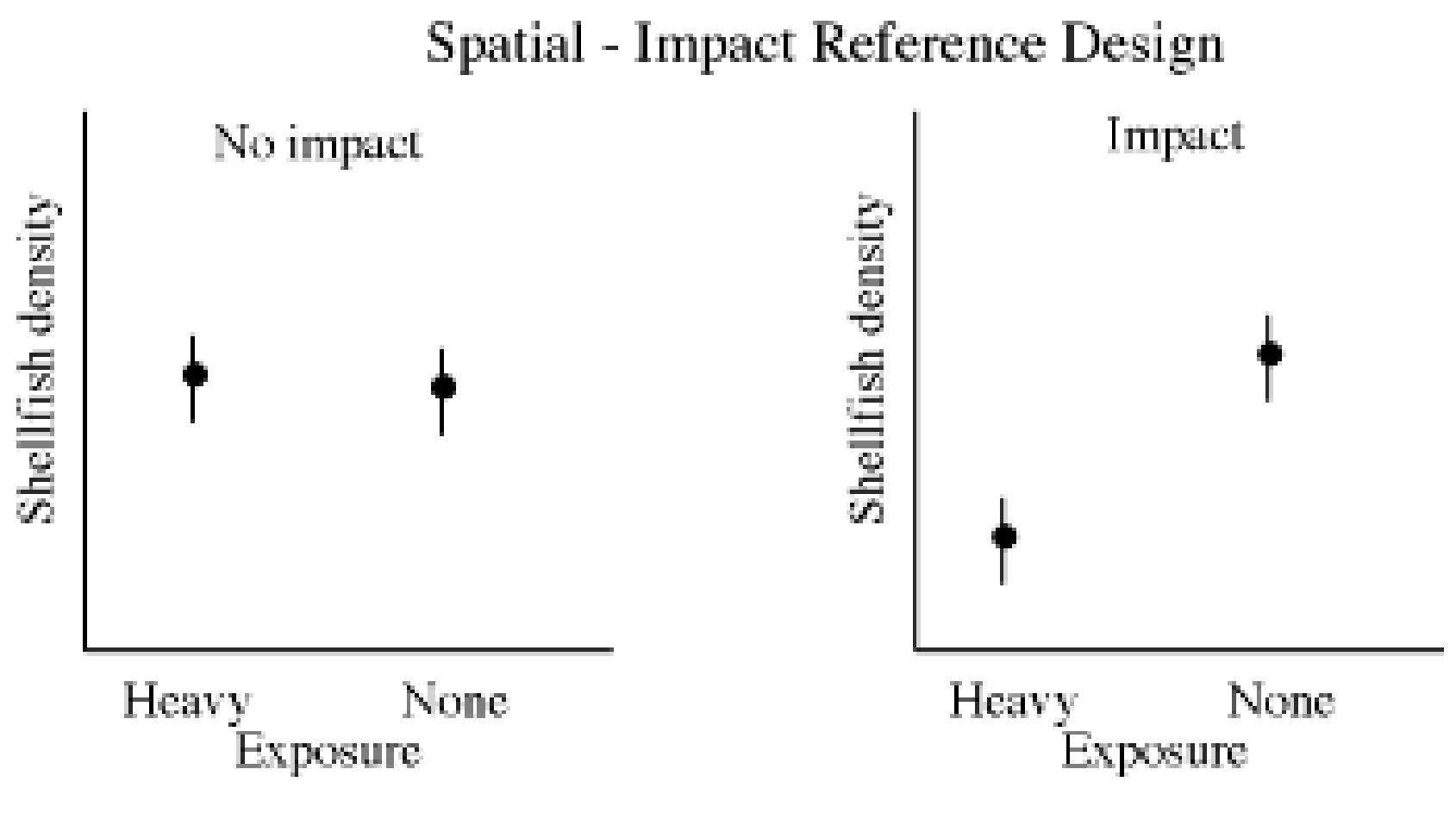
Beyond BACI

What do you do for long-term studies and/or no/few pre-impact measurements?

Wiens, J.A., Parker, K. R. (1995).
Analyzing the Effects of Accidental Environmental Impacts: Approaches and Assumptions.
Ecological Applications 5, 1069-1083.
`http://dx.doi.org/10.2307/2269355`.

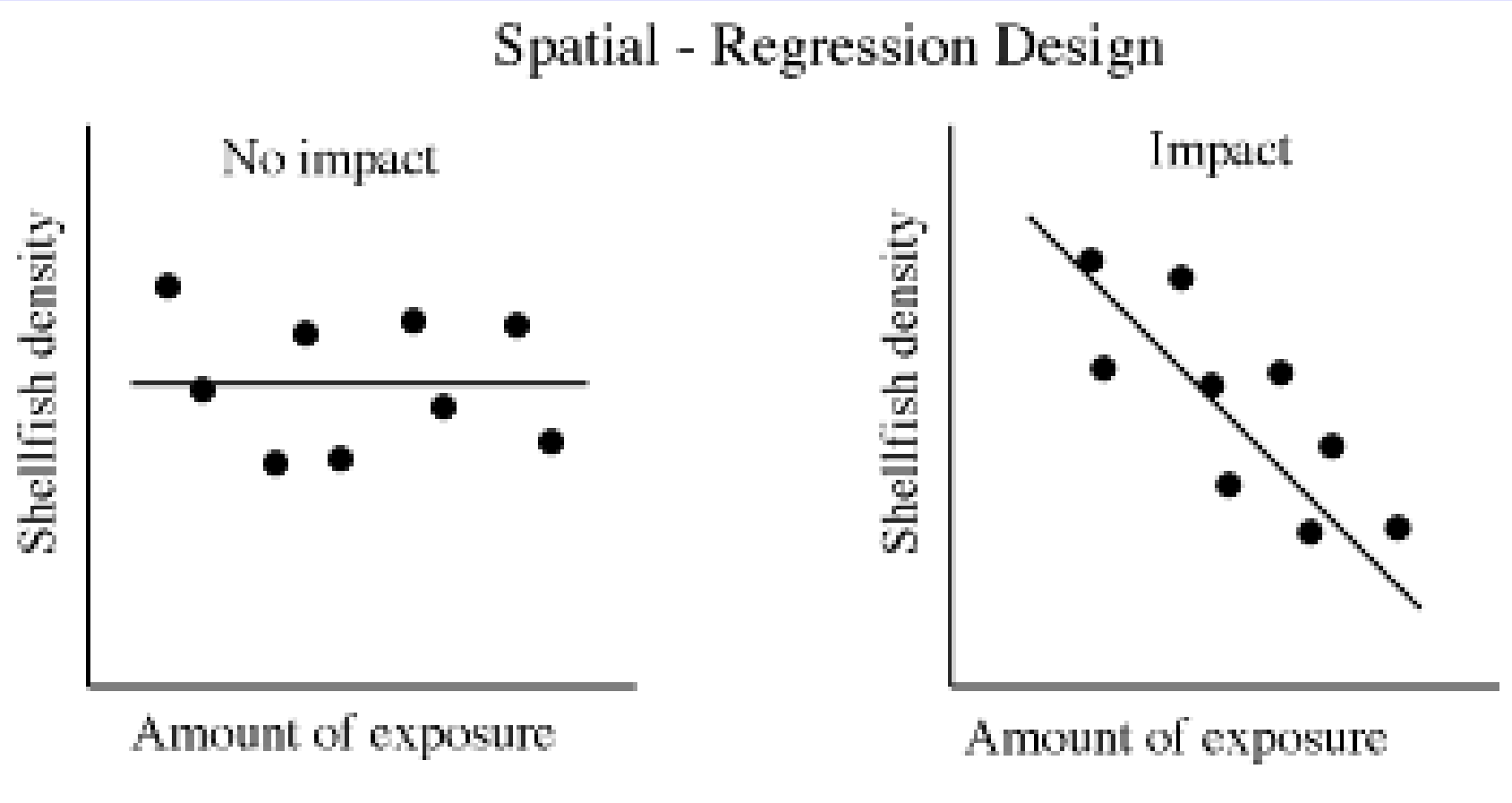
Beyond BACI - Spatial Impact-Reference design

Sampling is performed immediately after impact at two sites - the impacted and non-impacted sites.



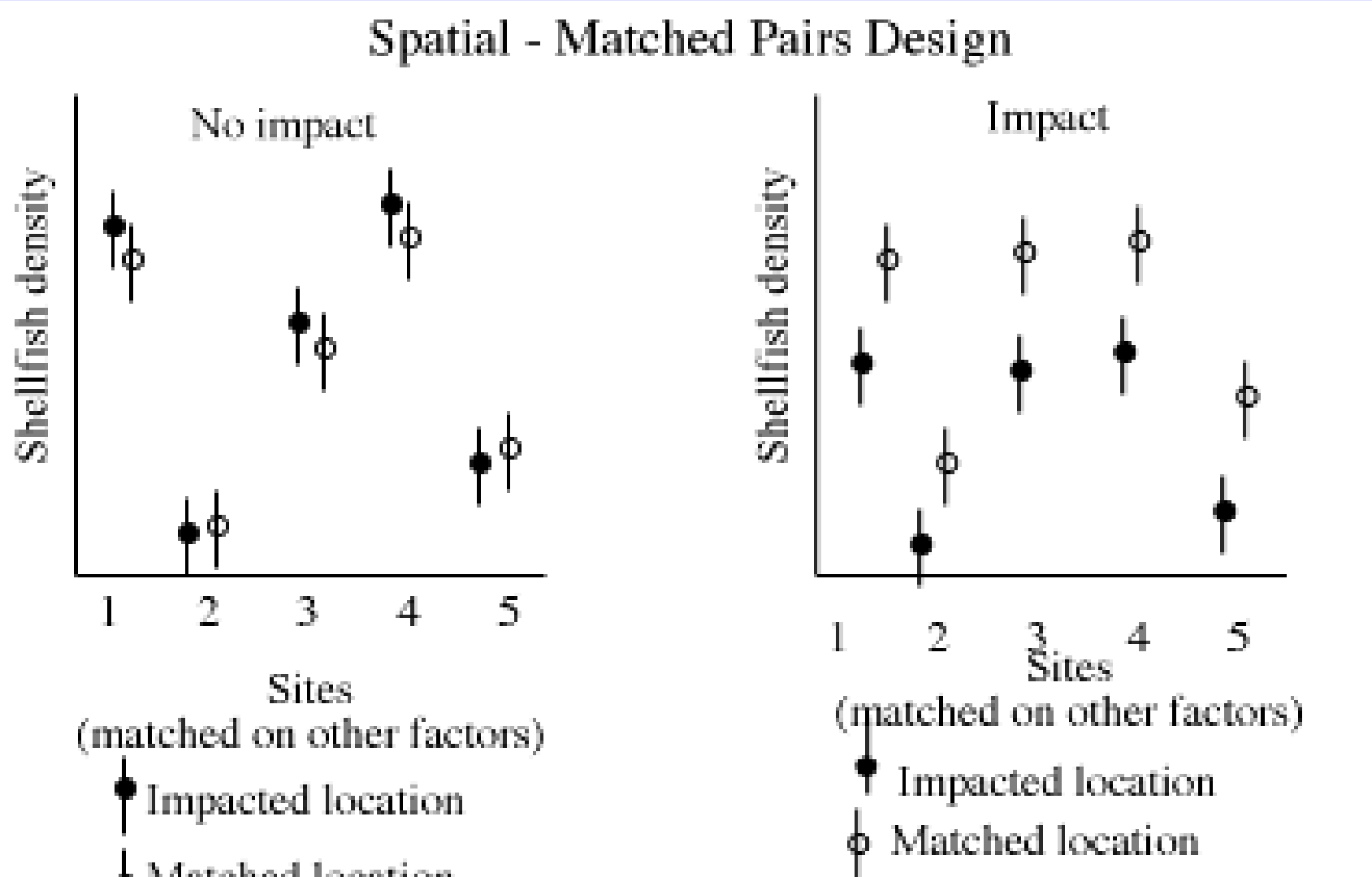
Beyond BACI - Spatial Regression design

Sampling is performed at a number of sites over the range of exposure (e.g. by the amount of oil washed ashore). A regression of abundance against the exposure is drawn.



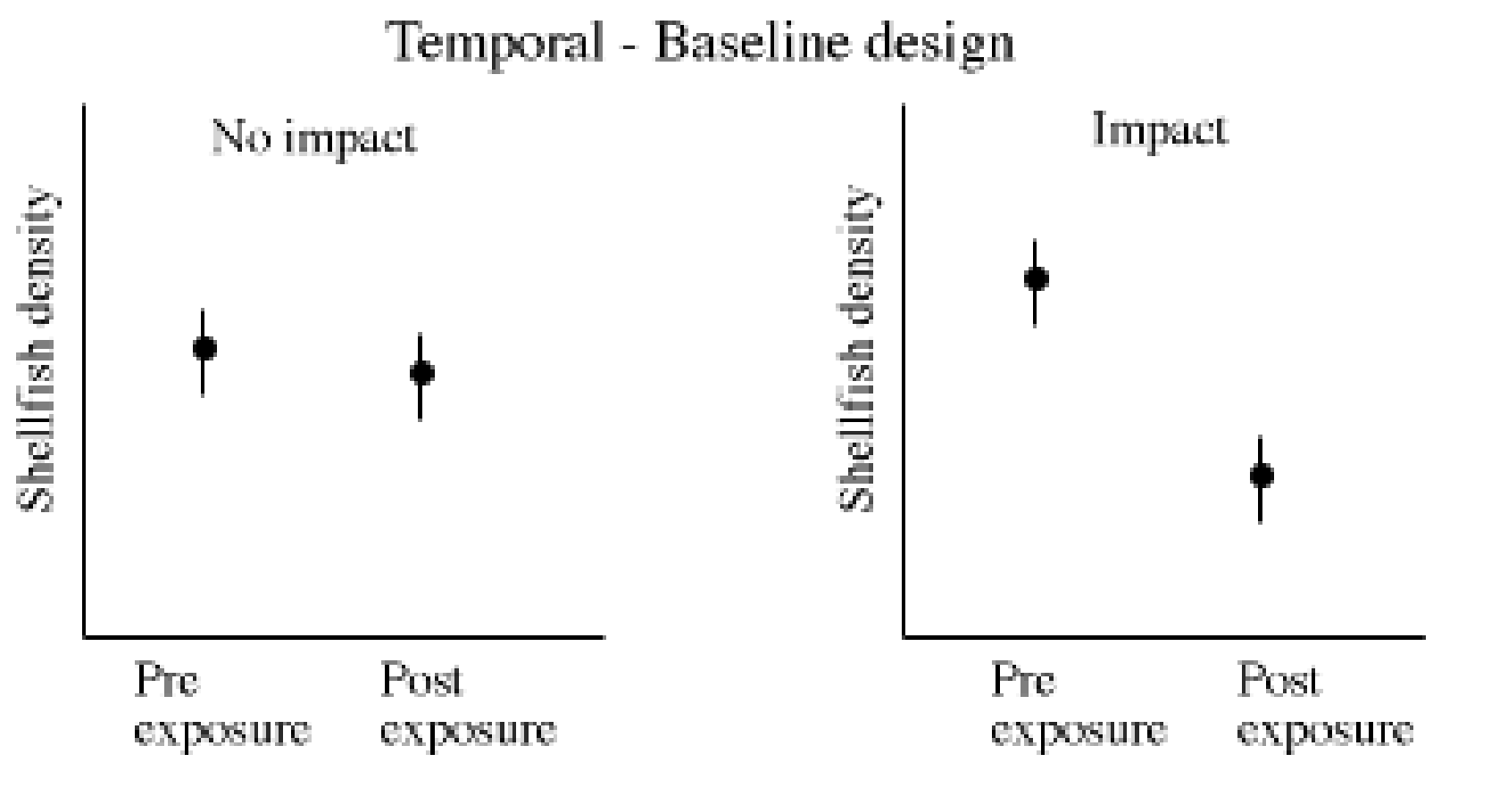
Beyond BACI - Spatial Matched-pair design

Sampling is done on randomly selected impact sites and control sites that are matched on relevant natural factors, e.g. type of substrate where the shell fish aggregate.



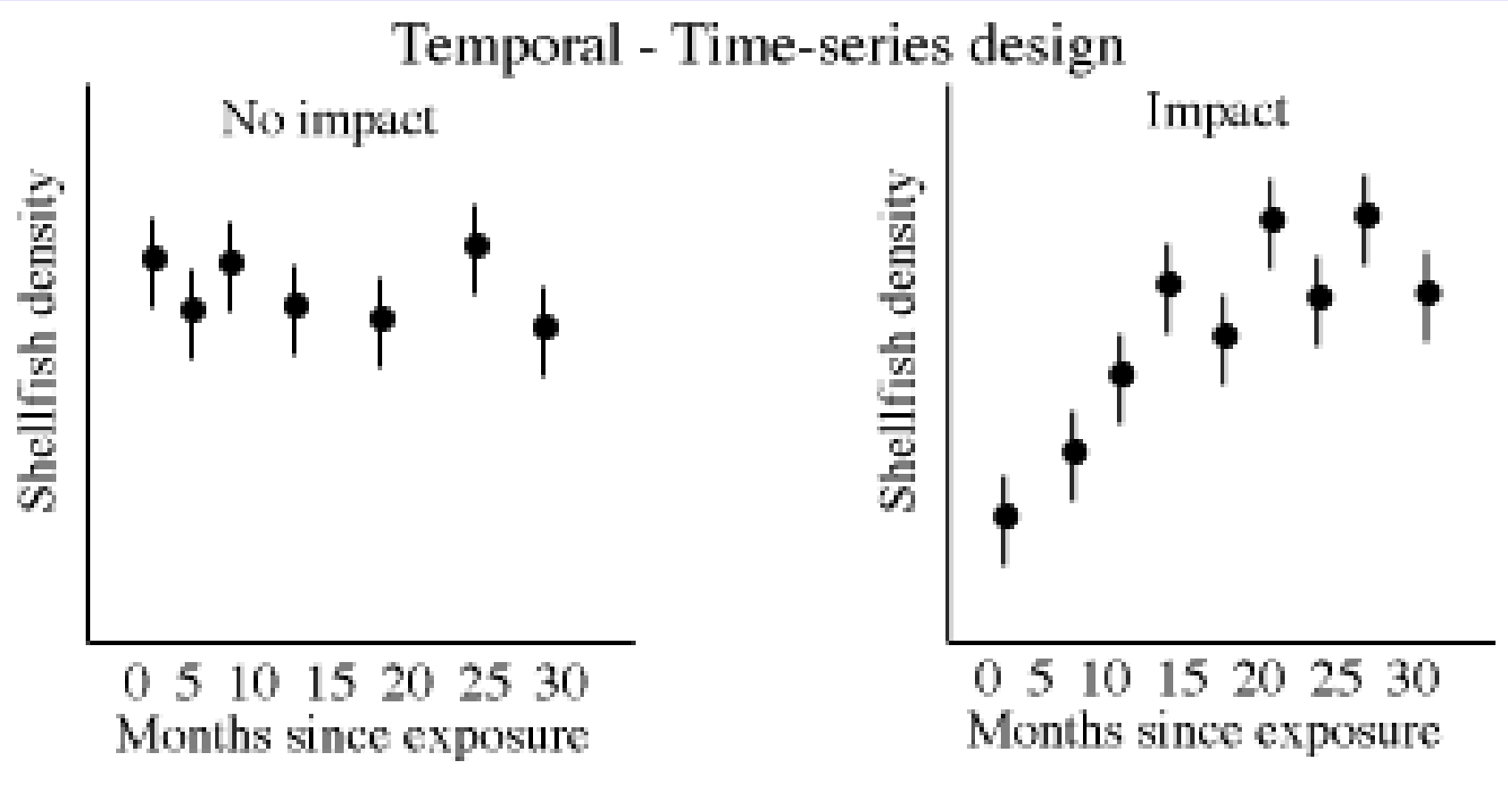
Beyond BACI - Temporal Baseline design

Sometimes, fortuitous surveys have been done at the same site before the impact occurred. Sampling takes place at the same site after the impact.



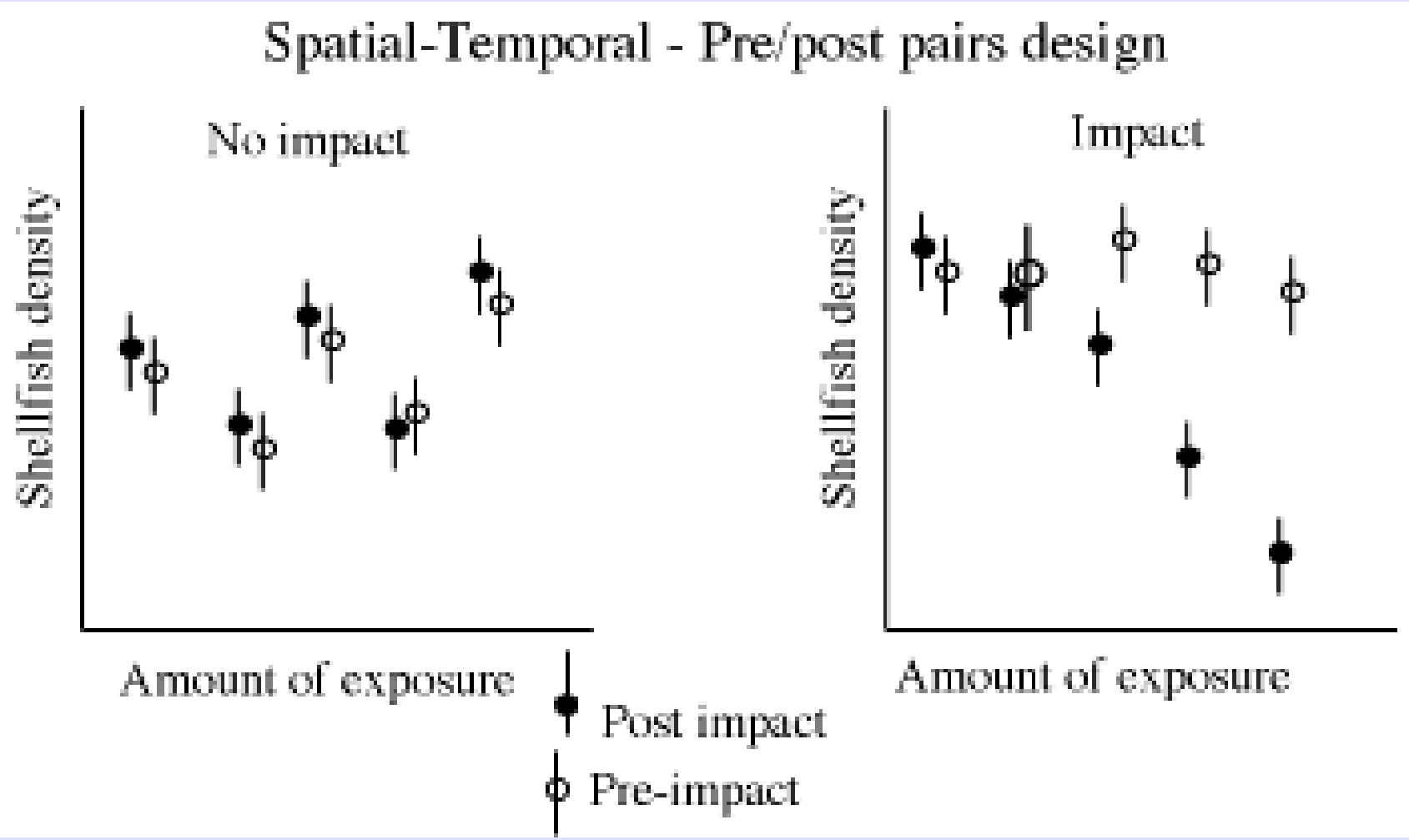
Beyond BACI - Temporal Time-series design

The impacted site is surveyed repeated over a long period of time (e.g. bi-monthly for 2 years) and the results plotted.



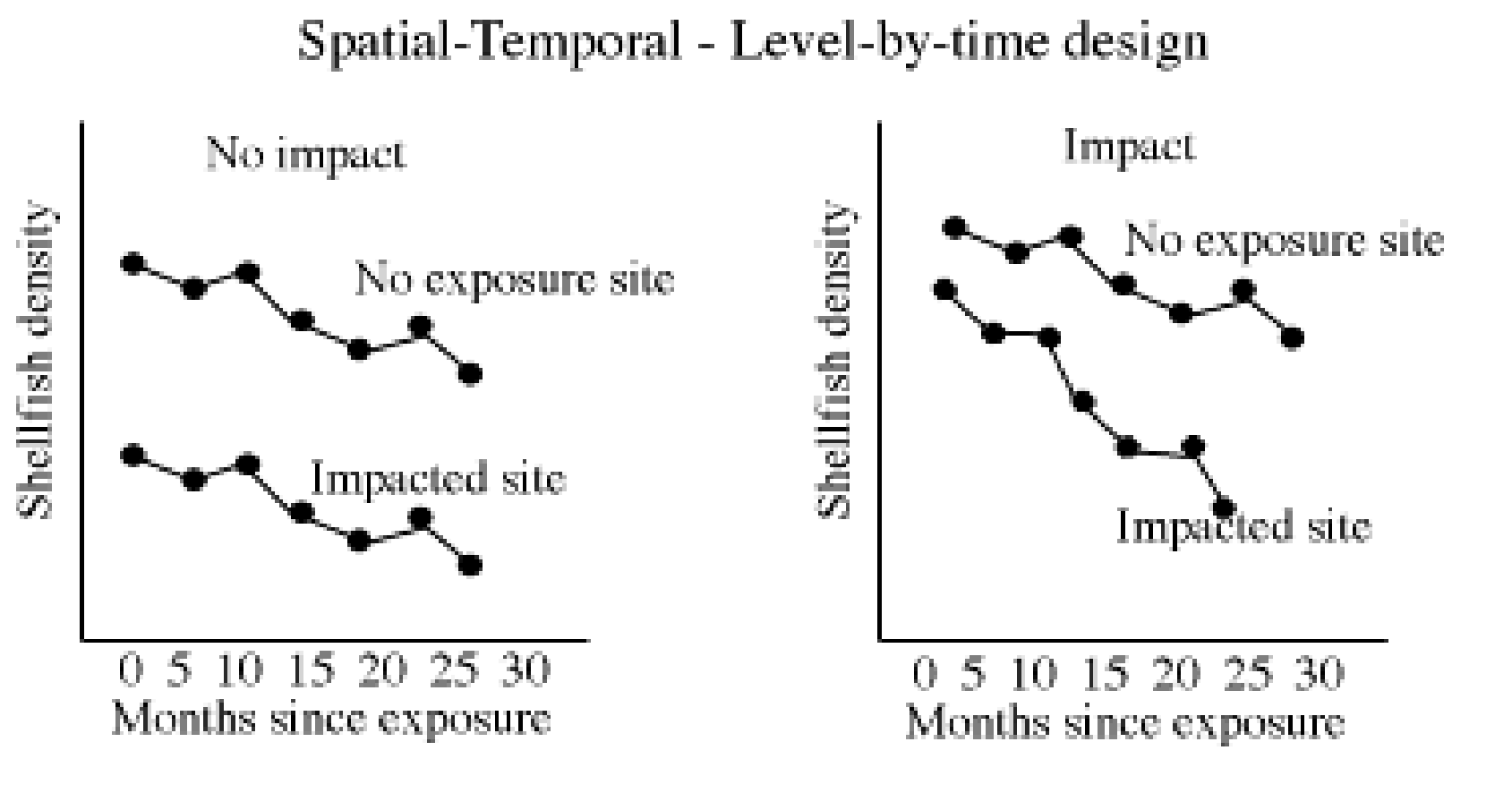
Beyond BACI - Temporal-Spatial Pre-post design

Similar to the classical BACI design except that pre/post samples are taken at sites that vary in the degree of exposure to the impact.



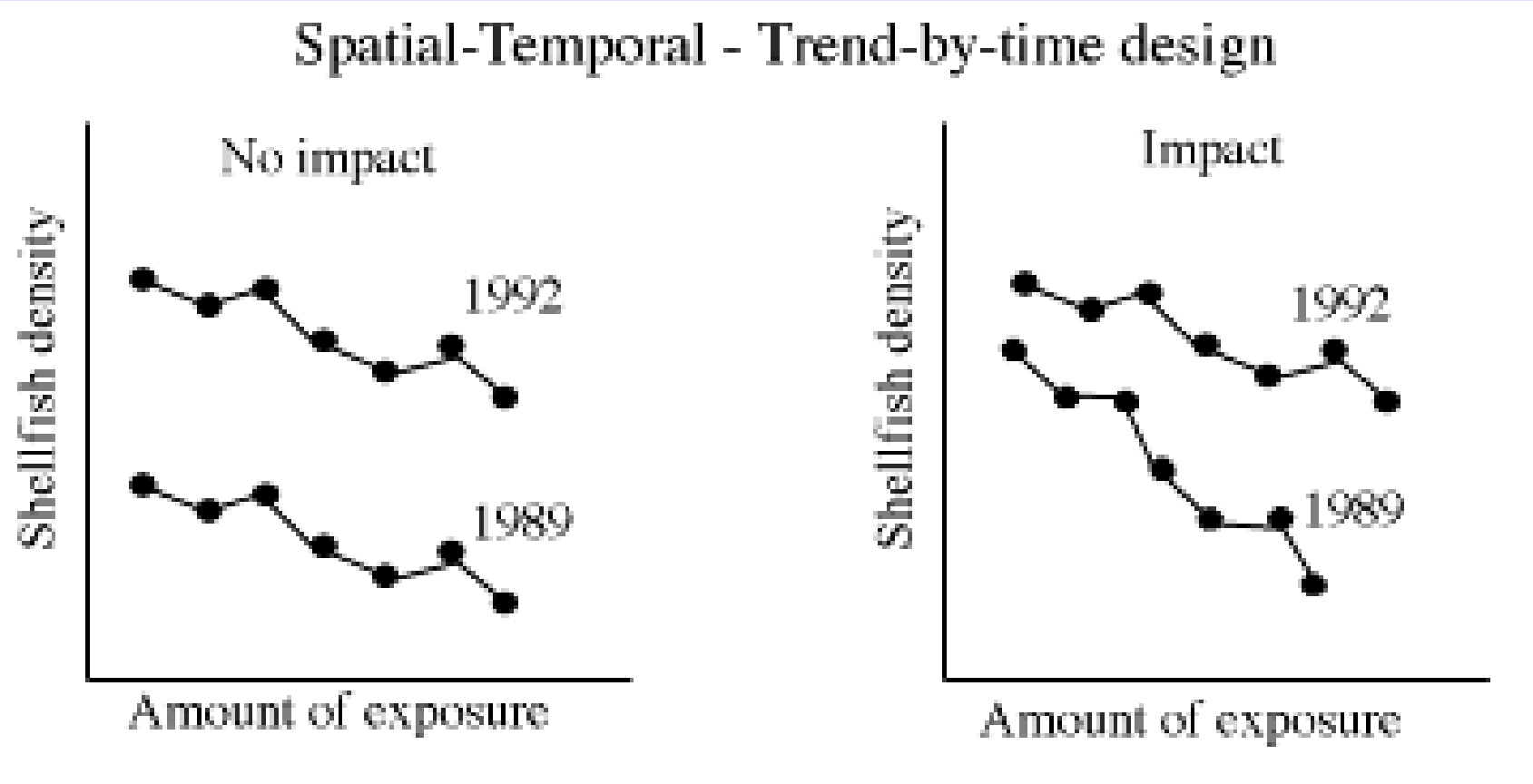
Beyond BACI - Temporal-Spatial Level-by-time design

The impact site is measured over time from the time of impact. A control site is also measured over time from the time of impact at the same sampling occasions.



Beyond BACI - Temporal-Spatial Impact trend-by-time design

The Regression design is performed at the impacted site just after impact. The same design is performed at the impacted site a year or longer after impact. Both plots of response vs. dose are plotted on the same graph.



Beyond BACI - Key Assumptions

Key assumptions for SPATIAL designs.

- Equal natural factors at impacted and non-impacted areas. However, because contamination was not randomized, there is no guarantee of equal natural factors.
- Sampling interval is short relative to temporal variation. This guarantees that the measurements show the effect of the impact and not just difference that would have occurred naturally over time.

Beyond BACI - Key Assumptions

Key assumptions for TEMPORAL designs.

- Natural factors are in steady-state equilibrium, i.e. the population levels remain the same over time in the absence of an impact.
- Differences in sampling personnel and sampling methods over time are inconsequential so that the observed differences are related to the impact and not to differences in methods.

Beyond BACI - Key Assumptions

Key assumptions for SPATIAL-TEMPORAL designs.

- Natural factors and the biological resource are in dynamic equilibrium among area. The level of a resource changes similarly for different areas – responding similarly to changing climatic conditions and populations.
- Consistent sampling methods over time.

Beyond BACI - Ranking Designs

Ability of initial impact and recovery?

Design	**Assessing initial impact**	**Assessing recovery**
Spatial Impact-reference	x	
Spatial Regression	x	
Spatial Matched pairs	x	
Temporal Baseline	x	
Temporal Time series	x	x
ST Pre-post pairs	x	
ST Level-by-time	x	x
ST Trend-by-time	x	x

Beyond BACI - Defensibility

Defensibility to determine if impact occurred (4=better)

Design	Ranking
Spatial Impact-reference	2
Spatial Regression	2
Spatial Matched pairs	2
Temporal Baseline	1
Temporal Time series	2
ST Pre-post pairs	3
ST Level-by-time	4
ST Trend-by-time	4

Summary

Four standard BACI designs:

1. Single impact site; single control site; one year before; one year after.
2. Single/multiple impact site; multiple control sites; one year before; one year after.
3. Single impact site; single control site; multiple years before; multiple years after.
4. Single impact site; multiple control sites; multiple years before; multiple years after.

Summary

Analysis of such designs

- For all but simple BACI (Design 1), mixed-effect ANOVA needed due to presence of multiple-sources of variation. [Some simplification possible under special cases.]
- Beware of pseudo-replication (quadrats vs. sites).
- Single site/single year designs have NARROW inference space.
- *Excel* - hopeless; *R* - you get what you pay for; *SAS* - best
- See my web pages for examples.

Planning BACI designs

- Need estimates of quadrat-to-quadrat variance and site-year interaction variance.
- Site effects and year effects “cancel” and can be ignored.
- Usually better to do more sites and/or year than to measure more quadrats in each site-year combination.

Summary

- Weins and Parker (1995) paper if no or limited pre-impact measurements.

DO NOT PANIC!

`http://www.stat.sfu.ca/~cschwarz/CourseNotes`

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