

Appendix C: Demonstration of selected features

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```
library(dsem)
library(dynlm)
library(ggplot2)
library(reshape)
library(gridExtra)
library(phylopath)
```

`dsem` is an R package for fitting dynamic structural equation models (DSEMs) with a simple user-interface and generic specification of simultaneous and lagged effects that could be either recursive or non-recursive in structure. We here highlight a few features in particular.

Comparison with dynamic linear models

We first demonstrate that `dsem` gives identical results to `dynlm` for a well-known econometric model, the Klein-1 model.

```
data(KleinI, package="AER")
TS = ts(data.frame(KleinI, "time"=time(KleinI) - 1931))

# dynlm
fm_cons <- dynlm(consumption ~ cprofits + L(cprofits) + I(pwage + gwage), data = TS)
fm_inv <- dynlm(invest ~ cprofits + L(cprofits) + capital, data = TS) #
fm_pwage <- dynlm(pwage ~ gnp + L(gnp) + time, data = TS)

# dsem
sem = "
  # Link, lag, param_name
  cprofits -> consumption, 0, a1
  cprofits -> consumption, 1, a2
  pwage -> consumption, 0, a3
  gwage -> consumption, 0, a3

  cprofits -> invest, 0, b1
  cprofits -> invest, 1, b2
  capital -> invest, 0, b3

  gnp -> pwage, 0, c2
  gnp -> pwage, 1, c3
  time -> pwage, 0, c1
"
tsdata = TS[,c("time", "gnp", "pwage", "cprofits", "consumption",
               "gwage", "invest", "capital")]
fit = dsem( sem=sem,
```

```

        tsdata = tsdata,
        estimate_delta0 = TRUE,
        control = dsem_control(
            quiet = TRUE,
            newton_loops = 0) )
#> 1 regions found.
#> Using 1 threads
#> 1 regions found.
#> Using 1 threads

# Compile
m1 = rbind( summary(fm_cons)$coef[-1,],
            summary(fm_inv)$coef[-1,],
            summary(fm_pwage)$coef[-1,] )[,1:2]
m2 = summary(fit$sdrep)[1:9,]
m = rbind(
    data.frame("var"=rownames(m1),m1,"method"="OLS","eq"=rep(c("C","I","Wp"),each=3)),
    data.frame("var"=rownames(m1),m2,"method"="GMRF","eq"=rep(c("C","I","Wp"),each=3))
)
m = cbind(m, "lower"=m$Estimate-m$Std..Error, "upper"=m$Estimate+m$Std..Error )

# ggplot estimates
longform = melt( as.data.frame(KleinI) )
longform$year = rep( time(KleinI), 9 )
ggplot( data=longform, aes(x=year, y=value) ) +
  facet_grid( rows=vars(variable), scales="free" ) +
  geom_line( )

ggplot(data=m, aes(x=interaction(var,eq), y=Estimate, color=method)) +
  geom_point( position=position_dodge(0.9) ) +
  geom_errorbar( aes(ymax=as.numeric(upper),ymin=as.numeric(lower)),
                width=0.25, position=position_dodge(0.9)) #

p3 = plot( as_fitted_DAG(fit) ) +
  expand_limits(x = c(-0.2,1) )
p4 = plot( as_fitted_DAG(fit, lag=1), text_size=4 ) +
  expand_limits(x = c(-0.2,1), y = c(-0.2,0) )
grid.arrange( arrangeGrob(p3, p4, nrow=2) )

```

Results show that both packages provide (almost) identical estimates and standard errors.

We can also compare results using the Laplace approximation against those obtained via numerical integration of random effects using MCMC. In this example, MCMC results in somewhat higher estimates of exogenous variance parameters (presumably because those follow a chi-squared distribution with positive skewness), but otherwise the two produce similar estimates.

```

library(tmbstan)

# MCMC for both fixed and random effects
mcmc = tmbstan( fit$obj, init="last.par.best" )
summary_mcmc = summary(mcmc)

```

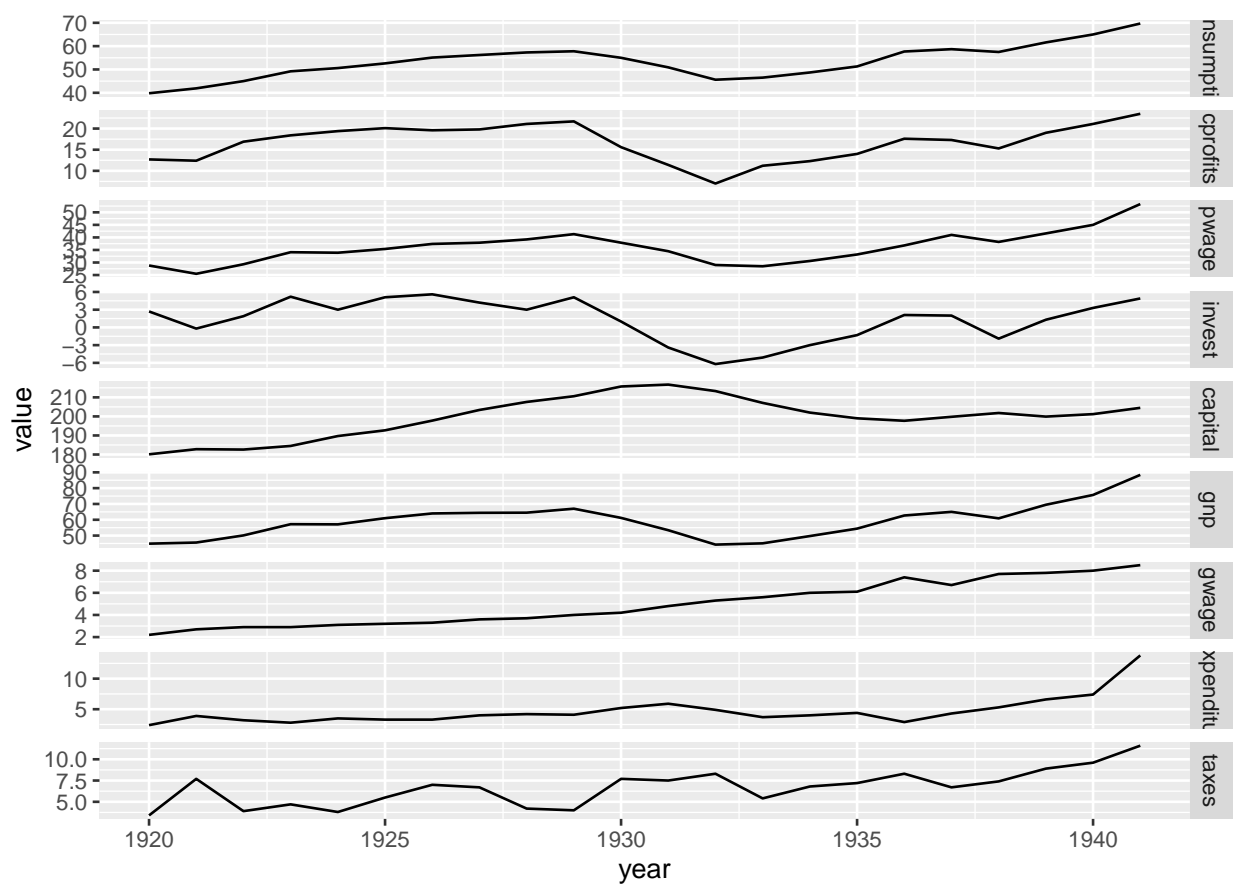


Figure 1: Econometric variables fitted to demonstrate dynamic structural equation modelling

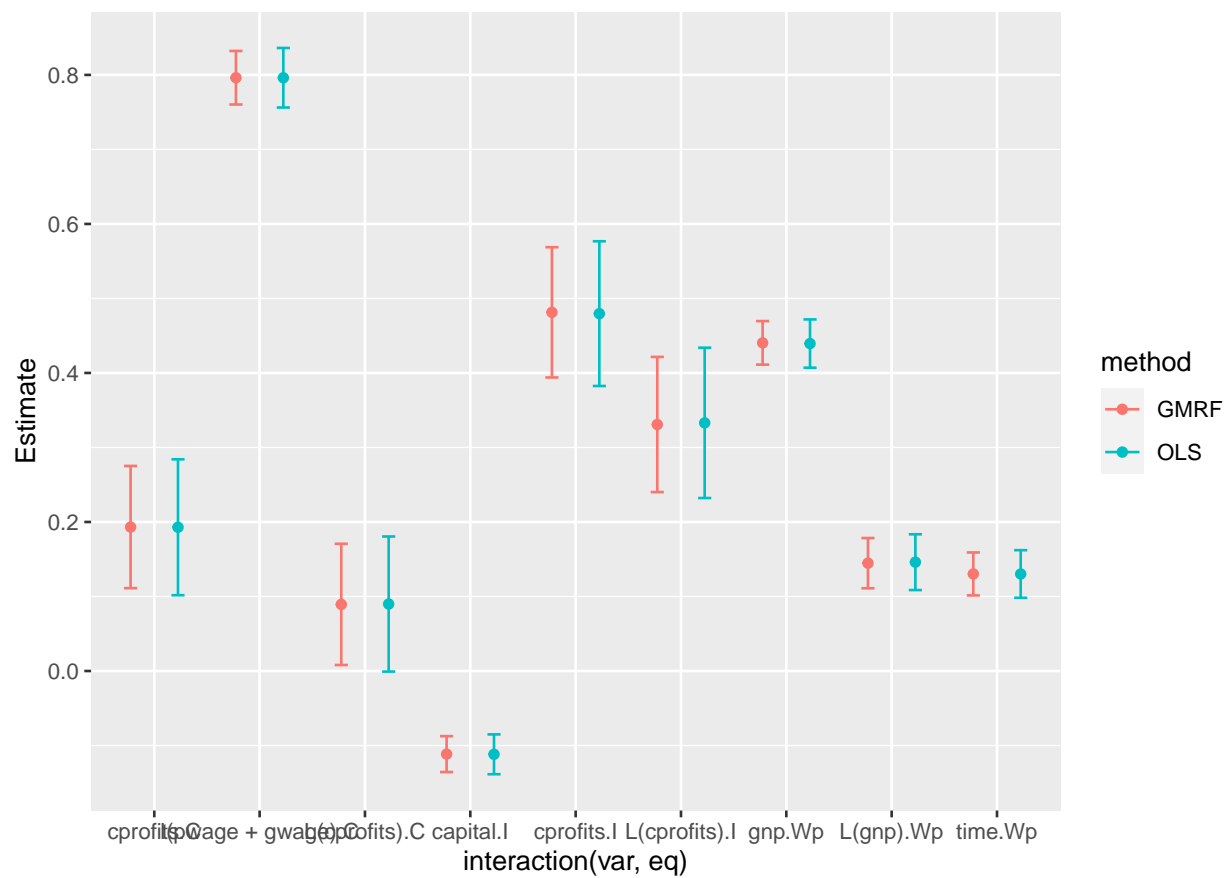


Figure 2: Comparison of package dsem and package dynlm when fitting a dynamic structural equation model to econometric data

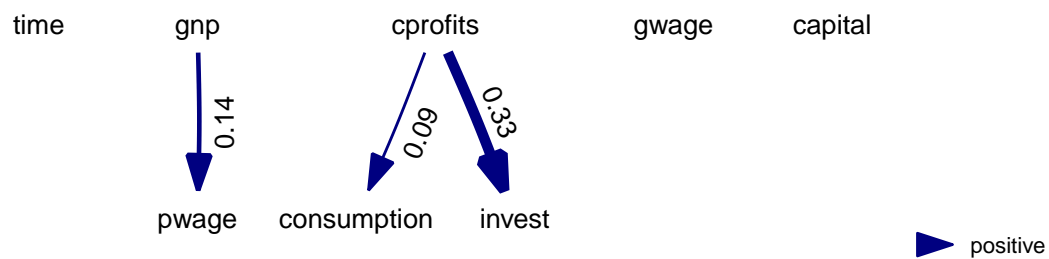
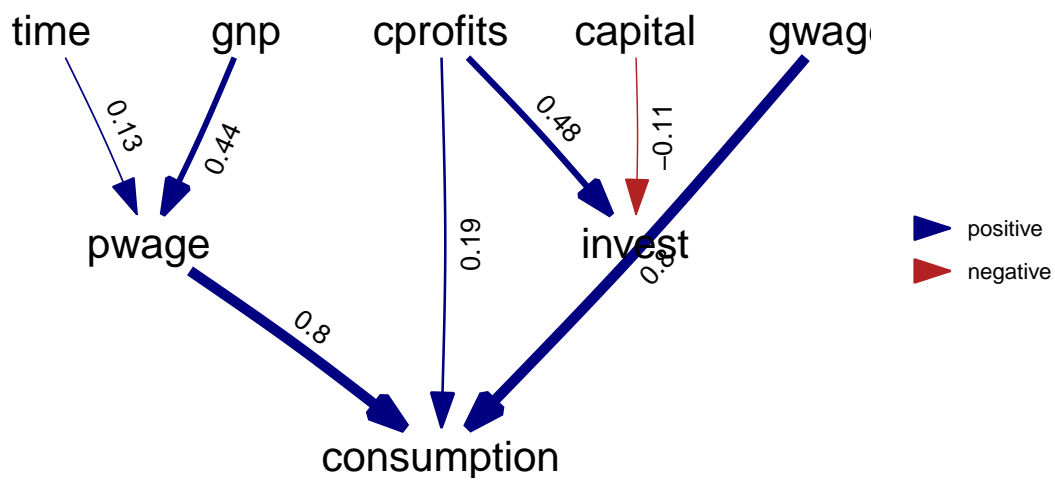


Figure 3: Estimated structural model among econometric variables

```

# long-form data frame
m1 = summary_mcmc$summary[1:17,c('mean','sd')]
rownames(m1) = paste0( "b", seq_len(nrow(m1)) )
m2 = summary(fit$sdrep)[1:17,c('Estimate','Std. Error')]
m = rbind(
  data.frame('mean'=m1[,1], 'sd'=m1[,2], 'par'=rownames(m1), "method"="MCMC"),
  data.frame('mean'=m2[,1], 'sd'=m2[,2], 'par'=rownames(m1), "method"="LA")
)
m$lower = m$mean - m$sd
m$upper = m$mean + m$sd

# plot
ggplot(data=m, aes(x=par, y=mean, col=method)) +
  geom_point( position=position_dodge(0.9) ) +
  geom_errorbar( aes(ymin=as.numeric(lower),ymax=as.numeric(upper)),
    width=0.25, position=position_dodge(0.9)) #

```

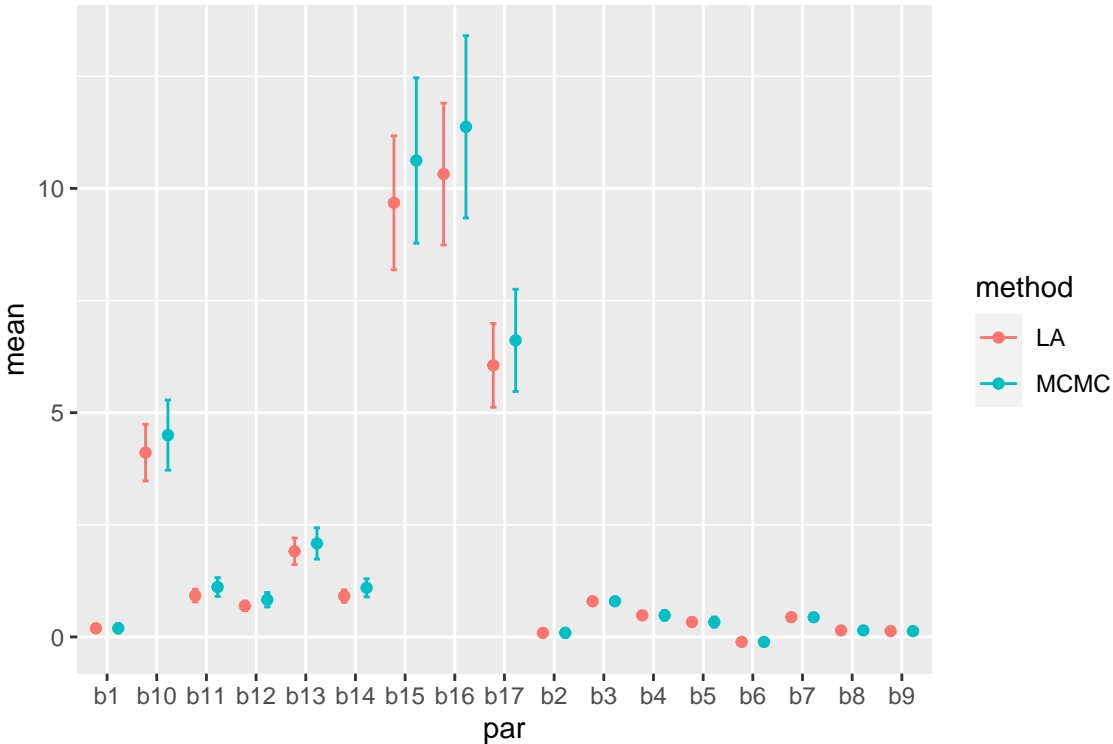


Figure 4: Comparison of Laplace approximation and Markov chain Monte Carlo estimates when fitting an econometric example using dynamic structural equation models

Comparison with vector autoregressive models

We next demonstrate that `dsem` gives similar results to a vector autoregressive (VAR) model. To do so, we analyze population abundance of wolf and moose populations on Isle Royale from 1959 to 2019, downloaded from their website (Vucetich, JA and Peterson RO. 2012. The population biology of Isle Royale wolves and moose: an overview. URL: www.isleroyalewolf.org).

This dataset was previously analyzed by in Chapter 14 of the User Manual for the R-package MARSS (Holmes, E. E., M. D. Scheuerell, and E. J. Ward (2023) Analysis of multivariate time-series using the MARSS package. Version 3.11.8. NOAA Fisheries, Northwest Fisheries Science Center, 2725 Montlake Blvd E., Seattle, WA 98112, DOI: 10.5281/zenodo.5781847).

Here, we compare fits using `dsem` with `dynlm`, as well as a vector autoregressive model package `vars`, and finally with MARSS.

```
data(isle_royale)
data = ts( log(isle_royale[,2:3]), start=1959)

sem = "
  # Link, lag, param_name
  wolves -> wolves, 1, arW
  moose -> wolves, 1, MtoW
  wolves -> moose, 1, WtoM
  moose -> moose, 1, arM
"
# initial first without delta0 (to improve starting values)
fit0 = dsem( sem = sem,
             tsdata = data,
             estimate_delta0 = FALSE,
             control = dsem_control(
               quiet = TRUE,
               getstd = FALSE) )
#> Warning in nlminb(start = out$opt$par, objective = obj$fn, gradient = obj$gr, : NA/NaN function eval
# Refit with delta0
fit = dsem( sem = sem,
            tsdata = data,
            estimate_delta0 = TRUE,
            control = dsem_control( quiet=TRUE,
                                   parameters = fit0$obj$env$parList() ) )

# dynlm
fm_wolf = dynlm( wolves ~ 1 + L(wolves) + L(moose), data=data ) #
fm_moose = dynlm( moose ~ 1 + L(wolves) + L(moose), data=data ) #

# MARSS
library(MARSS)
z.royale.dat <- t(scale(data.frame(data),center=TRUE,scale=FALSE))
royale.model.1 <- list(
  Z = "identity",
  B = "unconstrained",
  Q = "diagonal and unequal",
  R = "zero",
  U = "zero"
)
kem.1 <- MARSS(z.royale.dat, model = royale.model.1)
#> Success! abstol and log-log tests passed at 16 iterations.
#> Alert: conv.test.slope.tol is 0.5.
#> Test with smaller values (<0.1) to ensure convergence.
#>
#> MARSS fit is
#> Estimation method: kem
```

```

#> Convergence test: conv.test.slope.tol = 0.5, abstol = 0.001
#> Estimation converged in 16 iterations.
#> Log-likelihood: -3.21765
#> AIC: 22.4353   AICc: 23.70964
#>
#>
#> Estimate
#> B.(1,1)      0.8669
#> B.(2,1)     -0.1240
#> B.(1,2)      0.1417
#> B.(2,2)      0.8176
#> Q.(X.wolves,X.wolves) 0.1341
#> Q.(X.moose,X.moose) 0.0284
#> x0.X.wolves 0.2324
#> x0.X.moose -0.6476
#> Initial states (x0) defined at t=0
#>
#> Standard errors have not been calculated.
#> Use MARSSparamCIs to compute CIs and bias estimates.
SE <- MARSSparamCIs( kem.1 )

# Using VAR package
library(vars)
var = VAR( data, type="const" )

### Compile
m1 = rbind( summary(fm_wolf)$coef[-1,], summary(fm_moose)$coef[-1,] )[,1:2]
m2 = summary(fit$sdrep)[1:4,]
#m2 = cbind( "Estimate"=fit$opt$par, "Std. Error"=fit$sdrep$par.fixed )[1:4,]
m3 = cbind( SE$parMean[c(1,3,2,4)], SE$par.se$B[c(1,3,2,4)] )
colnames(m3) = colnames(m2)
m4 = rbind( summary(var$varresult$wolves)$coef[-3,], summary(var$varresult$moose)$coef[-3,] )[,1:2]

# Bundle
m = rbind(
  data.frame("var"=rownames(m1), m1, "method"="dynlm", "eq"=rep(c("Wolf", "Moose"),each=2)),
  data.frame("var"=rownames(m1), m2, "method"="dsem", "eq"=rep(c("Wolf", "Moose"),each=2)),
  data.frame("var"=rownames(m1), m3, "method"="MARSS", "eq"=rep(c("Wolf", "Moose"),each=2)),
  data.frame("var"=rownames(m1), m4, "method"="vars", "eq"=rep(c("Wolf", "Moose"),each=2))
)
#knitr::kable( m1, digits=3)
#knitr::kable( m2, digits=3)

m = cbind(m, "lower"=m$Estimate-m$Std..Error, "upper"=m$Estimate+m$Std..Error )

# ggplot estimates ... interaction(x,y) causes an error sometimes
library(ggplot2)
library(ggpubr)
library(graph)
longform = reshape( isle_royale, idvar = "year", direction="long", varying=list(2:3), v.names="abundance" )
p1 = ggplot( data=longform, aes(x=year, y=abundance) ) +
  facet_grid( rows=vars(species), scales="free" ) +
  geom_point( )

```



```
p2 = ggplot(data=m, aes(x=interaction(var,eq), y=Estimate, color=method)) +
  geom_point( position=position_dodge(0.9) ) +
  geom_errorbar( aes(ymax=as.numeric(upper),ymin=as.numeric(lower)),
    width=0.25, position=position_dodge(0.9)) #
ggarrange( p1, p2,
  labels = c("Time-series data", "Estimated effects"),
  ncol = 1, nrow = 2)
```

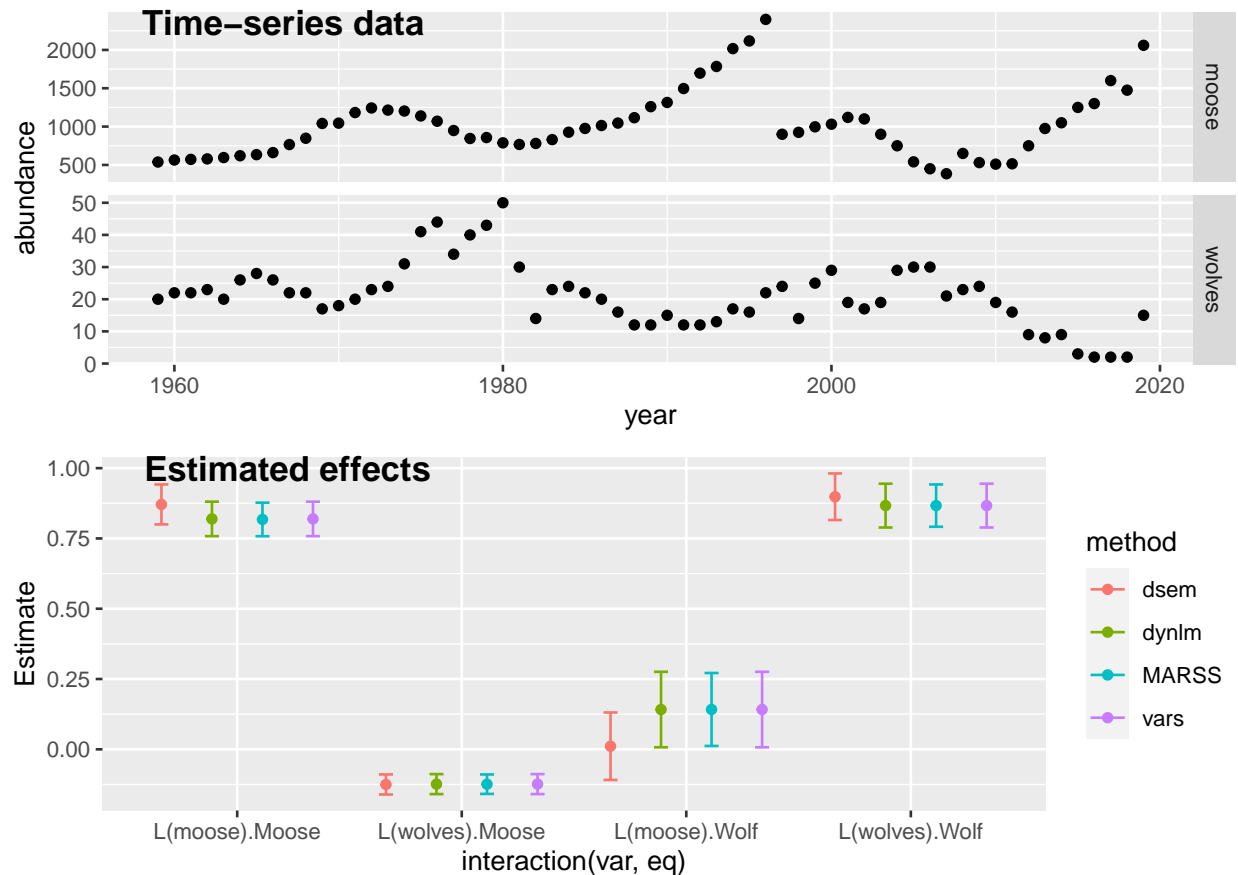


Figure 5: Time-series observations (top panel) and a comparison of estimated structural linkages (bottom panel) among alternative software for fitting a cross-lagged model for wolves and moose in Isle Royale

```
plot( as_fitted_DAG(fit, lag=1), rotation=0 ) +
  geom_edge_loop( aes( label=round(weight,2), direction=0)) + #arrow=arrow(), , angle_calc="along",
  expand_limits(x = c(-0.1,0) )
```

Results again show that `dsem` can estimate parameters for a vector autoregressive model (VAM), and it exactly matches results from `vars`, using `dynlm`, or using `MARSS`.

Multi-causal ecosystem synthesis

We next replicate an analysis involving climate, forage fishes, stomach contents, and recruitment of a predatory fish.

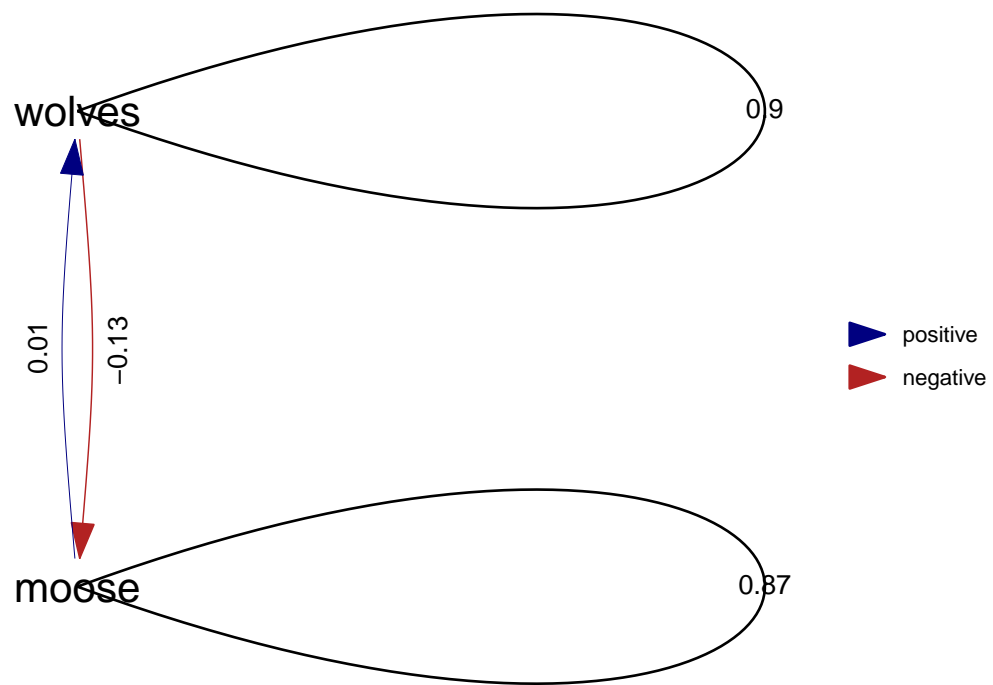


Figure 6: Estimated structural model representing cross-lagged interactions between wolves and moose in Isle Royale

```

data(bering_sea)
Z = ts( bering_sea )
family = rep('fixed', ncol(bering_sea))

# Specify model
sem = "
  # Link, lag, param_name
  log_seaice -> log_CP, 0, seaice_to_CP
  log_CP -> log_Cfall, 0, CP_to_Cfall
  log_CP -> log_Esummer, 0, CP_to_E
  log_PercentEuph -> log_RperS, 0, Seuph_to_RperS
  log_PercentCop -> log_RperS, 0, Scop_to_RperS
  log_Esummer -> log_PercentEuph, 0, Esummer_to_Suph
  log_Cfall -> log_PercentCop, 0, Cfall_to_Scop
  log_SSB -> log_RperS, 0, SSB_to_RperS

  log_seaice -> log_seaice, 1, AR1, 0.001
  log_CP -> log_CP, 1, AR2, 0.001
  log_Cspring -> log_Cspring, 1, AR3, 0.001
  log_Cfall -> log_Cfall, 1, AR4, 0.001
  log_Esummer -> log_Esummer, 1, AR5, 0.001
  log_SSB -> log_SSB, 1, AR6, 0.001
  log_RperS -> log_RperS, 1, AR7, 0.001
  log_PercentEuph -> log_PercentEuph, 1, AR8, 0.001
  log_PercentCop -> log_PercentCop, 1, AR9, 0.001
"

# Fit
fit = dsem( sem = sem,
            tsdata = Z,
            family = family,
            control = dsem_control(use_REML=FALSE, quiet=TRUE) )
#> Warning in nlminb(start = out$opt$par, objective = obj$fn, gradient = obj$gr, : NA/NaN function eval
#> Warning in nlminb(start = out$opt$par, objective = obj$fn, gradient = obj$gr, : NA/NaN function eval
ParHat = fit$obj$env$parList()
# summary( fit )

# Timeseries plot
oldpar <- par(no.readonly = TRUE)
par( mfcol=c(3,3), mar=c(2,2,2,0), mgp=c(2,0.5,0), tck=-0.02 )
for(i in 1:ncol(bering_sea)){
  tmp = bering_sea[,i,drop=FALSE]
  tmp = cbind( tmp, "PSEM"=ParHat$x_tj[,i] )
  SD = as.list(fit$sdrep,what="Std.")$x_tj[,i]
  tmp = cbind( tmp, outer(tmp[,2],c(1,1)) +
               outer(iffelse(is.na(SD),0,SD),c(-1,1)) )
  #
  plot( x=rownames(bering_sea), y=tmp[,1], ylim=range(tmp,na.rm=TRUE),
        type="p", main=colnames(bering_sea)[i], pch=20, cex=2 )
  lines( x=rownames(bering_sea), y=tmp[,2], type="l", lwd=2,
         col="blue", lty="solid" )
  polygon( x=c(rownames(bering_sea),rev(rownames(bering_sea))),

```

```

    y=c(tmp[,3],rev(tmp[,4])), col=rgb(0,0,1,0.2), border=NA )
}

```

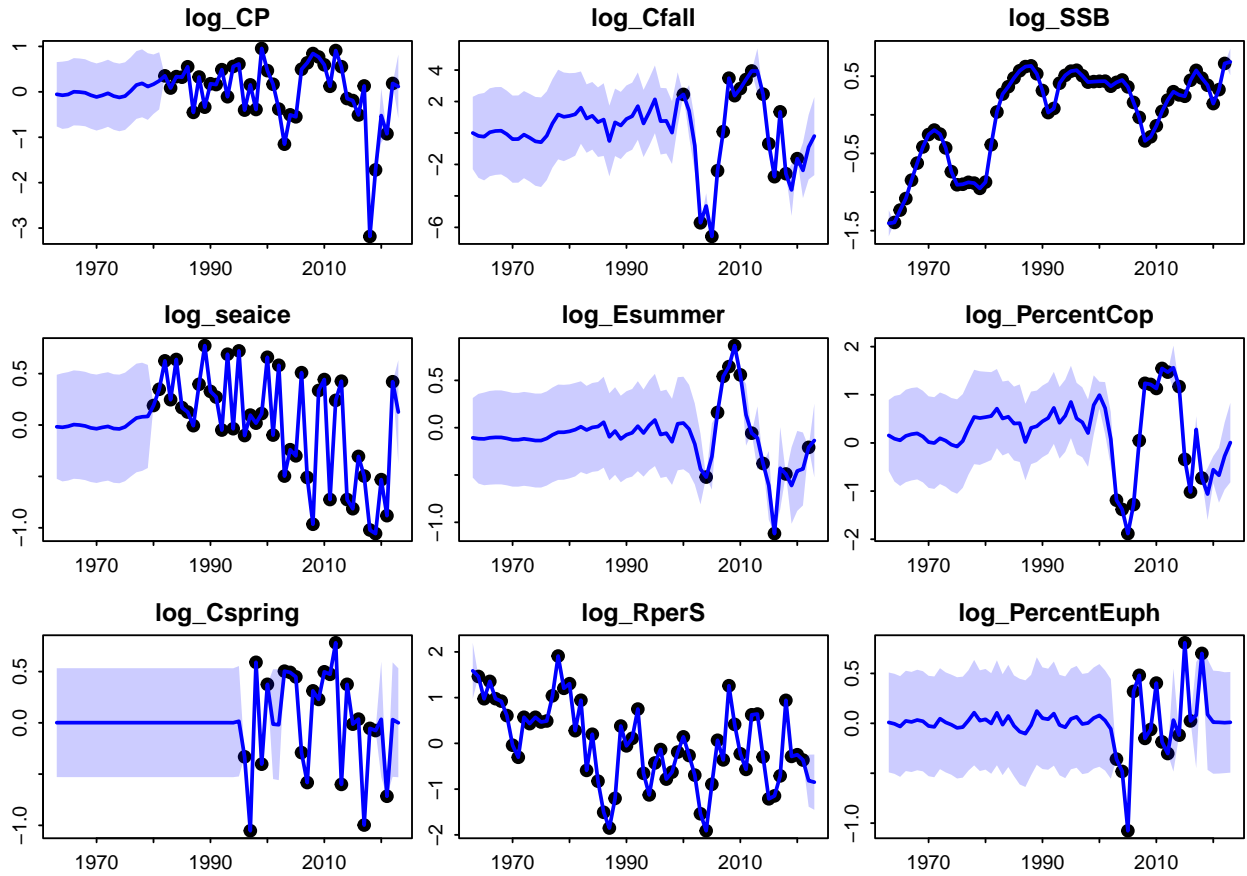


Figure 7: Time-series observations (dots) and estimates (blue lines and shading) for variables affecting recruitment for Alaska pollock in the eastern Bering Sea

```

par(oldpar)

```

```

#
library(phylopath)
library(ggplot2)
library(ggpubr)
library(reshape)
library(gridExtra)
longform = melt( bering_sea )
longform$year = rep( 1963:2023, ncol(bering_sea) )
p0 = ggplot( data=longform, aes(x=year, y=value) ) +
  facet_grid( rows=vars(variable), scales="free" ) +
  geom_point( )

p1 = plot( (as_fitted_DAG(fit)), edge.width=1, type="width",
  text_size=4, show.legend=FALSE,
  arrow = grid::arrow(type='closed', 18, grid::unit(10,'points')) ) +

```

```

    scale_x_continuous(expand = c(0.4, 0.1))
p1$layers[[1]]$mapping$edge_width = 1
p2 = plot( (as_fitted_DAG(fit, what="p_value")), edge.width=1, type="width",
          text_size=4, show.legend=FALSE, colors=c('black', 'black'),
          arrow = grid::arrow(type='closed', 18, grid::unit(10,'points')) ) +
    scale_x_continuous(expand = c(0.4, 0.1))
p2$layers[[1]]$mapping$edge_width = 0.5

ggarrange(p1, p2, labels = c("Simultaneous effects", "Two-sided p-value"),
          ncol = 1, nrow = 2)

```

These results are further discussed in the paper describing dsem.

Site-replicated trophic cascade

Finally, we replicate an analysis involving a trophic cascade involving sea stars predators, sea urchin consumers, and kelp producers.

```

data(sea_otter)
Z = ts( sea_otter[, -1] )

# Specify model
sem = "
  Pycno_CANNERY_DC -> log_Urchins_CANNERY_DC, 0, x2
  log_Urchins_CANNERY_DC -> log_Kelp_CANNERY_DC, 0, x3
  log_Otter_Count_CANNERY_DC -> log_Kelp_CANNERY_DC, 0, x4

  Pycno_CANNERY_UC -> log_Urchins_CANNERY_UC, 0, x2
  log_Urchins_CANNERY_UC -> log_Kelp_CANNERY_UC, 0, x3
  log_Otter_Count_CANNERY_UC -> log_Kelp_CANNERY_UC, 0, x4

  Pycno_HOPKINS_DC -> log_Urchins_HOPKINS_DC, 0, x2
  log_Urchins_HOPKINS_DC -> log_Kelp_HOPKINS_DC, 0, x3
  log_Otter_Count_HOPKINS_DC -> log_Kelp_HOPKINS_DC, 0, x4

  Pycno_HOPKINS_UC -> log_Urchins_HOPKINS_UC, 0, x2
  log_Urchins_HOPKINS_UC -> log_Kelp_HOPKINS_UC, 0, x3
  log_Otter_Count_HOPKINS_UC -> log_Kelp_HOPKINS_UC, 0, x4

  Pycno_LOVERS_DC -> log_Urchins_LOVERS_DC, 0, x2
  log_Urchins_LOVERS_DC -> log_Kelp_LOVERS_DC, 0, x3
  log_Otter_Count_LOVERS_DC -> log_Kelp_LOVERS_DC, 0, x4

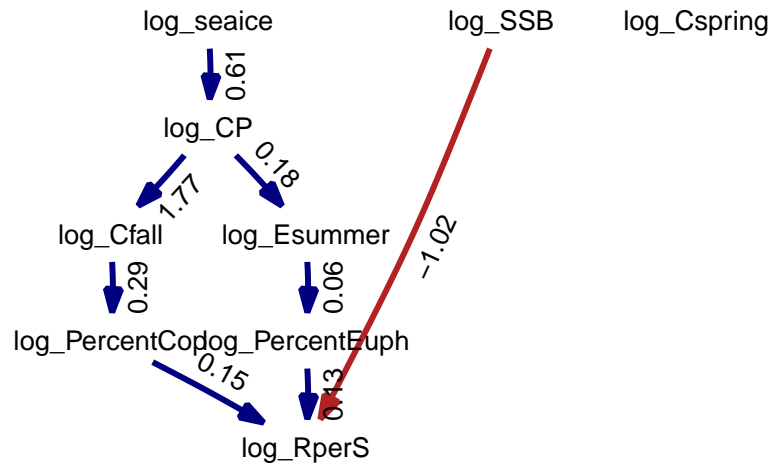
  Pycno_LOVERS_UC -> log_Urchins_LOVERS_UC, 0, x2
  log_Urchins_LOVERS_UC -> log_Kelp_LOVERS_UC, 0, x3
  log_Otter_Count_LOVERS_UC -> log_Kelp_LOVERS_UC, 0, x4

  Pycno_MACABEE_DC -> log_Urchins_MACABEE_DC, 0, x2
  log_Urchins_MACABEE_DC -> log_Kelp_MACABEE_DC, 0, x3
  log_Otter_Count_MACABEE_DC -> log_Kelp_MACABEE_DC, 0, x4

  Pycno_MACABEE_UC -> log_Urchins_MACABEE_UC, 0, x2

```

Simultaneous effects



Two-sided p-value

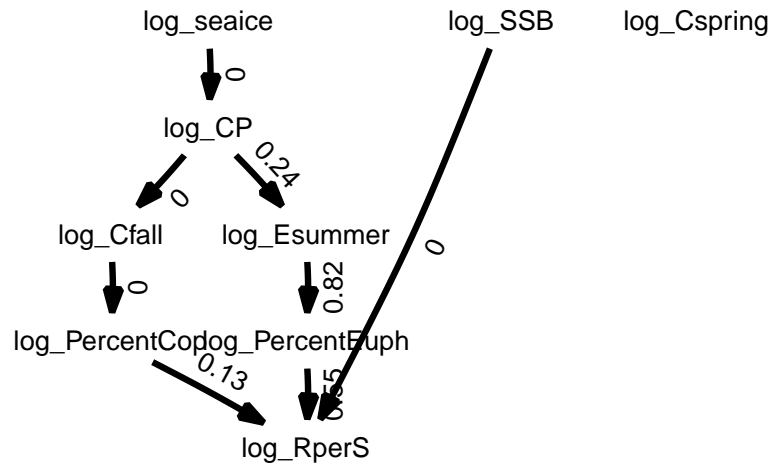


Figure 8: Structural model representing ecosystem linkages affecting recruitment for Alaska pollock in the eastern Bering Sea

```

log_Urchins_MACABEE_UC -> log_Kelp_MACABEE_UC, 0, x3
log_Otter_Count_MACABEE_UC -> log_Kelp_MACABEE_UC, 0, x4

Pycno_OTTER_PT_DC -> log_Urchins_OTTER_PT_DC, 0, x2
log_Urchins_OTTER_PT_DC -> log_Kelp_OTTER_PT_DC, 0, x3
log_Otter_Count_OTTER_PT_DC -> log_Kelp_OTTER_PT_DC, 0, x4

Pycno_OTTER_PT_UC -> log_Urchins_OTTER_PT_UC, 0, x2
log_Urchins_OTTER_PT_UC -> log_Kelp_OTTER_PT_UC, 0, x3
log_Otter_Count_OTTER_PT_UC -> log_Kelp_OTTER_PT_UC, 0, x4

Pycno_PINOS_CEN -> log_Urchins_PINOS_CEN, 0, x2
log_Urchins_PINOS_CEN -> log_Kelp_PINOS_CEN, 0, x3
log_Otter_Count_PINOS_CEN -> log_Kelp_PINOS_CEN, 0, x4

Pycno_SIREN_CEN -> log_Urchins_SIREN_CEN, 0, x2
log_Urchins_SIREN_CEN -> log_Kelp_SIREN_CEN, 0, x3
log_Otter_Count_SIREN_CEN -> log_Kelp_SIREN_CEN, 0, x4

# AR1
Pycno_CANNERY_DC -> Pycno_CANNERY_DC, 1, ar1
log_Urchins_CANNERY_DC -> log_Urchins_CANNERY_DC, 1, ar2
log_Otter_Count_CANNERY_DC -> log_Otter_Count_CANNERY_DC, 1, ar3
log_Kelp_CANNERY_DC -> log_Kelp_CANNERY_DC, 1, ar4

Pycno_CANNERY_UC -> Pycno_CANNERY_UC, 1, ar1
log_Urchins_CANNERY_UC -> log_Urchins_CANNERY_UC, 1, ar2
log_Otter_Count_CANNERY_UC -> log_Otter_Count_CANNERY_UC, 1, ar3
log_Kelp_CANNERY_UC -> log_Kelp_CANNERY_UC, 1, ar4

Pycno_HOPKINS_DC -> Pycno_HOPKINS_DC, 1, ar1
log_Urchins_HOPKINS_DC -> log_Urchins_HOPKINS_DC, 1, ar2
log_Otter_Count_HOPKINS_DC -> log_Otter_Count_HOPKINS_DC, 1, ar3
log_Kelp_HOPKINS_DC -> log_Kelp_HOPKINS_DC, 1, ar4

Pycno_HOPKINS_UC -> Pycno_HOPKINS_UC, 1, ar1
log_Urchins_HOPKINS_UC -> log_Urchins_HOPKINS_UC, 1, ar2
log_Otter_Count_HOPKINS_UC -> log_Otter_Count_HOPKINS_UC, 1, ar3
log_Kelp_HOPKINS_UC -> log_Kelp_HOPKINS_UC, 1, ar4

Pycno_LOVERS_DC -> Pycno_LOVERS_DC, 1, ar1
log_Urchins_LOVERS_DC -> log_Urchins_LOVERS_DC, 1, ar2
log_Otter_Count_LOVERS_DC -> log_Otter_Count_LOVERS_DC, 1, ar3
log_Kelp_LOVERS_DC -> log_Kelp_LOVERS_DC, 1, ar4

Pycno_LOVERS_UC -> Pycno_LOVERS_UC, 1, ar1
log_Urchins_LOVERS_UC -> log_Urchins_LOVERS_UC, 1, ar2
log_Otter_Count_LOVERS_UC -> log_Otter_Count_LOVERS_UC, 1, ar3
log_Kelp_LOVERS_UC -> log_Kelp_LOVERS_UC, 1, ar4

Pycno_MACABEE_DC -> Pycno_MACABEE_DC, 1, ar1
log_Urchins_MACABEE_DC -> log_Urchins_MACABEE_DC, 1, ar2
log_Otter_Count_MACABEE_DC -> log_Otter_Count_MACABEE_DC, 1, ar3

```

```

log_Kelp_MACABEE_DC -> log_Kelp_MACABEE_DC, 1, ar4

Pycno_MACABEE_UC -> Pycno_MACABEE_UC, 1, ar1
log_Urchins_MACABEE_UC -> log_Urchins_MACABEE_UC, 1, ar2
log_Otter_Count_MACABEE_UC -> log_Otter_Count_MACABEE_UC, 1, ar3
log_Kelp_MACABEE_UC -> log_Kelp_MACABEE_UC, 1, ar4

Pycno_OTTER_PT_DC -> Pycno_OTTER_PT_DC, 1, ar1
log_Urchins_OTTER_PT_DC -> log_Urchins_OTTER_PT_DC, 1, ar2
log_Otter_Count_OTTER_PT_DC -> log_Otter_Count_OTTER_PT_DC, 1, ar3
log_Kelp_OTTER_PT_DC -> log_Kelp_OTTER_PT_DC, 1, ar4

Pycno_OTTER_PT_UC -> Pycno_OTTER_PT_UC, 1, ar1
log_Urchins_OTTER_PT_UC -> log_Urchins_OTTER_PT_UC, 1, ar2
log_Otter_Count_OTTER_PT_UC -> log_Otter_Count_OTTER_PT_UC, 1, ar3
log_Kelp_OTTER_PT_UC -> log_Kelp_OTTER_PT_UC, 1, ar4

Pycno_PINOS_CEN -> Pycno_PINOS_CEN, 1, ar1
log_Urchins_PINOS_CEN -> log_Urchins_PINOS_CEN, 1, ar2
log_Otter_Count_PINOS_CEN -> log_Otter_Count_PINOS_CEN, 1, ar3
log_Kelp_PINOS_CEN -> log_Kelp_PINOS_CEN, 1, ar4

Pycno_SIREN_CEN -> Pycno_SIREN_CEN, 1, ar1
log_Urchins_SIREN_CEN -> log_Urchins_SIREN_CEN, 1, ar2
log_Otter_Count_SIREN_CEN -> log_Otter_Count_SIREN_CEN, 1, ar3
log_Kelp_SIREN_CEN -> log_Kelp_SIREN_CEN, 1, ar4
"

# Fit model
fit = dsem( sem = sem,
            tsdata = Z,
            control = dsem_control(use_REML=FALSE, quiet=TRUE) )
# summary( fit )

#
library(phylopath)
library(ggplot2)
library(ggpubr)
get_part = function(x){
  vars = c("log_Kelp","log_Otter","log_Urchin","Pycno")
  index = sapply( vars, FUN=\(y) grep(y,rownames(x$coef))[1] )
  x$coef = x$coef[index,index]
  dimnames(x$coef) = list( vars, vars )
  return(x)
}
p1 = plot( get_part(as_fitted_DAG(fit)), type="width", show.legend=FALSE)
p1$layers[[1]]$mapping$edge_width = 0.5
p2 = plot( get_part(as_fitted_DAG(fit, what="p_value" )), type="width",
            show.legend=FALSE, colors=c('black', 'black'))
p2$layers[[1]]$mapping$edge_width = 0.1

longform = melt( sea_otter[,-1], as.is=TRUE )
#> Warning in type.convert.default(X[[i]], ...): 'as.is' should be specified by the caller; using TRUE

```



```

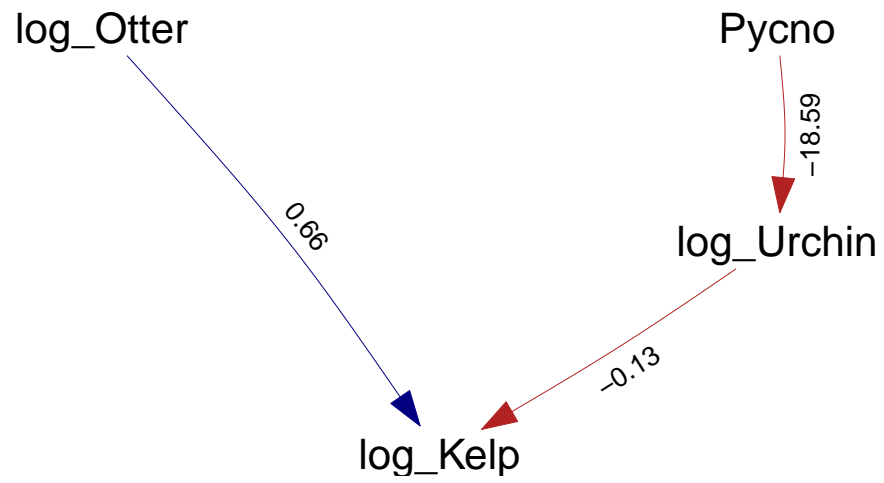
longform$X1 = 1999:2019[longform$X1]
#> Warning in 1999:2019[longform$X1]: numerical expression has 1008 elements: only the first used
longform$Site = gsub( "log_Kelp_", "",
                     gsub( "log_Urchins_", "",
                           gsub( "Pycno_", "",
                                 gsub( "log_Otter_Count_", "", longform$X2))))
longform$Species = sapply( seq_len(nrow(longform)), FUN=\(i)gsub(longform$Site[i], "", longform$X2[i]) )
p3 = ggplot( data=longform, aes(x=X1, y=value, col=Species) ) +
      facet_grid( rows=vars(Site), scales="free" ) +
      geom_line( )

ggarrange(p1 + scale_x_continuous(expand = c(0.3, 0)),
          p2 + scale_x_continuous(expand = c(0.3, 0)),
          labels = c("Simultaneous effects", "Two-sided p-value"),
          ncol = 1, nrow = 2)

```

Again, these results are further discussed in the paper describing dsem.

Simultaneous effects



Two-sided p-value

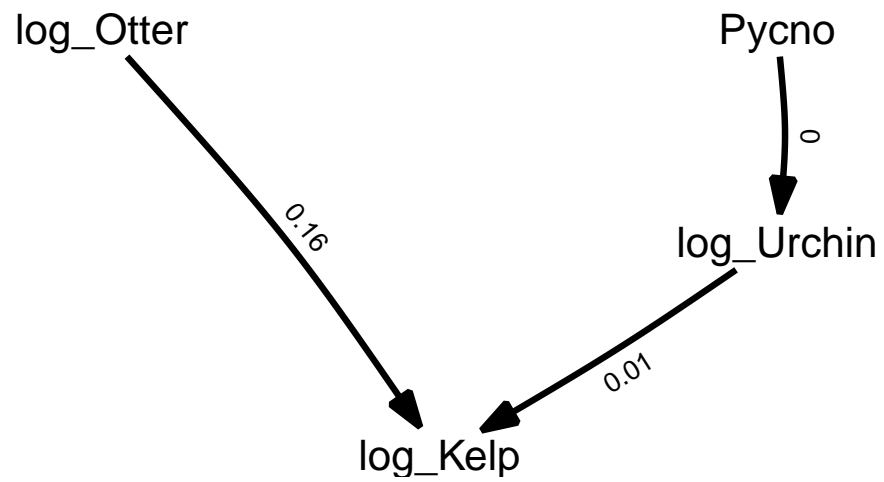


Figure 9: Structural model representing a trophic cascade