An integrated analysis of the marine social-ecological system of the Strait of Georgia over the past four decades, and development of a regime shift index

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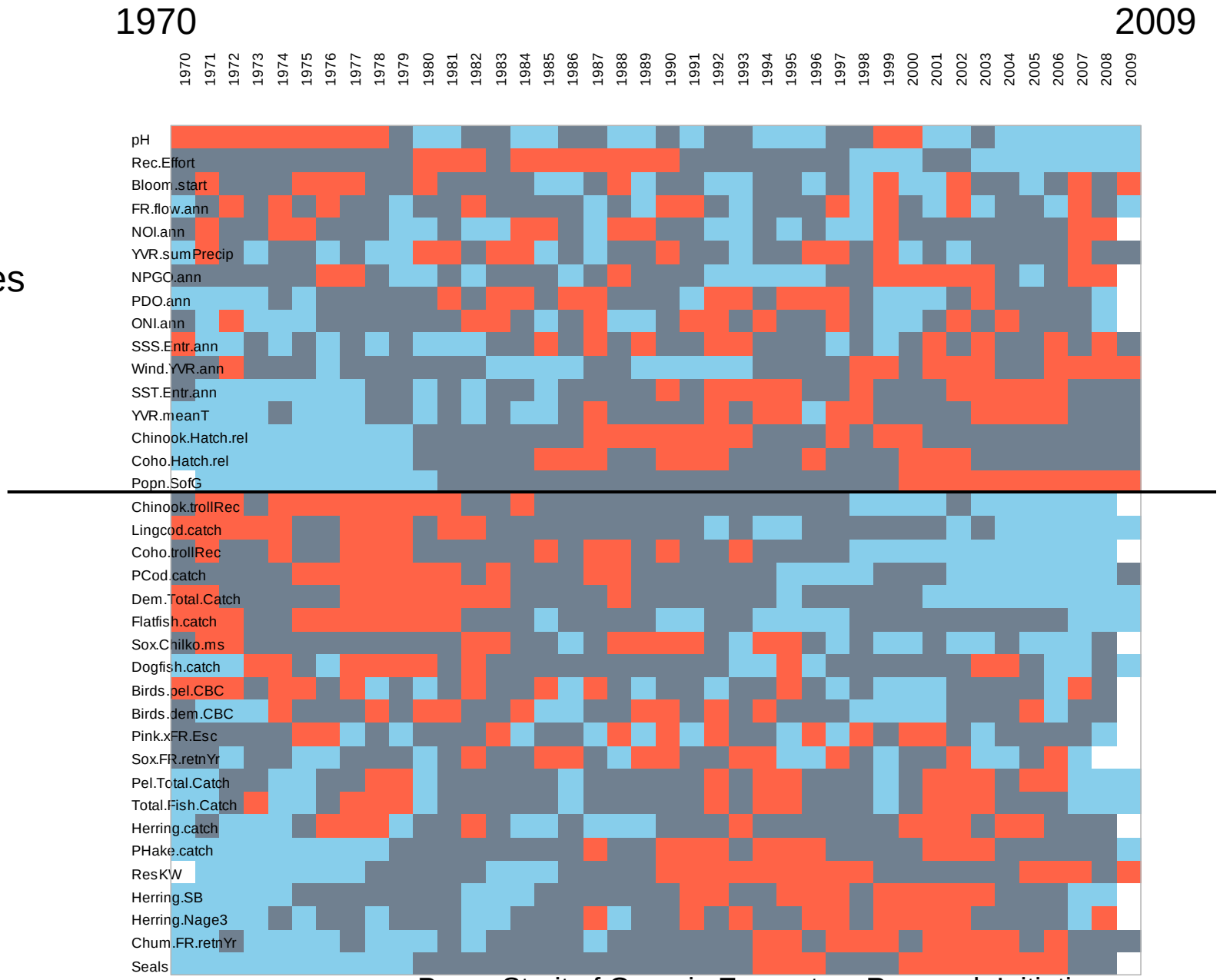
i) develop a Driver-Pressure-State-Impact-Response framework for the Strait of Georgia marine social-ecological system;

ii) use this framework in a structured approach to begin identifying a core set of indicators of ecosystem state and ecosystem responses to drivers and pressures in the Strait of Georgia;

iii) develop an approach to use these indicators to assess and integrate impacts and changes in the Strait

Variables included in analyses (with <4 missing years from 1970-2009):

	Drivers & Pressures:	States & Impacts:
Natural	NOI (annual)	Bloom start date (modelled)
	ONI (annual) – Nino Index	Sockeye marine survival (Chilko Lk)
	PDO (annual)	Herring (number at age 3)
	NPGO (annual)	Herring (spawning biomass)
	Wind (YVR annual)	Sockeye (returns to Fraser R.)
	YVR (air temp, annual mean)	Pink (escapement, excluding FR)
	YVR (precip., annual sum)	Chum (returns to Fraser R.)
	SST (Entrance Is., annual)	Seals (annual number)
	SSS (Entrance Is., annual)	Killer whales (residents, annual #)
	Fraser R. (flow vol, annual)	Seabirds – demersal feeding (Christmas Bird Count)
	pH (annual modal values)	Seabirds – pelagic feeding (Christmas Bird Count)
Human	Chinook (hatchery releases)	Herring (catch)
	Coho (hatchery releases)	Flatfish (catch)
	Recreational effort	Pacific cod (catch)
	Human population (of Regional Districts around the SofG)	Lingcod (catch)
		Pacific hake (catch)
		Dogfish (catch)
		Total fish catch
		Total pelagic catch
		Total demersal catch
		Chinook catch (recreational)
		Coho catch (recreational)


1970
2009
1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Drivers and Pressures
pH
Rec.Effort
Bloom.start
FR.flow.ann
NOI.ann
YVR.sumPrecip
NPGO.ann
PDO.ann
ONI.ann
SSS.Entr.ann
Wind.YVR.ann
SST.Entr.ann
YVR.meanT
Chinook.Hatch.rel
Coho.Hatch.rel
Popn.SofG
States and Impacts
Chinook.trollRec
Lingcod.catch
Coho.trollRec
PCod.catch
Dem.Total.Catch
Flatfish.catch
Sox.Chilko.ms
Dogfish.catch
Birds.pel.CBC
Birds.dem.CBC
Pink.xFR.Esc
Sox.FR.retnYr
Pel.Total.Catch
Total.Fish.Catch
Herring.catch
PHake.catch
ResKW
Herring.SB
Herring.Nage3
Chum.FR.retnYr
Seals

Drivers & Pressures:

Natural:
NOI (annual)
ONI (annual) – Nino Index
PDO (annual)
NPGO (annual)
Wind (YVR annual)
YVR (air temp, annual mean)
YVR (precip., annual sum)
SST (Entrance Is., annual)
SSS (Entrance Is., annual)
Fraser R. (flow vol, annual)
pH (annual modal values)

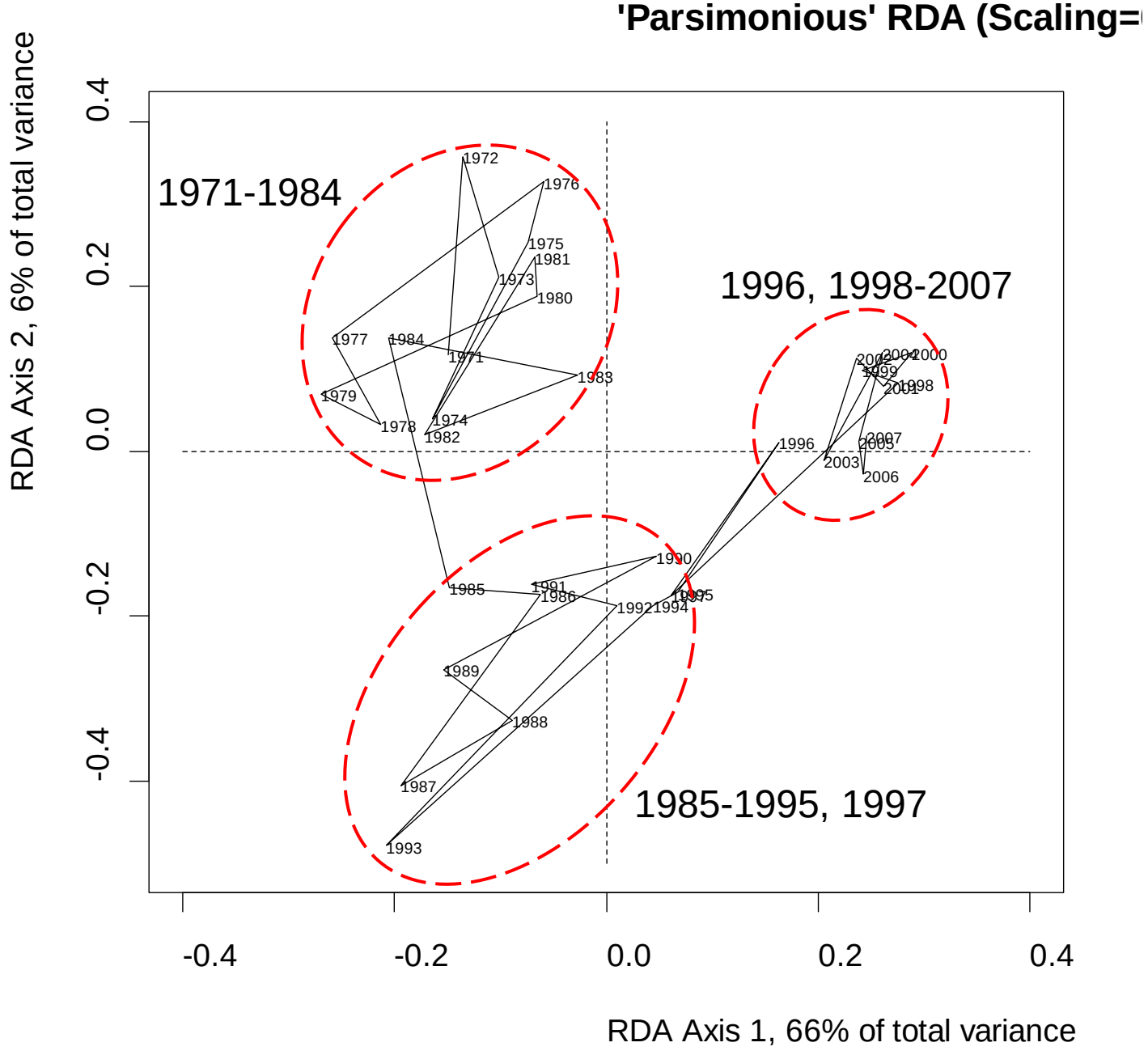
Human:
Chinook (hatchery releases)
Coho (hatchery releases)
Recreational effort
Human population (Strait of Georgia)

States & Impacts:

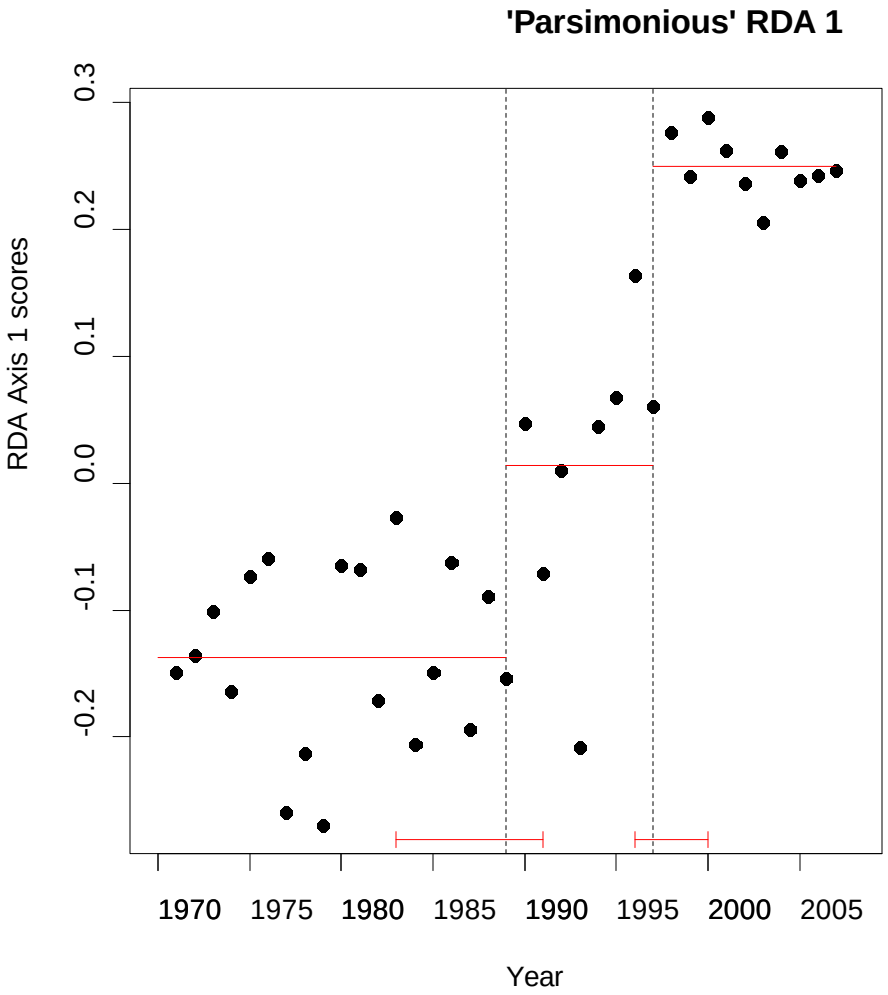
Natural:
Bloom start date (modelled)
Sockeye marine survival (Chilko Lk)
Herring (number at age 3)
Herring (spawning biomass)
Sockeye (returns to Fraser R.)
Pink (escapement, excluding FR)
Chum (returns to Fraser R.)
Seals (annual number)
Killer whales (residents, annual #)
Seabirds – demersal feeding
Seabirds – pelagic feeding

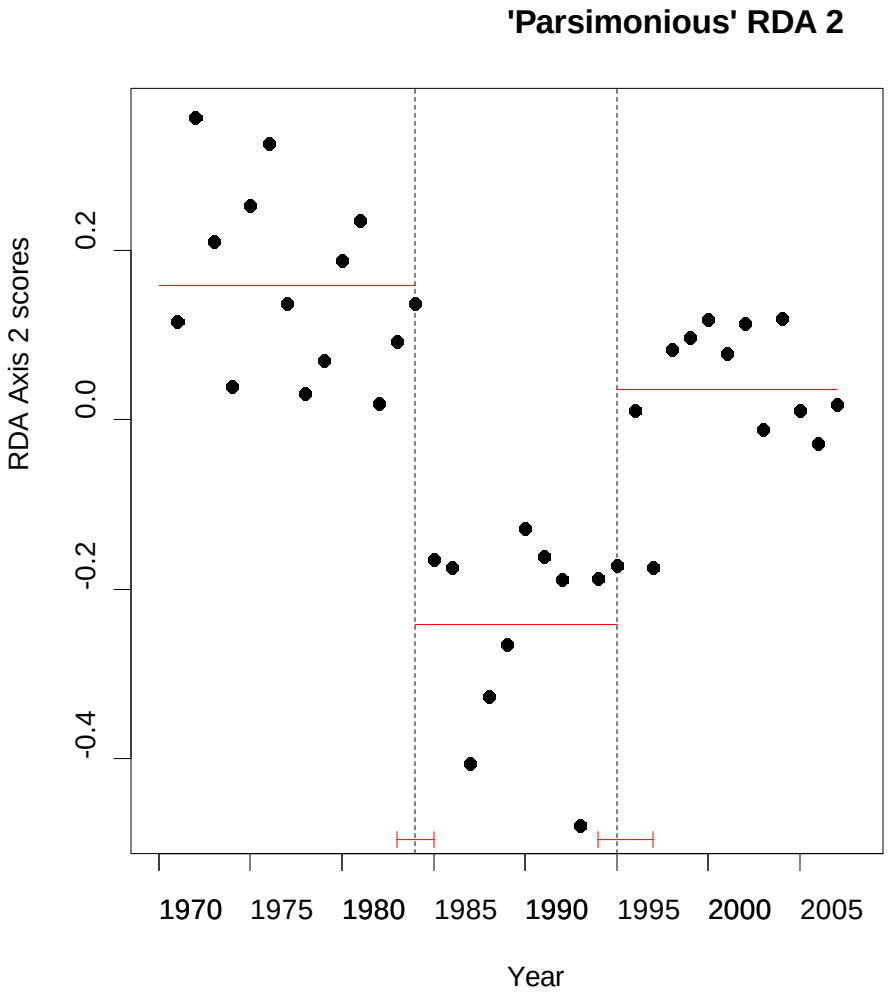
Human:
Herring (catch)
Flatfish (catch)
Pacific cod (catch)
Lingcod (catch)
Pacific hake (catch)
Dogfish (catch)
Total fish catch
Total pelagic catch
Total demersal catch
Chinook catch (recreational)
Coho catch (recreational)

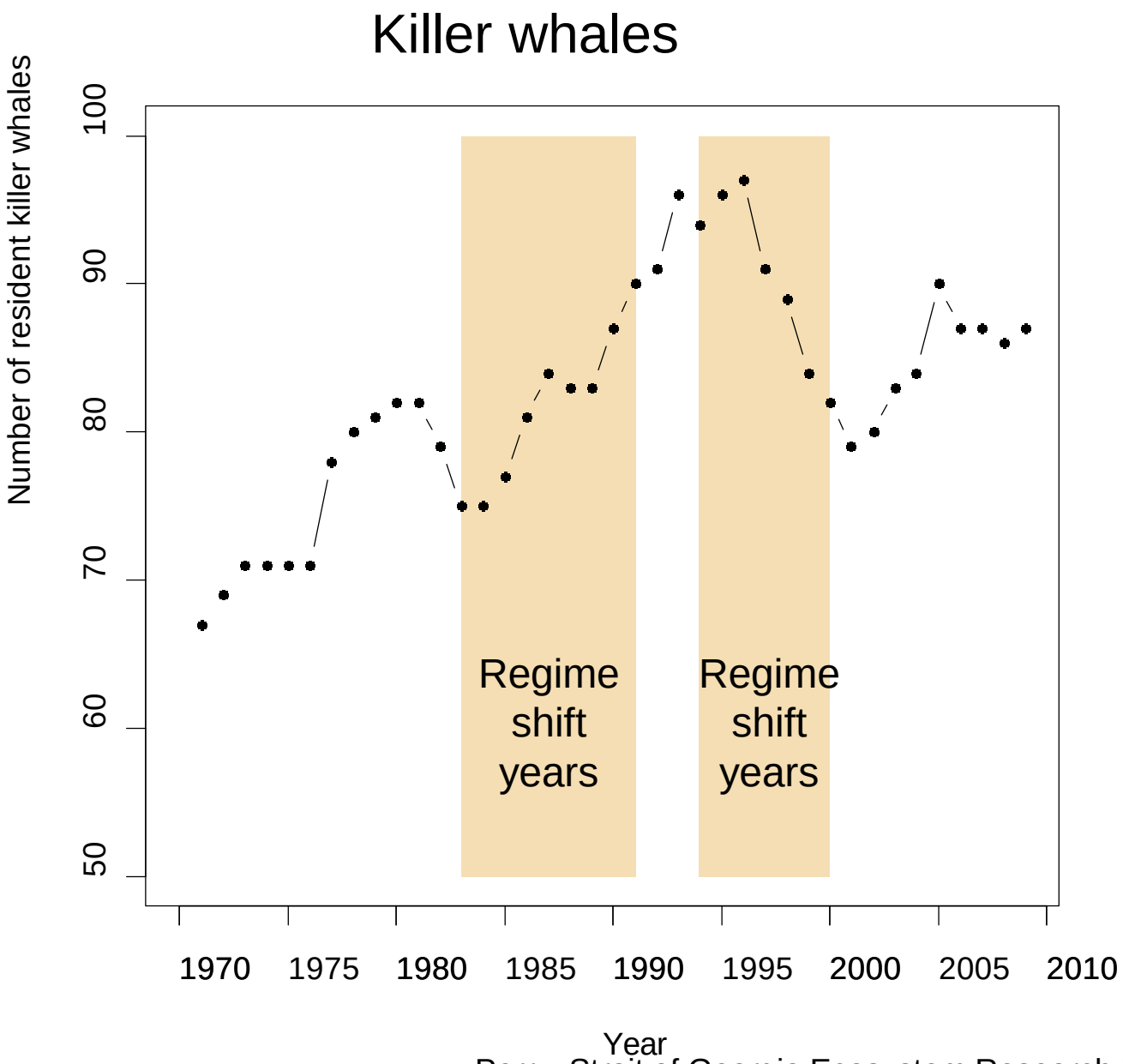
Redundancy Analysis Independent variables	Dependent variables	R^2_{adj}	Significance of model	Prop'n of total variance accounted by all RDA axes
All drivers and pressures	States and Impacts	0.72	0.001	0.84
Natural and Human 'parsimonious' drivers and pressures: SST (Entrance Island), Wind (YVR, annual mean), NPGO (annual mean) Populaton, Recreational fishing effort (annual), Hatchery releases of Chinook	States and Impacts	0.67	0.001	0.73


'Parsimonious' RDA (Scaling=
RDA Axis 2, 6% of total variance
0.4
0.2
0.0
-0.2
-0.4
1971-1984
1996, 1998-2007
1985-1995, 1997
1972
1976
1975
1981
1973
1980
1977
1984
1971
1983
1979
1978
1974
1982
2000
2004
2002
1999
1998
2001
1996
2007
2005
2003
2006
1990
1985
1991
1986
1995
1992
1994
1989
1988
1987
1993
-0.4
-0.2
0.0
0.2
0.4
RDA Axis 1, 66% of total variance

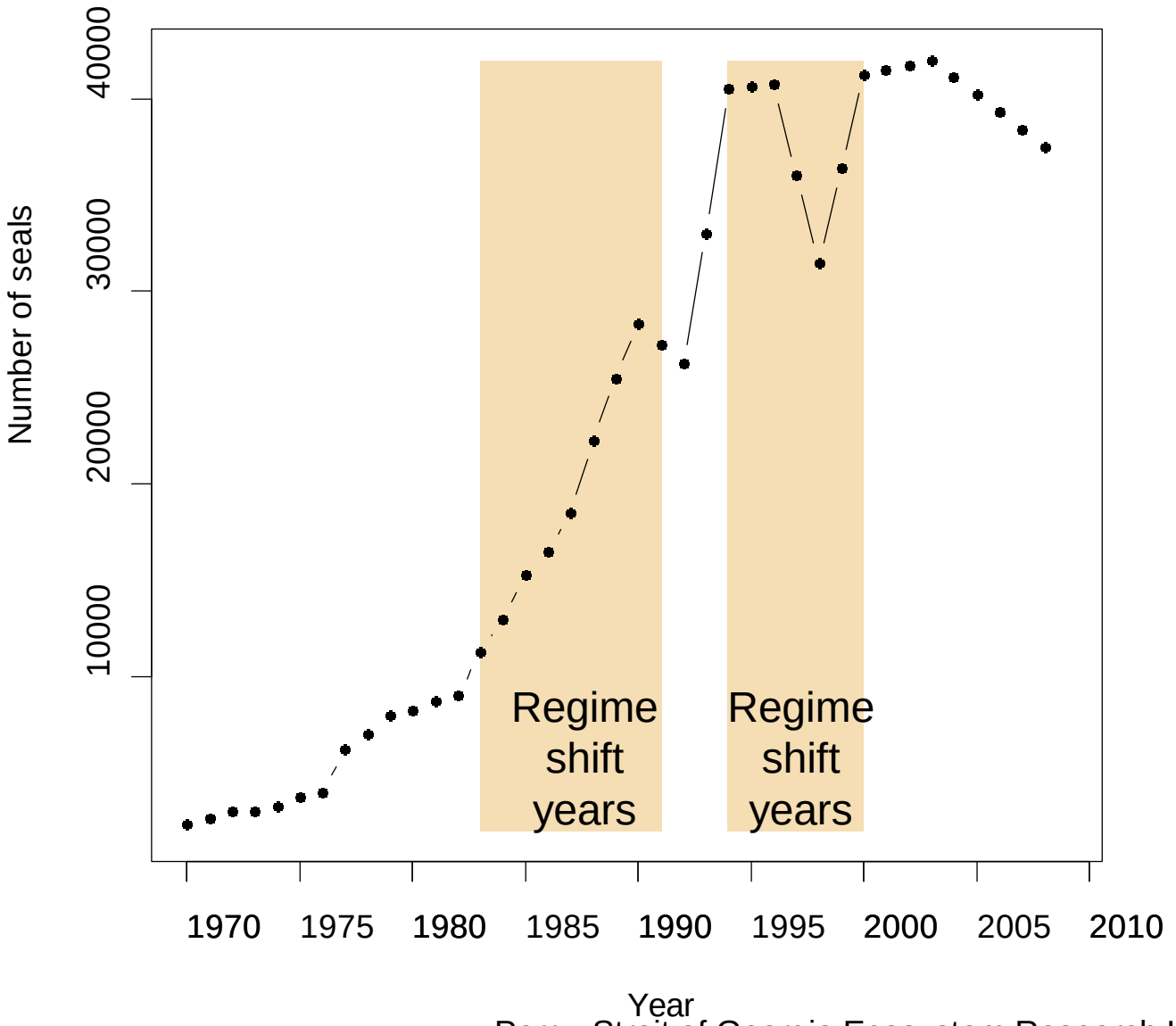
Identification of significant change in time series






Killer whales
Number of resident killer whales
100
90
80
70
60
50
1970
1975
1980
1985
1990
1995
2000
2005
2010
Regime shift years
Regime shift years
Year

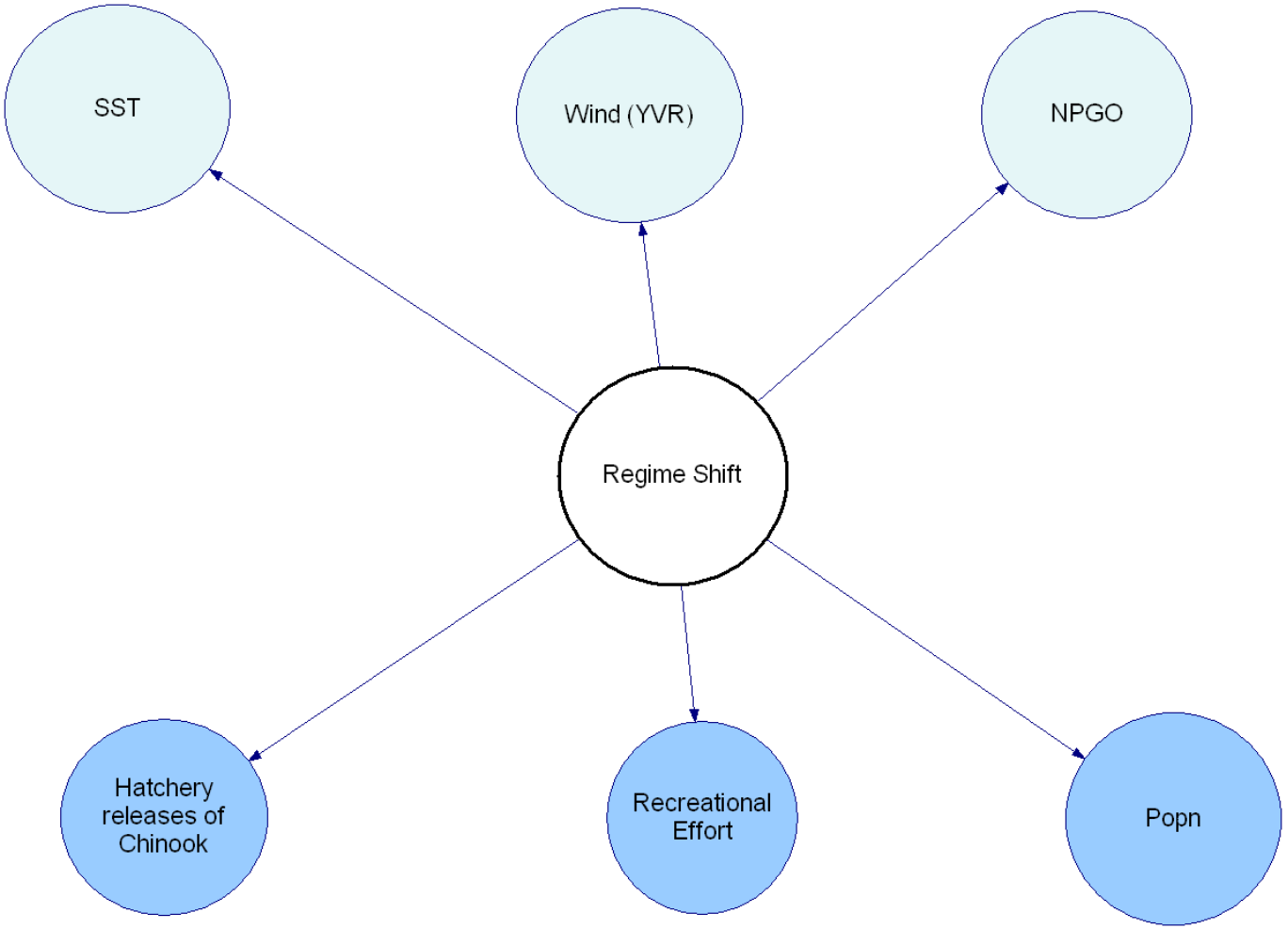
Harbour seals



Bayesian Network Model to predict regime shifts/changes in ecosystem structure based on the 'parsimonious' RDA analyses

Natural Drivers

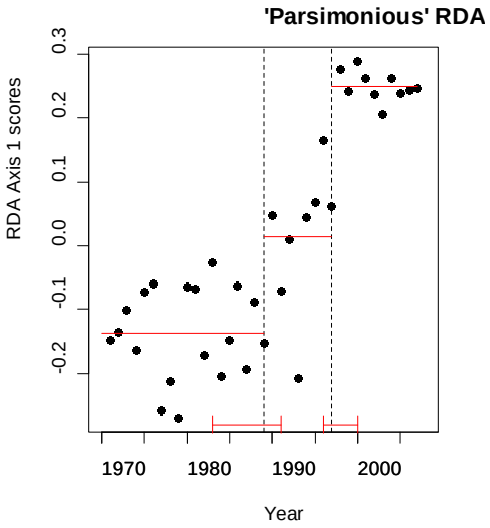
Human Drivers

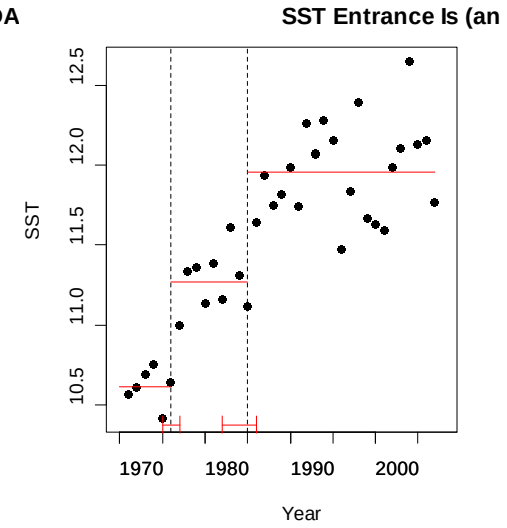


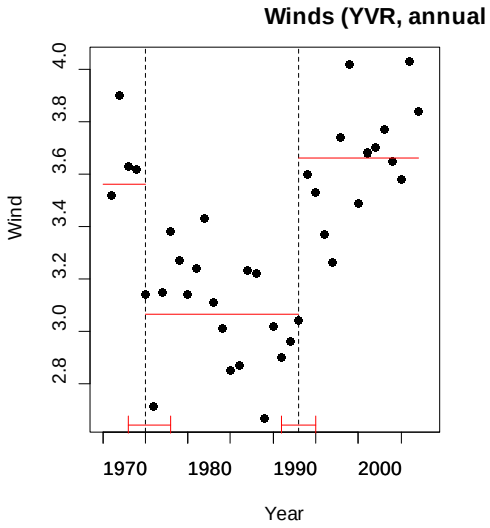
Identification of significant changes in time series of:

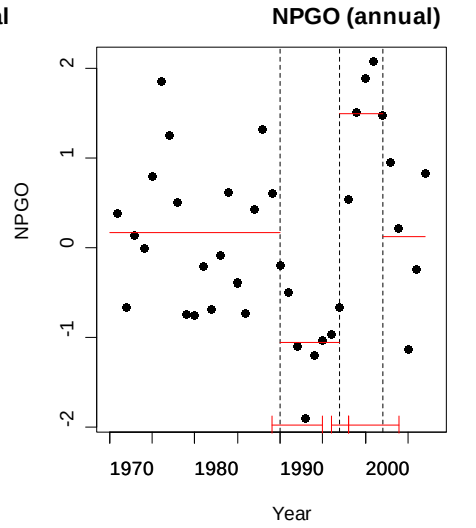
RDA 1 and 2 of the States and Impacts (dependent variables)

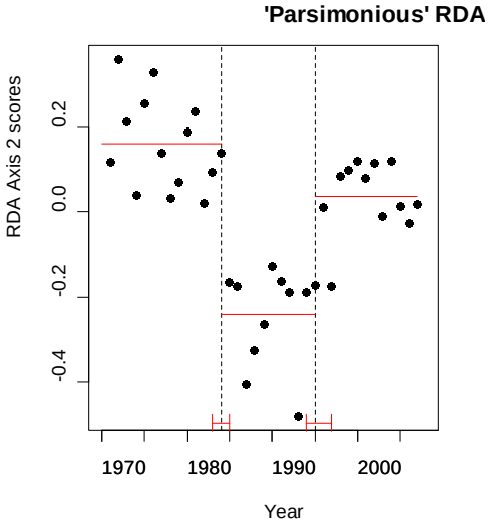
‘Parsimonious’ natural and human explanatory variables

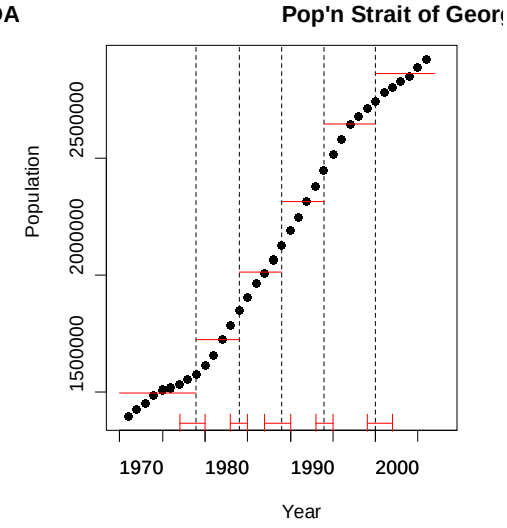


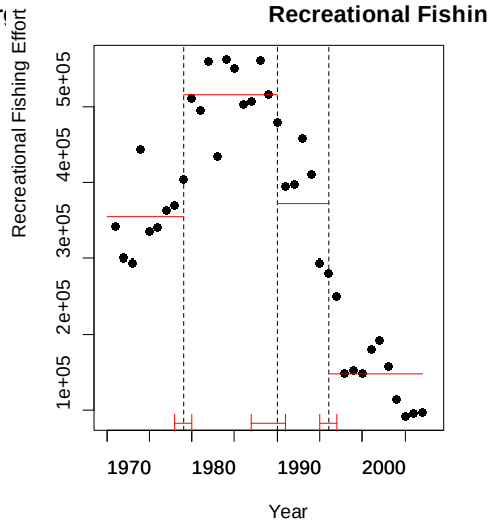


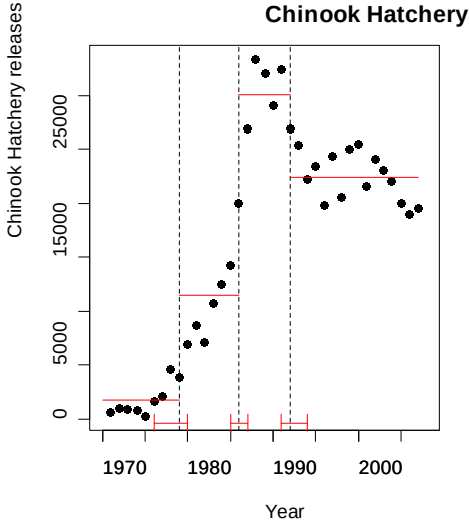


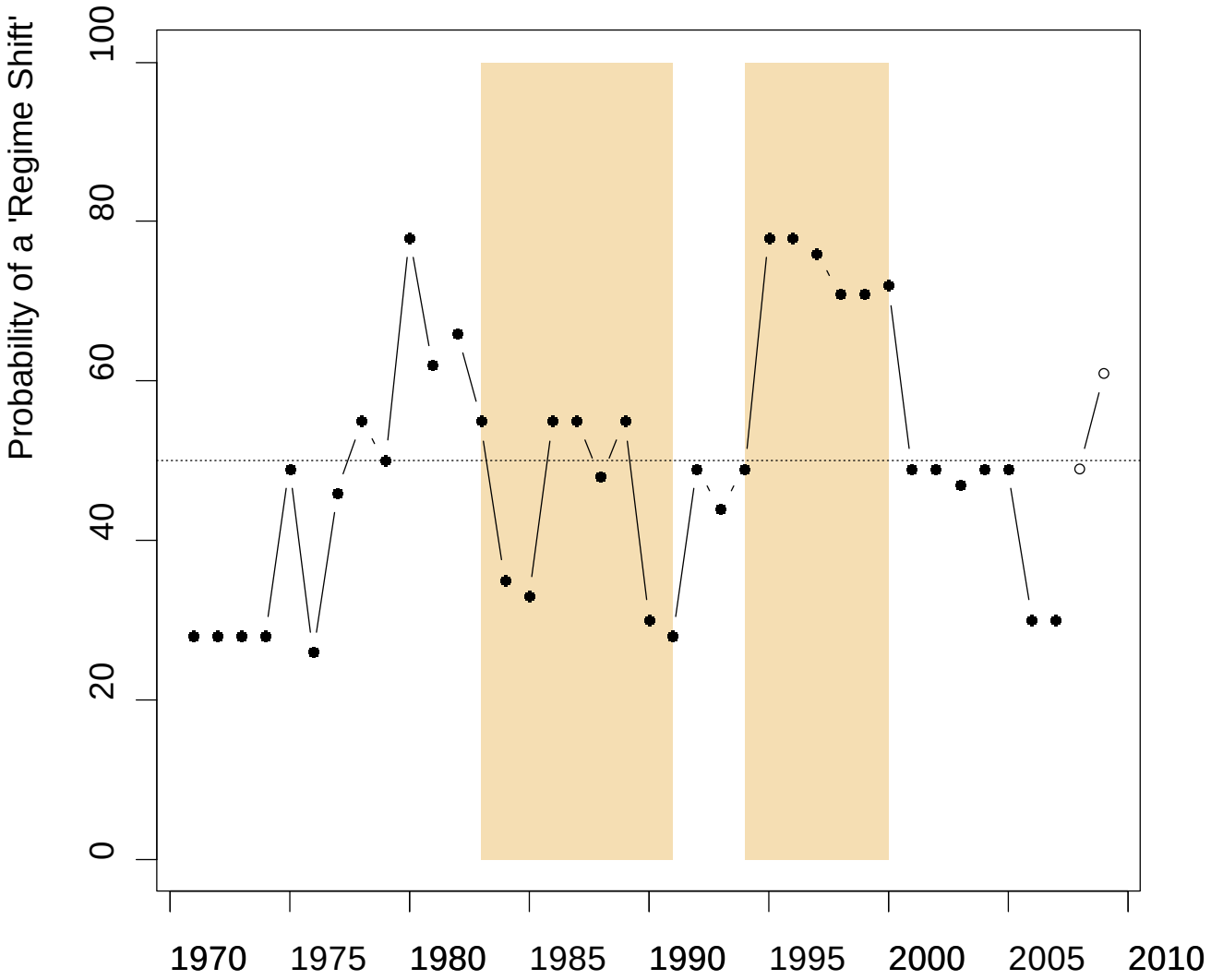











Probability of a 'Regime Shift'
0
20
40
60
80
100
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year