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Environmental determinants of recruitment success of King George whiting

Gregory Jenkins, David Hatton and Kerry Black

Project No. 98/141

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Marine and Freshwater Resources Institute, PO Box 114, Queenscliff, Vic 3225

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NON-TECHNICAL SUMMARY

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Principal Investigator: Dr Greg Jenkins

Address: Marine and Freshwater Resources Institute
P.O. Box 114
Queenscliff, Vic 3225
Tel: (03) 5258 0111 Fax: (03) 5258 0270
Email: greg.jenkins@nre.vic.gov.au

Objectives:

1) To determine the linkage between annual variation in larval transport, simulated by hydrodynamic modelling, and annual variation in recruitment to the King George whiting fishery.

2) To determine the linkage between annual variation in habitat cover and annual variation in recruitment to the King George whiting fishery.

3) To determine the linkage between other environmental variables and variation in recruitment to the King George whiting fishery

Non Technical Summary

Outcomes achieved

The results of this study will allow managers of the King George whiting fishery to make predictions of catches up to five years ahead and will help determine the reasons for increases or declines in the catch. The results of the study also emphasise the importance of habitat for the continued viability of this fishery, and therefore the need to protect important areas of habitat.

Catches of King George whiting in Victorian bays and inlets vary greatly from year to year. This research was aimed at finding out how much of this variation was due to the environment, and whether we could use measures of environmental variables to predict catches in the future. King George whiting spawn along the coast of Bass Strait in late autumn/winter and the small (2 to 20 mm) larvae drift in Bass Strait for three to five months before settling in shallow seagrass and algal habitats in bays and inlets. The juveniles grow within the bays and reach the minimum legal size limit by about 3 years of age. By the age of 5 years most whiting have moved out of the bay onto the coast where they live their adult lives. This means that the bay and inlet fishery is based on a very narrow age range of older juvenile (also known as subadult) fish. This life history means that environmental factors that influence growth and survival in the larval and juvenile stage could have a major impact on the catch.

We found that years with strong westerly winds correspond to higher catches five years later. This time lag suggests that the positive effect of strong westerly winds is occurring in the larval stage, resulting in more larvae settling in seagrass beds of bays and inlets. Strong westerly winds could increase larval settlement in two major ways. Firstly, strong westerly winds would result in stronger currents to the east transporting larvae more rapidly from spawning grounds in western Victoria. Secondly, strong westerly winds could increase the amount of food for larvae in the water column though increased nutrients coming from the southern ocean, resulting in higher larval growth and survival. The idea that strong westerly winds resulted in the transport of more larvae to bays and inlets was tested using computer models of water currents and adding 'virtual' larvae in the predicted spawning areas and counting numbers arriving in bays and inlets. The results did not support the idea that increased transport of larvae resulted in higher catches, suggesting that the role of westerly winds may be more in the increase in food for larvae leading to higher larval survival.

We also found a relationship between the ocean warming (southern oscillation index) cycle and whiting catch. This cycle that affects global climate fluctuates between warm water (El Niño) and cool water (La Niña) in the equatorial eastern Pacific. We found that La Niña years led to higher catches about one year later, suggesting that this climate variation was affecting juveniles that were soon to reach legal size. We found that La Niña years were characterised by increased rainfall, decreased air pressure, and increased water levels. One explanation for increased catches after La Niña years is that rainfall runoff introduces nutrients into the bays that stimulate the food chain to produce more of the invertebrates such as worms and shellfish that are eaten by juvenile whiting.

The third environmental relationship we found was that while strong westerly winds can lead to an increased catch in five years, they can also reduce catch in the year that they occur. Such weather patterns with strong winds and numerous cold fronts probably reduce the effectiveness of fishing because the fishing gear doesn't work as well, fish behaviour changes so they are less easy to catch, or fisherman may move to more sheltered areas that have less fish.

Finally, we used aerial photographs taken over the past 50 years to see whether the amount of seagrass in Port Phillip Bay has changed over that period. We found that, for the sites we looked at, seagrass has either remained steady or increased in area over time, corresponding with a long-term increase in catch of King George whiting over the same period. Interestingly, there has been a major increase in seagrass in the south-eastern portion of the bay (Sorrento to Rosebud), an area also known to be a major site for larval settlement. It seems likely that the increase in habitat area is partially responsible for the increase in King George whiting catch in Port Phillip Bay.

KEYWORDS: Environment; transport; recruitment; King George whiting; hydrodynamics; numerical modelling; seagrass

FINAL REPORT

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Background

Research in recent years has shown that King George whiting are spawned offshore and do not enter bay and inlet habitats until larvae are 3-5 months old (Jenkins & May 1994, Jenkins et al. 2000). Juveniles develop within bays and inlets until the age of about 5 years before moving offshore at the time of reproductive maturity (Smith & MacDonald 1997, Fowler et al. 1999). The fishery in Victorian bays and inlets is therefore entirely concentrated on one or two year classes of subadult fish (Smith & MacDonald 1997). Thus, the fishery would be expected to be highly dependent on variability in recruitment. The King George whiting fishery in Victorian bays and inlets has been reasonably stable on a scale of decades, but shows a great deal of variation at a scale of years. For example, major peaks in catches occurred in the years around 1974 and 1990 (Smith & MacDonald 1997).

Recruitment variation is most likely to be generated in two distinct phases: the pelagic larval phase drifting in Bass Strait, and the juvenile phase inhabiting shallow seagrass and algal beds of bays and inlets (Jenkins et al. 1997, Jenkins & Wheatley 1998). Our research, based on the length of larval life and computer models of currents in Bass Strait, suggests that most fish in central Victorian bays and inlets are probably spawned along the coast from approximately Cape Otway to Cape Jaffa in South Australia (Jenkins et al. 2000). Thus, yearly variation in current patterns in Bass Strait may have a significant effect on the number of larvae arriving in bays and inlets. Yearly variation in planktonic food production in Bass Strait may also influence the mortality of larvae and therefore the numbers reaching bays and inlets (Harris et al. 1988). In the second phase that may effect recruitment variability, yearly variation in the 'quality' of habitats used by juveniles may effect recruitment (Connolly et al. 1999).

The trends in catch data suggest that both of these phases could be important. Peaks of catches in 74' and 90' coincided in Port Phillip Bay and Corner Inlet although there was no major change in seagrass cover apparent (Smith & MacDonald 1997). Factors affecting larvae in Bass Strait would influence all bays equally and would explain why the bays show the same trends. The same peaks were present in Western Port, however, there was a long-term decline in catch over the period compared with a long-term increase in the other bays (Smith & MacDonald 1997). This suggests that the well documented seagrass loss in Western Port (Shepherd et al. 1989) may have influenced recruitment.

Our recent study, where we predicted spawning areas of King George whiting using hydrodynamic modelling, showed variable results for the three years investigated. Predicted spawning areas were similar for 1989 and 1995 but in 1994 the spawning area predicted to have supplied larvae extended further west and larval transport was faster (Jenkins et al. 2000). Our monitoring of larvae entering Port Phillip showed very high numbers in 1994, and this appears to be translating into large numbers entering the fishery over the past couple of years.

The characteristics of the King George whiting fishery are such that it may be possible to predict catch rates years in advance from knowledge of current patterns in Bass Strait and variability in juvenile habitat cover. We propose to test these ideas by comparing historical catches with 30 years of predictions of larval transport in Bass Strait based on computer modelling (together with other climatic data) and also comparison with aerial photographic indices of habitat cover over the same period.

Pre-recruitment indices of year-class strength have proven to be valuable tools for fishery managers in other important fisheries. Environmental variables that correlate with pre-recruit abundances can be particularly valuable because the data is relatively simple and inexpensive to collect. Environmental variables that have been shown to correlate with recruitment include rainfall (Crecco et al. 1986), sea surface temperatures (Francis 1993, Rutherford & Houde 1995), winds and currents (Harris et al. 1988, Thresher 1994), river flow (Harris 1988) and the ENSO cycle (Pearce &

Phillips 1988, Kope & Botsford 1990, Jordan et al. 1995). One example is the western rock lobster fishery, where the strength of settlement of the puerulis stage can be used to predict recruitment to the fishery approximately four years later (Pearce & Phillips 1988). Settlement of pleuruli is in turn related to fluctuations in sea level, a function of the strength of the Leeuwin current and the El Niño southern oscillation (Pearce & Phillips 1988). Another example is the important role of pre-recruit surveys of juvenile snapper to predict future catches of snapper in Hauraki Gulf, New Zealand. A very strong relationship has been found between pre-recruit abundance and summer - autumn sea surface temperature (Francis 1993).

Pre-recruit indices have received little consideration in the past for King George whiting. South Australian scientists have looked in detail at environmental factors affecting abundances of juvenile Australian salmon and have found a significant relationship with sea level (K. Jones, pers. comm.), however, similar detailed studies have not been carried out for King George whiting. In this study we test for relationships between individual climatic variables and fishery recruitment, and we also combine climatic variables into realistic models of larval transport that we hypothesise may influence subsequent fishery recruitment. The results may make it possible for managers to predict fishery recruitment in future years based on physical variables such as winds and sea levels along the coast.

Need

Many fisheries benefit from pre-recruit indices of year-class strength that can be used to predict fishery fluctuations (eg. western rock lobster, snapper). The King George whiting fishery is particularly sensitive to recruit variability because the fishery is based almost entirely on one or two year-classes of sub-adult fish. There is a need for a pre-recruit index that can be used to forecast the strength of recruitment to the fishery in future years. We propose to evaluate two possible indices; linkage with annual variation in climatological and physical oceanographic variables that influence larval transport, and, linkage with annual variation in habitat cover for King George whiting.

Objectives

1) To determine the linkage between annual variation in larval transport, simulated by hydrodynamic modelling, and annual variation in recruitment to the King George whiting fishery.
2) To determine the linkage between annual variation in habitat cover and annual variation in recruitment to the King George whiting fishery.
3) To determine the linkage between other environmental variables and variation in recruitment to the King George whiting fishery

Methods

Numerical hydrodynamic modelling

We used climatic and oceanographic data (primarily sea levels and wind vectors) in our computer model of currents along the southern coast of Australia to predict the numbers of larvae entering central Victorian bays and inlets over the past 30 years. The western boundary of the model grid was placed near Ceduna, South Australia (Fig. 1) using the boundary condition techniques proved by Middleton and Black (1994). This involved adding coastal-trapped wave oscillations to the boundary sea levels using measured coastal water levels at Thevenard (Ceduna). Measured winds were taken from Ceduna, Cape Borda (Kangaroo Island), Cape Nelson (Portland), Cape Otway, Wilson’s Promontory, Flinders Island, Low Head (Tasmania) and Gabo Island (Jenkins et al. 2000) and interpolated using inverse distance weighting (Black 1995) onto each model cell. The model was verified by comparing predicted sea levels with actual sea levels at Port Stanvac (Adelaide), Portland and Point Lonsdale (Jenkins et al. 2000). The sea level indicates the current strength along the shelf due to set-up and set-down caused by the Coriolis force.

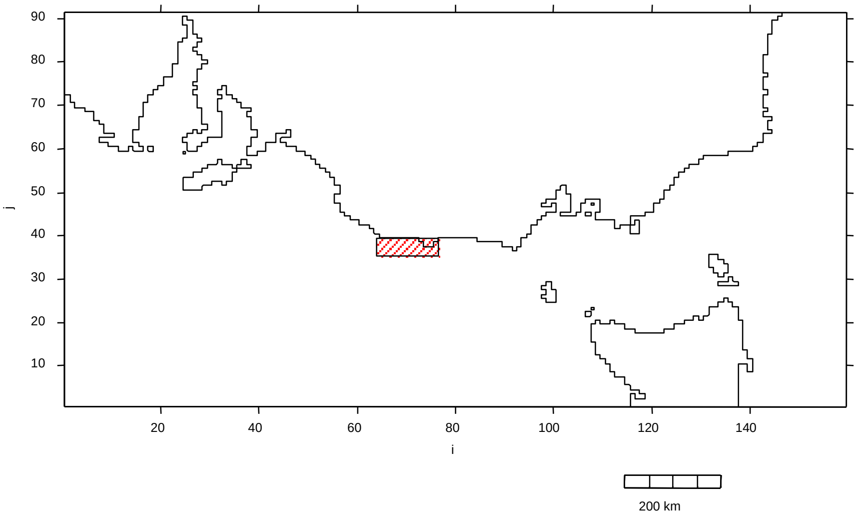

Fig. 1. Numerical modelling grid for simulations of King George whiting dispersal. The shaded area represents the release area for neutrally buoyant particles.

We used the three-dimensional hydrodynamic model 3DD (Black 1995) and dispersal model POL3DD (Black 1996). The three-dimensional hydrodynamic model had six depth strata, 0-5, 5-15, 15-35, 35-55, 55-75, and 75-6000 m. The model region was based on a grid of 10 x 10 km square cells, 178 cells east-west by 91 cells north-south (Fig. 1). In the dispersal model the horizontal eddy diffusivity was set at 0.0015 $m^2 s^{-1}$. The period simulated was from March 1 to November 30 of each year. Larvae were modelled as neutrally buoyant and moving randomly throughout the depth range. Simulated larvae were released from random positions within a rectangular area (Fig. 1) centred in the highest predicted region of spawning predicted by Jenkins et al. (2000).

Modelling scenario 1

In this scenario there was a constant release of particles from May 1 to June 30. This was the major period of spawning of Victorian recruits determined by Jenkins et al. (2000). Particles were released at a rate of 25 per hour and had a maximum larval duration of 175 d, the maximum larval duration recorded from otoliths (Jenkins et al.

2000). Particles were counted if they entered a sampling 'box' offshore from each bay (Fig. 2).

Modelling scenario 2

This scenario was equivalent to scenario one except that the number of particles released followed an approximate normal distribution over the release period to better represent the actual distribution of spawning determined by Jenkins et al. (2000). This was achieved by incrementing the number of particles released from 50 per 10 hours for the first six days, 100 per 10 hours for the next six days and so on to a maximum of 250 per 10 hours and then reduced back to 50 per 10 hours.

Modelling scenario 3

The final scenario uses the same release conditions as scenario 2, however in this case the larval duration is reduced to 140 days, and an exponential decline in numbers (representing planktonic mortality) is applied such that 10% of the particles released still remain after 120 days. In this scenario a single sampling box was used, orientated north to south near the entrance to Port Phillip Bay (Fig. 2).

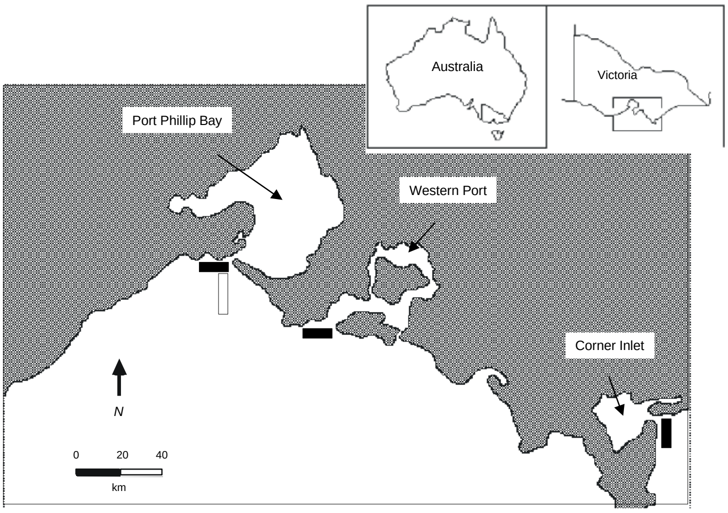

Fig. 2. Position of model 'boxes' where simulated larvae are recorded. Closed boxes, scenarios 1 and 2; open box, scenario 3. Insets: location of the study area on the Victorian coast and location of Victoria within Australia.

Climatic variables

The southern oscillation index is based on the air pressure difference between Darwin and Tahiti. Negative values represent El Niño or ocean warming in the Pacific, while positive values represent La Niña or ocean cooling in the Pacific. This cycle is thought to influence recruitment of fishery species in southeastern Australia (Harris et al. 1988, Thresher 1994, Jordan et al. 1995).

Also implicated in variation in recruitment of southeast Australian fishery species is the strength of westerly winds (Harris et al. 1988, Thresher 1994). Winds were quantified in two ways. Firstly, information on wind strength and speed recorded at Cape Otway for the period of interest (May to November) was converted into cumulative vectors. Thus, the east-west (U) and north-south (V) vectors were calculated for each 3 hourly recording interval and summed over the sampling period.

The second way in which winds were quantified was by calculating the number of 'zonal westerly' days in each year. Criteria for 'zonal westerly' are detailed in Harris et al. (1988) and include isobars mostly aligned E-W, at least one cold front embedded in the westerly stream, and total duration of the weather system of more than one day.

Recently, the cycle of solar activity has been implicated in climate variation. Solar activity was quantified as the number of sunspots observed in a given year. Rainfall and air pressure data since 1960 was obtained from meteorological records for Laverton (near Melbourne). Water level data since 1968 was obtained from recordings at the Point Lonsdale tide gauge.

Analysis of historical seagrass cover

The second aspect of the study looks at linkages between annual variation in seagrass cover and annual variation in recruitment to the King George whiting fishery. We accessed aerial photography of the coastline at a number of sites in Port Phillip Bay that we know from field sampling are important settlement habitats for King George whiting. We obtained photographs from 5 sites (Fig. 3): Altona, Point Henry, Clifton Springs, Grassy Point (Port Arlington) and Blairgowrie (Plates 1-5); spanning the past 60 years. At Clifton Springs we quantified seagrass in two areas, a narrow band near shore and a more extensive area covering the wide shelf of approximately 2 m depth (Plate 3).

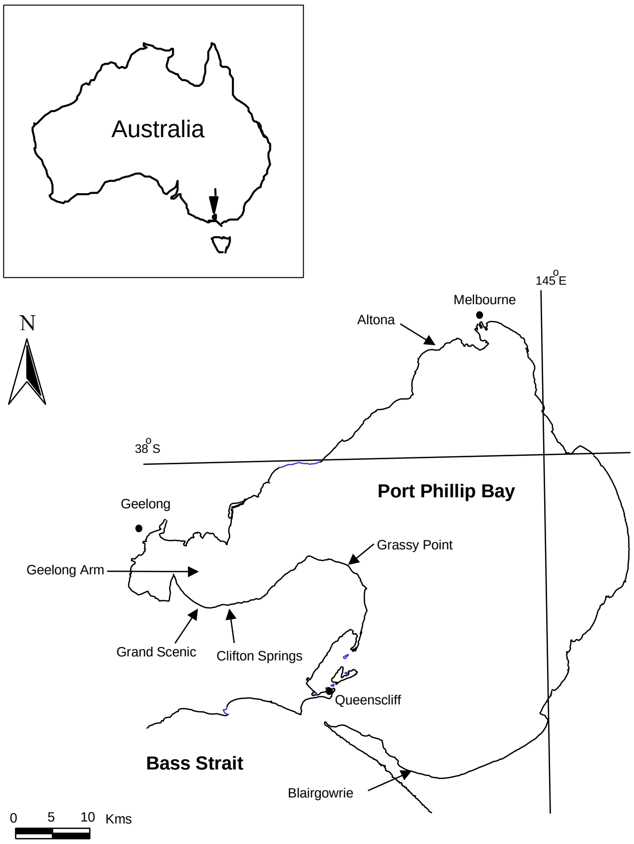

Fig. 3. Location of seagrass sites examined for historical aerial photography. Inset: Location of Port Phillip Bay on the Australian coast.

Plate 1. Seagrass mapping area for the Blairgowrie site.

Plate 2. Seagrass mapping area for the Grassy Point site.

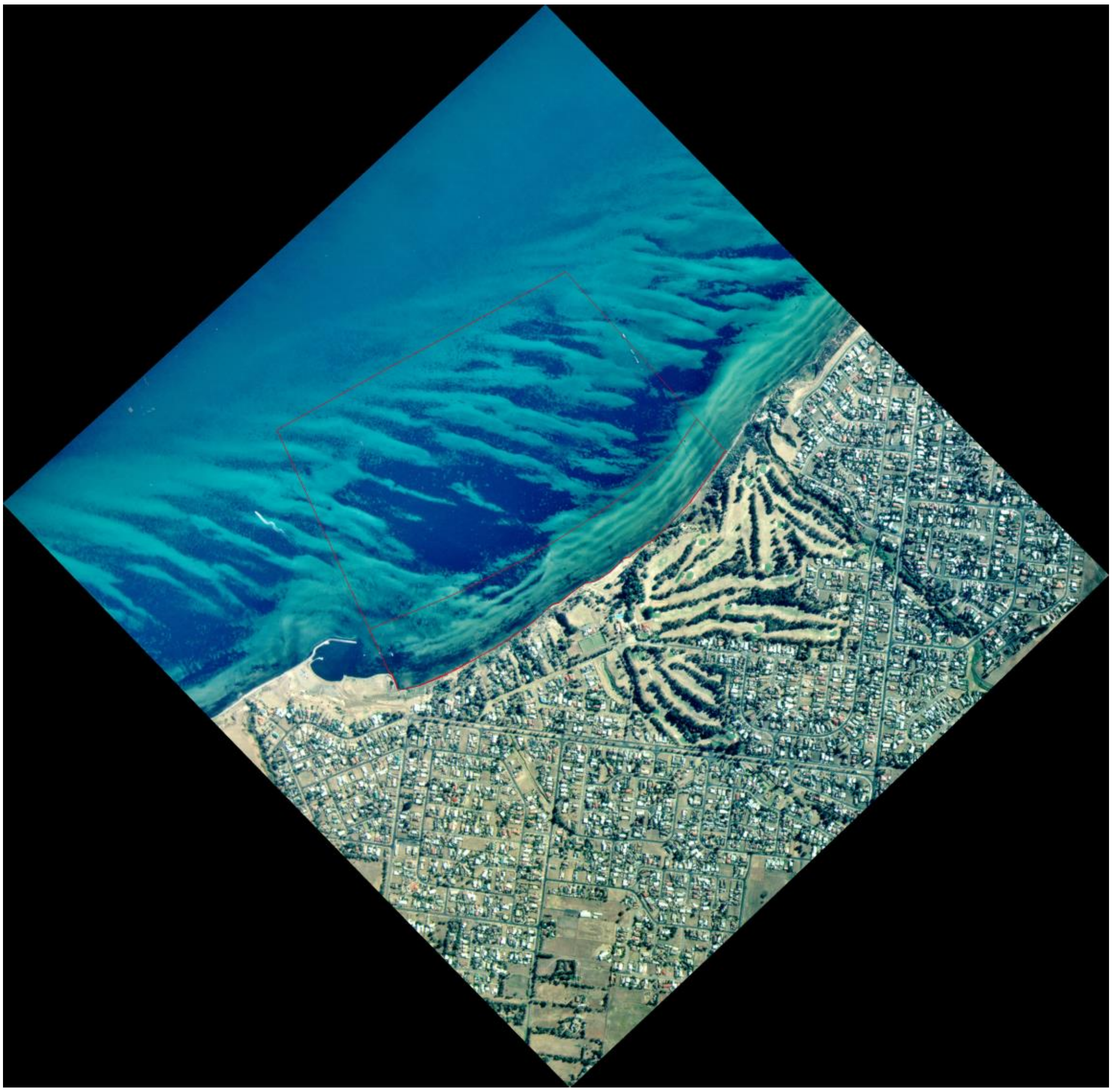

Plate 3. Seagrass mapping area for the Clifton Springs site.

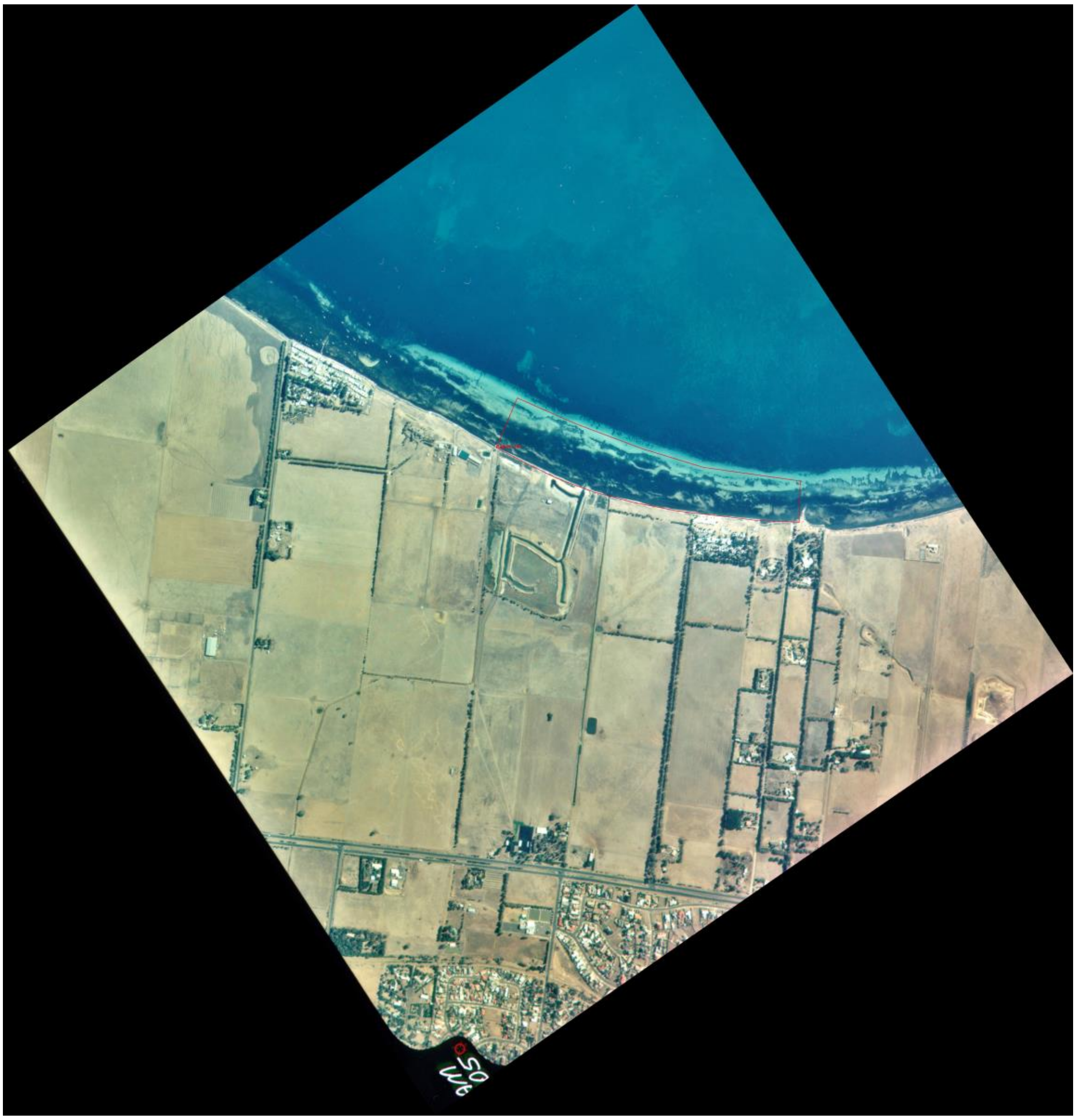

Plate 4. Seagrass mapping area for the Grand Scenic site.

Plate 5. Seagrass mapping area for the Altona site.

Scanning was required to convert hardcopy photographs into a digital format. The images were scanned (HP Scanjet 11c) and saved in a non-compressed Tagged Image File Format (TIFF). Rectification of the scanned images was then conducted to eliminate any aerial variations and distortions caused by camera angles. This was carried out using the GIS software, ER Mapper 6.1. Assigning the same datum, map projection and ground control points (obtained using ARCVIEW), allowed the geo-referencing of the scanned images to be completed in a consistent manner. Easting and Northing coordinates were located for common intersections and land boundaries using ARCVIEW. These ground control points (coordinates) were then assigned to each separate scanned photograph. To enable good spatial accuracy between the image coordinates and the coordinates obtained in ARCVIEW, a low root-mean-square error (RMS errors) was sought before proceeding to the next step. Still using ER Mapper, a study region was manually defined in one of the images within a site (Plates 1-5). This region was then imported in all other images for that site with only minimal adjustment to the coastal boundary. Defining such a boundary simplified classification and saved considerable time.

A classification was run and completed when 98% of the image remained unchanged. Classes were subjectively assigned to the classified image, which corresponded to the area of seagrass, and a raster to vector conversion was carried out. The vector conversion produced an outlined area of seagrass that could be verified against the rectified image. If the vector image was not a good match with the actual seagrass then the classification was adjusted accordingly (eg. a number of steps were retraced and improved). The final step was to convert the vector file into an ARCINFO format so that the GIS software ARCVIEW could be used to calculate the area of seagrass that was outlined.

Data analysis

Historical catches of King George whiting were from long term records of annual landings by weight. Log book returns from Victorian commercial fisherman were used to determine catch per unit effort in terms of weight of King George whiting per net shot. The analysis was restricted to seine nets (beach, haul, ring and garfish) that account for most of the King George whiting catch.

Similarity between time series of environmental variables, habitat variables and catch variables were tested using cross-correlation analysis that tests both direct and lagged correlations. The correlation statistic used was Pearson's *r*. The modified Chelton method (Pyper & Peterman 1997) was used to adjust the sample size N* used in correlations to account for the inflated probability of a type 1 error due to autocorrelation within time series. Where necessary, time series were log transformed and/or trend transformed (the residuals of a linear regression were used to remove trend) to make the time-series stationary.

Results

Comparison of catch with hydrodynamic modelling and environmental variables, 1968-1998

Catch

Hydrodynamic models were generated for the years 1968 to 1998. Catches over this period were highly variable. In Port Phillip Bay catches showed a cyclic pattern with approximately 2.5 cycles occurring over the 30 year period (Fig. 4A). This cyclic pattern was superimposed on a general upward trend over the period (Fig. 4A). The pattern for Western Port showed a cyclic pattern that was similar to Port Phillip however in this case superimposed on a downward trend (Fig. 4B). In Corner Inlet the general cyclic pattern of the other bays was recognisable, however shorter cycles of a few years period were also present (Fig. 4C). Like Port Phillip, the underlying trend in catch in Corner Inlet was upward (Fig. 4C). Catches of King George whiting in the three bays were highly correlated (Table 1).

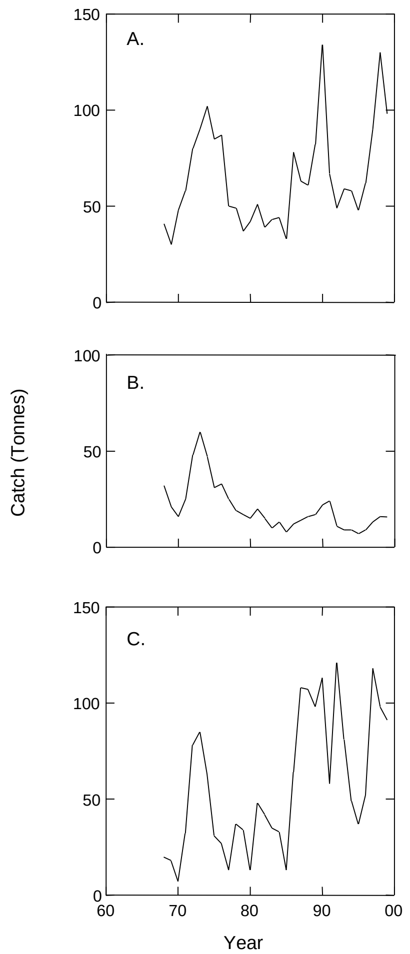

Fig. 4. Annual catch by weight of King George whiting for A) Port Phillip bay, B) Western Port and C) Corner Inlet

Table 1. Cross correlations between catches (tonnes) of King George whiting from three bays from 1968 to 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Western Port catch[1]			Corner Inlet catch[1]		
	Lag	N*	*r*	Lag	N*	*r*
Port Phillip catch[1]	0	10	0.825††	0	17	0.588†
Western Port catch[1]				0	15	0.655†

[1]Data log and trend transformed

Hydrodynamic modelling - Scenario 1

In this scenario of constant spawning output and zero larval mortality a cyclic pattern in annual particle arrival at bays was apparent. Like the catch data, particle arrival at each bay showed approximately 2.5 cycles over the 30 year period (Fig. 5). Also like catch data, particle arrival at Corner Inlet showed greater short-term (1-3 year) variability compared to the other bays (Fig. 5C). Unlike catch data, numbers of particles arriving at the bays showed a systematic decrease from west to east, with approximately an order of magnitude higher numbers in Port Phillip compared with Corner Inlet (Fig. 5).

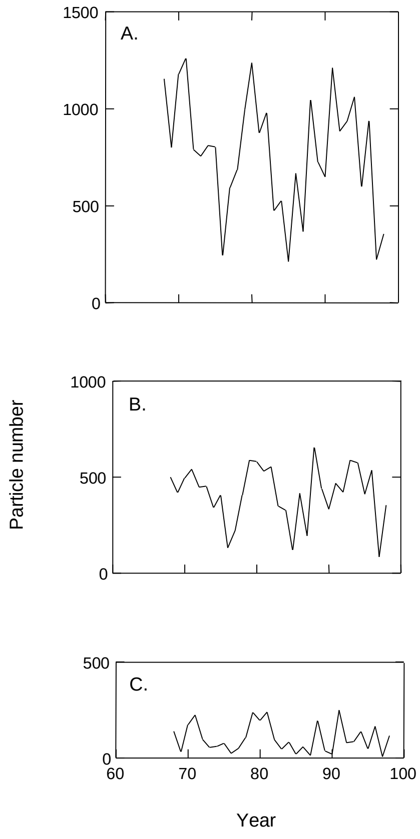

Fig. 5. Time series of annual particle numbers collected in modelling scenario 1; A) Port Phillip Bay box, B) Western Port box, C) Corner Inlet box

Hydrodynamic modelling - Scenario 2

In this scenario of a normal distribution of spawning output and zero larval mortality, shorter-term variability in particle arrival was more apparent than in scenario 1, and the longer-term cycle was less apparent (Fig. 6). Like scenario 1, numbers of particles arriving in model boxes decreased systematically from west to east (Fig. 6).

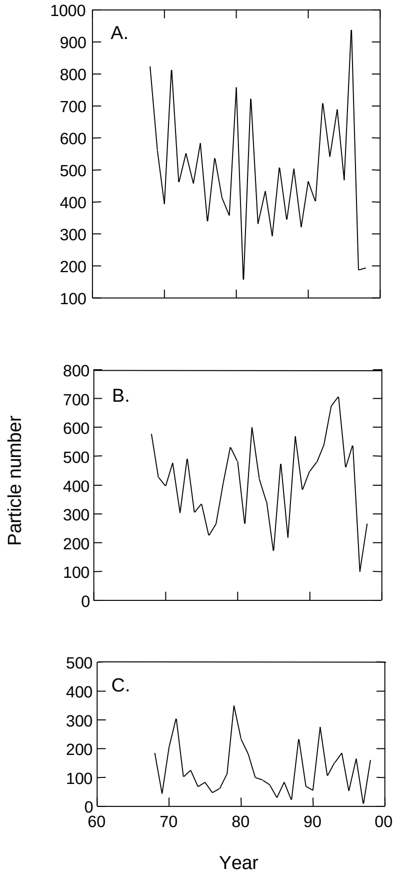

Fig. 6. Time series of annual particle numbers collected in modelling scenario 2; A) Port Phillip Bay box, B) Western Port box, C) Corner Inlet box

Hydrodynamic modelling - Scenario 3

In the third scenario, where particles were subjected to mortality over larval life, the arrival of particles to the Port Phillip Bay model box (Fig. 7) was similar to scenario one (Fig. 5A). Like scenario one, there was long-term variability with, in this case, three cycles apparent (Fig. 7). Also like scenario one there was a downward trend over the time series, however, in this case the trend was steeper (Fig 5A). The number of particles arriving (Fig. 7) was lower than in scenario 1 (Fig. 5A) due to the effects of the imposed mortality.

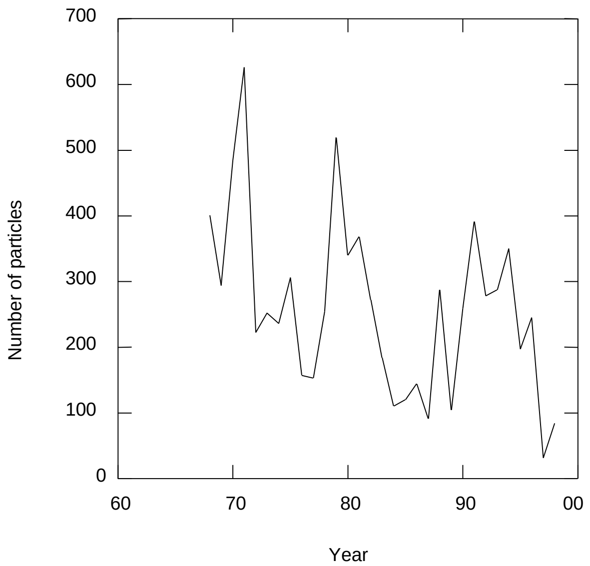

Fig. 7. Time series of annual particle numbers collected in the Port Phillip Bay model box in modelling scenario 3

Correlation between hydrodynamic modelling scenarios and catches

Numbers of particles collected in model boxes from the three modelling scenarios were not significantly correlated with King George whiting catches in the three bays (Table 2). Maximum positive correlations occurred mainly at lags of 6 to 8 years, while maximum negative correlations occurred mainly at 0 lag (Table 2).

Correlation between environmental variables and catches

Environmental variables related to the strength of westerly winds, west-east cumulative wind vector (Fig. 8A) and zonal westerlies (9A), showed a similar pattern with a decreasing trend and peaks at the start of the series around 1970, a second peak around 1980 and a third peak in the early 1990's. This pattern was similar to time-series of particle arrival in model runs, particularly for scenarios 1 and 3 with constant particle release (Figs 5,7). Environmental variables that measured the strength of westerly winds showed a similar correlation pattern with whiting catches. Maximum positive correlation occurred at lags of approximately 5 to 6 years, and there was a significant positive correlation for Port Phillip catch lagging the cumulative westerly wind vector at Cape Otway by 5 years (Table 3). Catches also typically showed negative correlations with variables measuring westerly winds at lags of 0 or 1 years. This relationship was significant for Port Phillip and Western Port catches correlating with the cumulative westerly wind vector at Cape Otway at 0 lag, and for Port Phillip catches and zonal westerlies at 0 lag (Table 3).

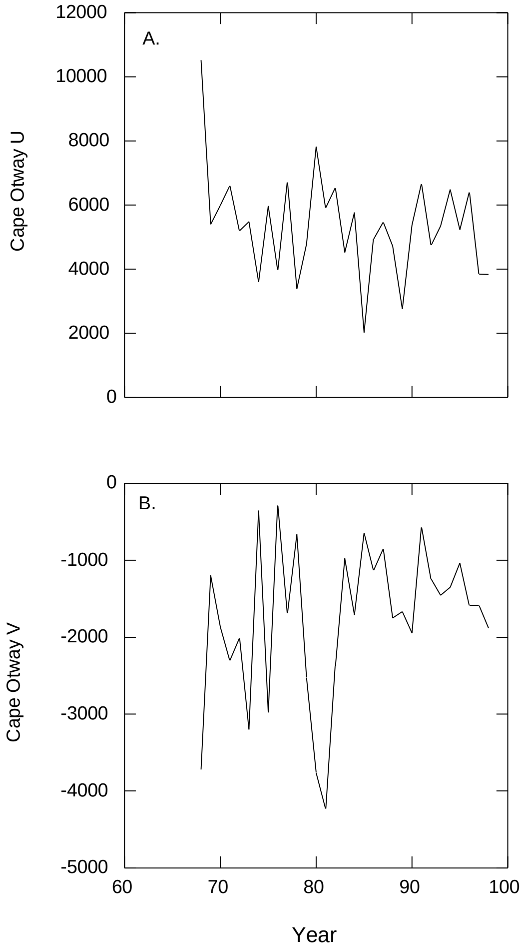

Fig. 8. Time series of annual cumulative wind vectors for winds measured at Cape Otway; A) east-west, B) north-south

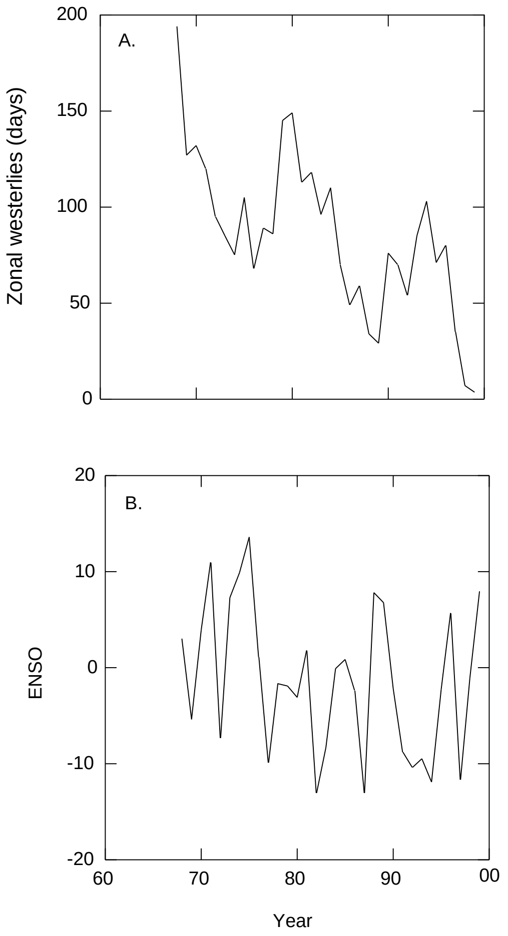

Fig. 9. Time series of the annual number of (A) days of zonal westerlies and (B) average El Niño southern Oscillation (ENSO)

Table 2. Cross correlations between particle numbers from hydrodynamic model runs and catches of King George whiting from three bays. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Sign	Port Phillip catch[1]			Western Port catch[1]			Corner Inlet catch[1]		
		Lag	N*	*r*	Lag	N*	*r*	Lag	N*	*r*
Scenario 1[2]	+ve	7		0.255 ns	8		0.349 ns	7		0.263 ns
	-ve	0		0.174 ns	0		0.129 ns	4		0.196 ns
Scenario 2	+ve	3		0.283 ns	7		0.311 ns	7		0.261 ns
	-ve	0		0.097 ns	0		0.319 ns	4		0.206
Scenario 3[3]	+ve	6		0.260 ns						
	-ve	0		0.229 ns						

[1]Data log and trend transformed
[2] Port Phillip data trend transformed
[3] Trend transformed

A different relationship was found between whiting catches and the El Niño southern Oscillation (ENSO) (Fig. 9B). In this case positive correlations occurred at lags of 0 and 1 year for both Port Phillip and Western Port, however no significant relationship occurred with catches in Corner Inlet (Table 3). No significant relationship was found between the north-south cumulative wind vector (Fig. 8B) and whiting catches (Table 3). No significant correlations were found between catch and average sea level at Point Lonsdale, and average air pressure and rainfall at Laverton (P>0.05).

Table 3. Cross correlations between environmental variables and catches of King George whiting from three bays from 1968 to 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Sign	Port Phillip catch[1]			Western Port catch[1]			Corner Inlet catch[1]		
		Lag	N*	*r*	Lag	N*	*r*	Lag	N*	*r*
Otway U[2]	+ve	5	24	0.409†	5		0.358 ns	5	24	0.372 ns
	-ve	0	22	0.427†	0	24	0.398†	1		0.177 ns
Otway V[2]	+ve	3		0.190 ns	2		0.250 ns	3		0.205 ns
	-ve	7		0.272 ns	7		0.191 ns	7		0.305 ns
ENSO[2]	+ve	0	26	0.472†	0	24	0.421†	0		0.198 ns
	+ve	1	27	0.422*	1	24	0.437*			
	-ve	6		0.301 ns	6		0.192 ns	5		0.287 ns
Zonal west[2]	+ve	5	12	0.428 ns	6		0.340 ns	6		0.339 ns
	-ve	0	10	0.629*	0	10	0.536 ns	0	16	0.421 ns

[1]Log and trend transformed
[2]Trend transformed

Regression analysis was performed using variables significantly correlated with catch in Port Phillip Bay (Table 4). Approximately 23% of the year to year variation in catch could be explained based on the east-west wind vector 5 years prior. The addition of the ENSO cycle one year prior to the catch increased the variance explained to 39%. Finally, if the strength of zonal westerlies in the year of the catch is included then 52% of the variation in catch can be explained.

Table 4. Regression equations relating the log and trend transformed Port Phillip Bay catch to trend transformed east-west wind vector at Cape Otway (5 years prior), trend transformed ENSO (1 year prior) and trend transformed zonal westerlies.

Regression coefficient				r^2
Otway U	ENSO	Zonal westerlies	Constant	
0.0001			-0.0054	0.226
0.0001	0.0204		0.0114	0.389
0.0001	0.0160	-0.0049	0.0048	0.522

Comparison of catch per unit effort with hydrodynamic modelling and environmental variables, 1979 -1998

Catch per unit effort (CPUE)

Fishing effort in Port Phillip bay has been relatively constant at approximately 3000 net shots per year (Fig. 10A). Effort in Western Port was much lower than in Port Phillip and showed a decreasing trend over the time period to below 1000 net shots per year by the late 1990's (Fig. 10B). There was a rapid increase in fishing effort in Corner Inlet from the start of the time-series to the early 1990's, rising from less than 1000 to nearly 4000 net shots per year (Fig. 10C).

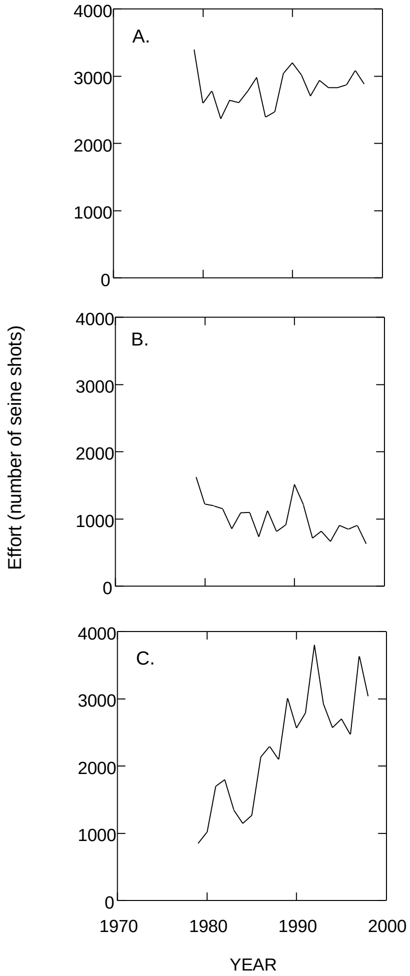

Fig. 10. Time series of annual effort in terms of number of seine shots; A) Port Phillip Bay, B) Western Port, C) Corner Inlet

The time series of CPUE in Port Phillip (Fig. 11A) largely reflected raw catch (Fig. 4A); the cyclic variability in the time series was apparently not a function of variation in effort. CPUE for Western Port was lower than for the other two bays and showed no trend over time (Fig. 11B), showing that the declining trend in catch (Fig. 4B) was mainly due to declining effort (Fig. 10B). Peaks in catch around 1990 and the late 1990's for Western Port (Fig. 4B) were also apparent in CPUE (Fig. 11B). In general the CPUE for Corner Inlet was the highest of any bay (Fig. 11C). A major peak in the Corner Inlet CPUE in 1997 represented the highest CPUE recorded for any bay of over 50 kg per shot (Fig. 11C). In comparison with raw catch (Fig. 4C), the time series of CPUE tended to emphasise the importance of the peak in 1997 (Fig. 11C).

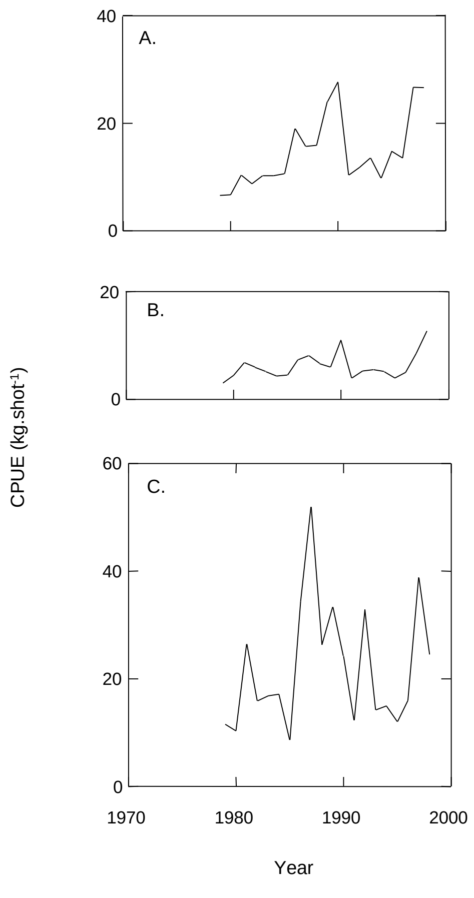

Fig. 11. Time series of annual catch per unit effort for seine netting; A) Port Phillip Bay box, B) Western Port box, C) Corner Inlet box

Like raw catch, time series of CPUE for the three bays were highly correlated (Table 5).

Table 5. Cross correlations between catch per unit effort (kg per net shot) of King George whiting from three bays between 1979 and 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Western Port CPUE[1]			Corner Inlet CPUE[1]		
	Lag	N*	*r*	Lag	N*	*r*
Port Phillip CPUE[1]	0	10	0.825††	0	17	0.588†
Western Port CPUE[1]				0	15	0.655†

[1]Data log and trend transformed

Correlation between hydrodynamic modelling scenarios and CPUE

Maximum positive correlations between modelling scenarios and CPUE for the three bays occurred mainly at lags of 6 or 7 years but were not significant (Table 6). Significant negative correlations occurred at 0 lag between scenarios 2 and 3, and Port Phillip CPUE (Table 6). A significant negative correlation also occurred at a lag of 1 year between scenario 2 and Western Port CPUE (Table 6).

Table 6. Cross correlations between particle numbers from hydrodynamic model runs and catch per unit effort (kg per net shot) of King George whiting from three bays between 1979 and 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Sign	Port Phillip CPUE[1]			Western Port CPUE[1]			Corner Inlet CPUE[1]		
		Lag	N*	*r*	Lag	N*	*r*	Lag	N*	*r*
Scenario 1[2]	+ve	7		0.300 ns	6		0.138 ns	6		0.263 ns
	-ve	0	12	0.524 ns	3		0.410 ns	0		0.326 ns
Scenario 2[3]	+ve	7		0.119 ns	4		0.280 ns	7		0.160 ns
	-ve	0	18	0.510†	1	17	0.519†	0		0.385
Scenario 3[2]	+ve	7		0.474 ns						
	-ve	0	11	0.595†						

[1]Log and trend transformed
[2]Trend transformed
[3]Western Port and Corner Inlet trend transformed

Correlation between environmental variables and CPUE

Westerly wind related variables showed positive correlations at a lag of approximately 6 years of up to 0.5, however, they were not statistically significant (Table 7). However, a significant negative correlation occurred at 0 lag between the Cape Otway west-east wind vector and Port Phillip CPUE, and a similar significant negative correlation occurred between zonal westerlies and CPUE for all bays (Table 7). Significant positive correlations occurred between ENSO and CPUE for Port Phillip at a 1 year lag and Western Port at a 2 year lag (Table 7).

Table 7. Cross correlations between environmental variables and CPUE of King George whiting from three bays from 1979 to 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Sign	Port Phillip CPUE[1]			Western Port CPUE[1]			Corner Inlet CPUE[1]		
		Lag	N*	*r*	Lag	N*	*r*	Lag	N*	*r*
Otway U[2]	+ve	6		0.418 ns	6		0.502 ns	6		0.501 ns
	-ve	0	18	0.498†	1		0.372 ns	0		0.203 ns
Otway V[2]	+ve	3		0.311 ns	3		0.294 ns	4		0.325 ns
	-ve	7		0.226 ns	0		0.279 ns	7		0.309 ns
ENSO[2]	+ve	1	18	0.485†	2	12	0.528†	1		0.279 ns
	-ve	6		0.308 ns	7		0.331 ns	5		0.355 ns
Zonal west[2]	+ve	6		0.450 ns	6		0.340 ns	7		0.434 ns
	-ve	0	10	0.731†	0	16	0.521†	0	14	0.618†

[1]Log and trend transformed
[2]Trend transformed

Comparison of long-term catch with environmental variables, 1945 –1998

Long-term catch

Catch of King George whiting has been steadily increasing since 1945 but also shows high cyclic variability (Fig. 12A). Catch in Western Port increased from 1945 to the early 1970's, but then decreased to a level much lower than the other bays in recent years (Fig. 12B). Like Port Phillip, the catch in Corner Inlet shows high cyclic variability superimposed on an increasing trend over time (Fig. 12C). Long-term catches of King George whiting were highly correlated amongst bays (Table 8).

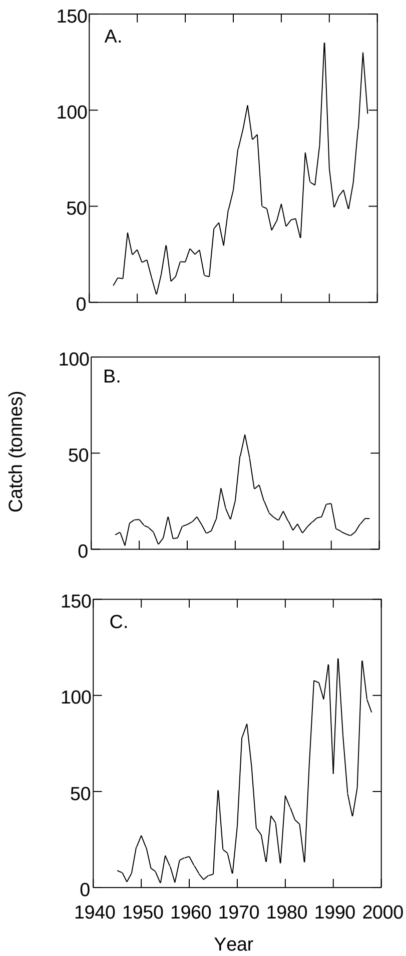

Fig. 12. Long-term time series of annual catch of King George whiting; A) Port Phillip Bay, B) Western Port, C) Corner Inlet

Table 8. Cross correlations between catch (tonnes) of King George whiting from three bays between 1945 and 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Western Port catch[1]			Corner Inlet catch[1]		
	Lag	N*	*r*	Lag	N*	*r*
Port Phillip catch[1]	0	27	0.812††	0	27	0.590††
Western Port catch[1]				0	37	0.511††

[1]Data log and trend transformed

Correlation between environmental variables and long-term catch

Zonal westerly winds have shown strong cyclic variability with approximately 5 cycles occurring over the past 50 years (Fig. 13A). This variability is superimposed on a very marked downward trend in the number of days of zonal westerlies (Fig. 13A). The El Niño southern oscillation shows high variability at the scale of a few years superimposed on a slight downward trend (Fig. 13B). Sun spot activity showed a very regular cycle with peaks at the end of each decade and troughs in the middle of each decade (Fig. 14).

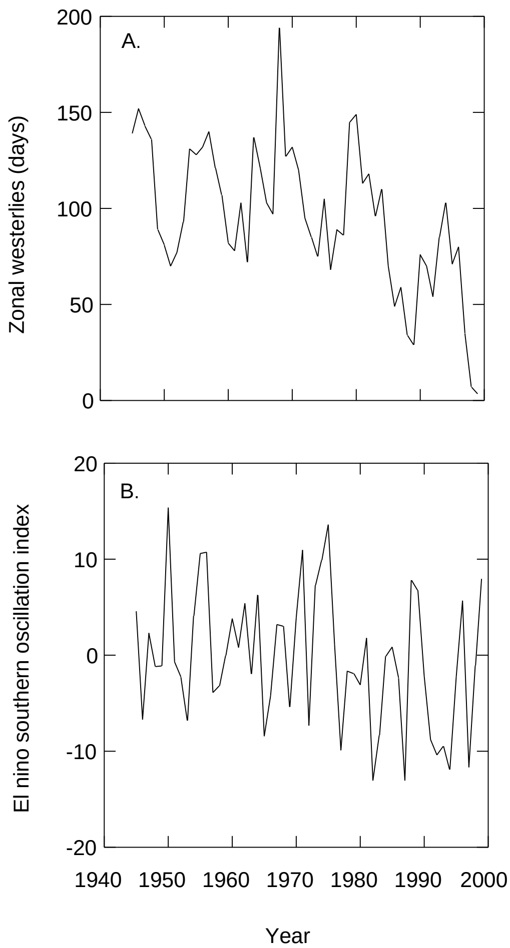

Fig. 13. Long-term time series of annual (A) number of days of zonal westerlies and (B) average El Niño southern Oscillation (ENSO)

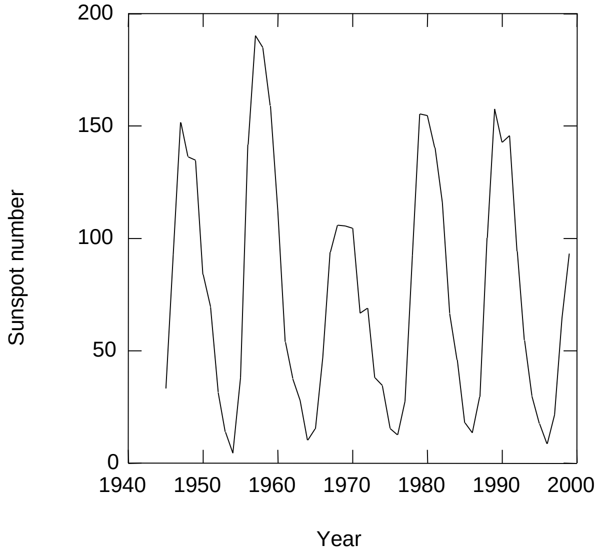

Fig. 14. Time series of annual numbers of sunspots

Long-term catches in Port Phillip and Western Port were significantly correlated with zonal westerlies at lags of 3, 4 and 5 years when based on raw data, however, the relationship was only significant for Port Phillip at a lag of 5 years when autocorrelation was taken into account (Table 9). In contrast to Port Phillip and Western Port, the Corner Inlet catch showed a significant negative correlation with zonal westerlies at 0 lag (Table 9). Long-term catch for Port Phillip and Western Port also showed significant positive correlations with the El Niño southern oscillation index at lags of 0 and 1 year (Table 9). No significant correlation was found between long-term catches and sun spot activity (Table 9).

Table 9. Cross correlations between environmental variables and long-term catch of King George whiting from three bays from 1945 to 1998. Maximum positive and negative correlations are presented with associated time lags in years. † <0.05, †† <0.001, ns = not significant

Variable	Sign	Port Phillip catch[1]			Western Port catch[1]			Corner Inlet catch[1]		
		Lag	N*	*r*	Lag	N*	*r*	Lag	N*	*r*
Zonal west[2]	+ve	3	22	0.340 ns	3	27	0.330 ns	3		0.250 ns
	+ve	4	22	0.381 ns	4	26	0.328 ns			
	+ve	5	22	0.442 †	5	25	0.353 ns			
	-ve	0		0.274 ns	0		0.123 ns	0	35	0.397†
ENSO[2]	+ve	0	50	0.345†	0	52	0.331†	0		0.183 ns
	+ve	1	49	0.328†	1	51	0.403††			
	-ve	3		0.177 ns	7		0.046 ns	5		0.114 ns
Sun spot	+ve	0		0.068 ns	1		0.008 ns	2		0.165
	-ve	6		0.146 ns	6		0.186 ns	5		0.248

[1]Log and trend transformed
[2]Trend transformed

Relationship between historical cover of seagrass in Port Phillip Bay and catch of King George whiting

Temporal change in seagrass cover

Sites varied in the temporal pattern of change in seagrass cover. At Blairgowrie, seagrass cover has shown a major increase since the 1960's, with short-term variation in cover at the scale of a few years superimposed on the increasing trend (Fig. 15). Fewer photographs were available for Grassy Point; highest cover of approximately 30% was recorded in an early photograph taken in 1947, the other photographs were taken since the mid 1960's and the cover has varied between approximately 10 and 25 % over that period (Fig. 16). Again, based on few years, the broad and nearshore areas at Clifton Springs have shown wide variability in seagrass cover with almost complete loss of seagrass in 1989 but a subsequent recovery (Fig. 17). Seagrass cover at the Grand Scenic showed wide variability ranging from 10% cover in the mid 1970's to 70 % cover in the early 1980's (Fig. 18). Superimposed on this variability was a generally upward trend from the 1960's to present (Fig.14). Seagrass cover at Altona was generally low (< 20%) from the mid 1950's to the late 1960's before increasing in cover substantially from the 1970's to the present (Fig. 19). There was evidence of major variability in cover at Altona at the scale of years, as occurred in the late 1990's where cover varied between 50 and 20% in successive years (Fig. 19).

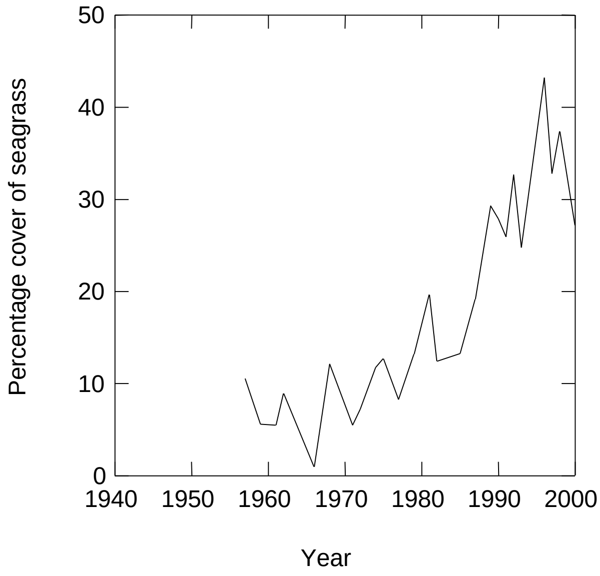

Fig. 15. Percentage seagrass cover at the Blairgowrie site based on historical aerial photographs.

Fig. 16. Percentage seagrass cover at the Grassy Point site based on historical aerial photographs.

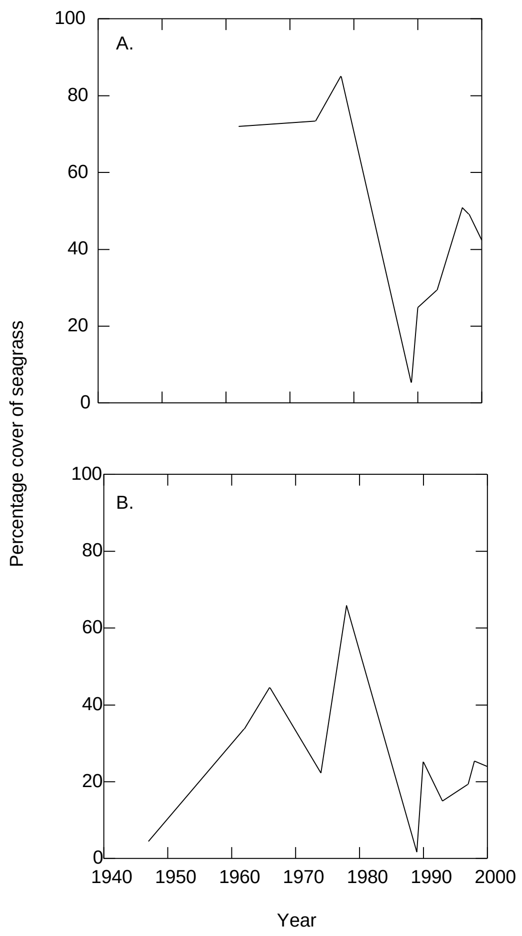

Fig. 17. Percentage seagrass cover at the Clifton Springs site based on historical aerial photographs; A) broad coverage, B) near-shore coverage

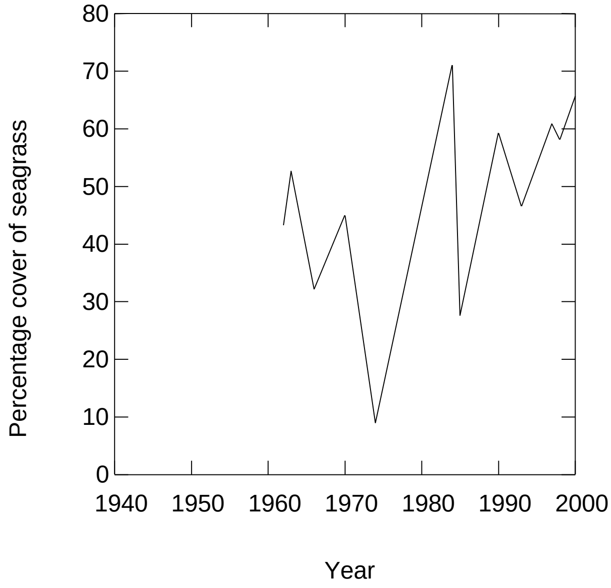

Fig. 18. Percentage seagrass cover at the Grand Scenic site based on historical aerial photographs

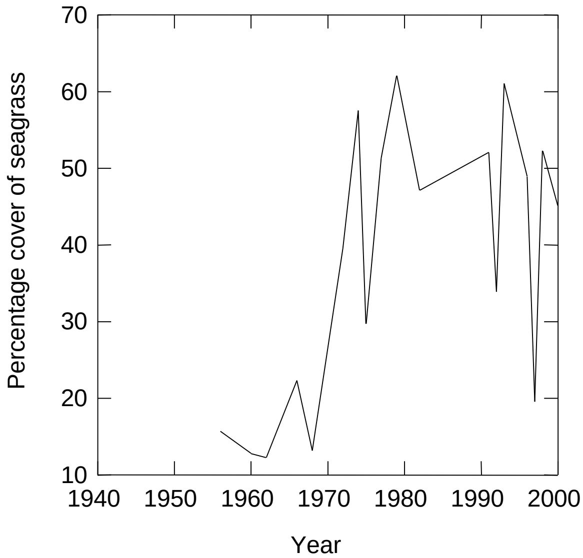

Fig. 19. Percentage seagrass cover at the Altona site based on historical aerial photographs

Correlation between seagrass cover, catch and environmental variables

The most reliable site for more detailed analysis was Blairgowrie due to the frequency of photography and confidence in identification of seagrass (Fig. 15). The increasing trend in the data was removed using a quadratic regression so that shorter-term variation could be compared with environmental variables in catch. Short-term variation in whiting catch was not correlated with seagrass cover at lags between 0 and 5 ($P>0.05$). In terms of environmental variables that might influence seagrass cover, there was a significant positive correlation between the El Niño southern oscillation index and seagrass cover ($r=0.514$, $n=24$, $P<0.02$), and a significant negative correlation between air pressure and seagrass cover ($r=-0.661$, $n=24$, $P<0.002$). Air pressure, in turn, was significantly negatively correlated with sea level ($r=-0.578$, $n=32$, $P<0.001$) and rainfall ($r=-0.334$, $n=40$, $P<0.05$).

Discussion

Both catch and catch per unit effort of King George whiting is highly correlated amongst Port Phillip Bay, Western Port and Corner Inlet over all the time scales examined. This strongly suggests that large-scale environmental variation exerts a significant control on the abundances of whiting. Similarity of catches in Port Phillip and Western Port could be partly explained by the fact that many fishermen holding dual licences that cover both bays (although CPUE should account for any similarity in effort for the two bays). Licences for Corner Inlet are separate from the other bays, however, and the fishing should be relatively independent.

Such broad-scale environmental factors might include those that would affect larvae in the planktonic phase. The larval duration in King George whiting is very long compared with most fish species (Jenkins & May 1994). Moreover, research strongly suggests that spawning occurs offshore from bays and inlets, and often a considerable distance from the settlement site (Jenkins et al. 2000). Thus, interannual variation in the current patterns carrying larvae could influence the number of larvae arriving at bays of central Victoria (Norcross & Shaw 1984, Polacheck et al. 1992, Werner et al.

1997). Alternatively, interannual variation in climate might influence planktonic productivity, and therefore the survival of larvae (Harris et al. 1988, Thresher et al. 1989, Heath & Gallego 1998).

Broad-scale climatic factors might also influence survival of juveniles and subsequently affect catches. For example, variation in variables such as water temperature and rainfall might influence important juvenile habitats such as seagrass. The decline in catch in Western Port from the 1970's that was not observed in Port Phillip or Corner Inlet was most likely related to the major decline in seagrass cover that occurred at this time (Shepherd et al. 1989, MacDonald 1992). This illustrates that influences on juvenile survival may affect catch in each bay more independently than effects on larvae.

Modelling scenarios, that might be expected to simulate larval transport, were not significantly correlated with catches. Nor were they correlated with CPUE, which should give a more reliable estimate of the population of whiting available. CPUE, however, showed a similar pattern over time to raw catch, and variation in effort (measured as number of net shots) contributed little to the overall variation in catch. We hypothesised that the strength of transport of larvae to bays would vary from year to year resulting in variation in the numbers of larvae settling in bays, and subsequent recruitment to the fishery. There are several possible explanations for the lack of correlation between model predictions and fish catch.

Firstly, the hypothesis may be false, interannual variation in the rate of larval transport may not be the dominant factor influencing recruitment. The primary source of variation in larval survival and recruitment in marine fish in south eastern Australia is thought to be planktonic productivity, influencing larval feeding rates and subsequent survival (Harris et al. 1988); transport may have a subordinate role. The significant correlation between the westerly wind vector at Cape Otway and catch in Port Phillip Bay lagged by 5 years suggests that transport of larvae by westerly winds may be an important factor. However, westerlies in the southern Australian region may also lead to higher planktonic productivity, and therefore survival of larvae

(Thresher et al. 1989). It is possible that if biological parameters were added to the models, including primary production and larval growth and survival, then the models may have a strong predictive capacity (Heath & Gallego 1998). More information on the biological processes occurring in the larval stage of King George whiting will be required for such bio-physical models. Some of this information, such as larval growth rate, is already available in the otolith microstructure of post-larvae (Jenkins & May 1994) sampled over the past 8 years.

Secondly, assumptions in the modelling may be incorrect. We chose to use the area predicted to have highest spawning, based on otolith daily increment and numerical modelling studies (Jenkins et al. 2000). These studies, however, suggested that spawning is widespread, occurring mainly west of Cape Otway, but, for some larvae entering Corner Inlet, spawning may have occurred on the nearby coast west of Wilson's Promontory (Jenkins et al. 2000). Our modelling results were inconsistent with the catch data in that the number of recruits was predicted to decrease from Port Phillip Bay east to Corner Inlet. Catches, however, did not show this trend. Thus, assuming that the only source of larvae was well to the west of Port Phillip Bay may have affected our results. A number of other assumptions may have also affected results, such as spawning period, larval duration, larval mortality, and variation in these from year to year. The assumptions used in the modelling could be greatly improved with better field information on the spawning and early life history of this species. For example, a study of gonad development of this species along the coast would help confirm spawning times and areas (Hyndes et al. 1998, Fowler et al. 1999).

Thirdly, the lack of correlation between model results and catch may have been due to an insufficiently long time series for sufficient statistical power. Variation in both catch and particle arrival in scenarios one and three occurs on a low frequency, with only approximately 2.5 cycles occurring in the thirty years studied. Thus, longer time series may be needed to evaluate relationships. The significant relationship between westerly winds at Cape Otway and catch, however, suggests that significant relationships can be detected for this length of time series.

Significant negative correlations were found for westerly wind related variables and catch in the 30 year data set, probably related to low catchability of fish in strong westerly years typified by frequent cold fronts and rough weather. The effect of bad weather, however, was not reflected in a simple reduction of the number of net shots. Variation in effort not measured here, such as change to less preferred but more protected fishing locality, or change in fish behaviour in bad weather, may have contributed to lower catches in strong westerly years. A negative effect of westerly weather on the environment and corresponding increase in mortality of older juvenile whiting is also possible but less likely.

A further significant correlation that occurred in both the 30 year and CPUE data set was a positive correlation between the ENSO cycle and catch at lags of 0 to 2 years. A positive relationship indicates that catches are highest up to two years after a la Niña period. This suggests an effect of the ENSO cycle in the juvenile stage. La Niña years were associated with low average barometric pressure and high sea level. Low barometric pressure was, in turn, associated with higher rainfall. Thus, La Niña years in the Port Phillip Bay area are characterised by high rainfall, low air pressure and corresponding high sea level. Such conditions might result in increased nutrient runoff that would stimulate increased benthic productivity. Such increased productivity could lead to increased weight of catch through higher growth rate, condition, and survival of juvenile whiting. However, no direct correlation was found between catch and sea level, air pressure or rainfall, so other unknown factors associated with La Niña years might be responsible for the significant correlation.

Like the short-term data sets, catches in each bay since 1945 are highly correlated suggesting a broad-scale influence of the environment. The long-term data set showed a significant correlation between zonal westerlies and catch lagged by 5 years. Whiting individuals probably reach legal size in their fourth year (3+) and few individuals remain in the bay after their fifth year (4+). The 5 year lag can be explained by the fact that catch was measured by weight rather than number, and therefore would be biased to larger individuals in the population. Thus, the strong zonal westerlies would correspond to the year of larval recruitment that resulted in a large catch 5 years later. Thus, strong westerlies were apparently associated with high larval recruitment. As discussed previously, this may have occurred due to increased rate of transport from spawning grounds in the west of Victoria to bays and inlets of central Victoria. More likely, however, given the lack of correspondence between model simulations and recruitment, is that strong westerlies result in enhanced planktonic productivity and, as a consequence, higher survival of larval.

That strong westerly wind years lead to higher larval settlement and subsequent catch is supported by annual monitoring of larval King George whiting settlement in Port Phillip Bay (Jenkins, unpublished data). Although the data series is still too short for rigorous analysis, there appears to be a strong relationship between the strength of westerly winds and larval settlement, and also larval settlement and catch lagged by 4 or 5 years (Jenkins, unpublished data).

As in the shorter-term correlations, the time series since 1945 also showed a significant positive correlation between the ENSO cycle and catch at lags of 0 and 1 year for Port Phillip and Western Port, again suggesting that La Niña years have a positive effect on the environment of older juveniles. Also, like the shorter-term correlations, there was a negative correlation between the strength of zonal westerlies and catch in Corner Inlet at 0 lag, probably because of a reduction in the efficiency of fishing or the catchability of fish.

In terms of predictive models for King George whiting catch, we found the approximately 23 % of the variation in catch in Port Phillip Bay could be explained by westerly wind strength 5 years prior. This proportion increased to 39 % if the ENSO cycle 1 year prior is included, and 52% if the westerly wind strength for the current year is included. This indicates that over 50 % of the variation in catch can be explained by three environmental variables. Furthermore, an indication in the catch trend could be obtained up to 5 years in advance. The use of actual settlement data from monitoring rather than the simple proxy of westerly wind strength might significantly improve the reliability of long-term predictions.

Historical aerial photography suggested that seagrass cover varied greatly over time, both in the short term (successive years) and the long term. The time-series of seagrass cover also varied with site, however, sites tended to show either a relatively stable mean cover or an increasing trend; there was no indication of a long-term decrease in seagrass cover in Port Phillip Bay. The data from Blairgowrie suggests that some of the shorter-term variation is related to the ENSO cycle, with greater cover in La Niña years that are characterised by low barometric pressure, increased rainfall and increased sea levels. Increased sea levels may be of major importance to the shallow water habitats studied because the *Heterozostera tasmanica* seagrass beds were near their upper depth limit. *H. tasmanica* can only survive limited periods of exposure and this sets the upper limit of distribution. An expansion in distribution might therefore occur in years of higher water level. Furthermore, increased rainfall might be expected to be conducive to seagrass growth, as rainfall would result in nutrients being released into the bay, and growth of the dominant seagrass species, *Heterozostera tasmanica*, is known to be nitrogen limited (Bulthuis et al. 1992).

Water level might also be a factor in the long-term increase in seagrass at Blairgowrie A change in sedimentary processes influencing the near-shore water depth could result in such a long-term change. Some of the positive effects of La Niña years on whiting catch may be mediated by improved conditions for habitat. Longer-term trends may also be important to whiting catch, for example, the Blairgowrie area has consistently had very high numbers of settling larvae in annual monitoring (Jenkins, unpublished data), and the long-term increase in seagrass in this area may partly explain the long-term increase in catch in Port Phillip Bay. One of the factors thought to have contributed to the start of the major seagrass decline in Western Port was the strong El Niño conditions that occurred in the early 1970's, exposing seagrass to very low tides and high temperatures over summer. These conditions in combination with smothering by sediment from the catchment may have initiated the seagrass mortality (Shepherd et al. 1989).

Benefits

This research has shown that a significant proportion of the variation in catch of King George whiting is due to fluctuations in the environment. Thus, management can use this information when assessing the effects of fishing. Fluctuations in catch can be attributed to the environment that might otherwise be attributed to fishing pressure. The information gained from this research can be used to make predictions of catch up to 5 years in advance, with improved predictions one year in advance. Variation in catch moving in a different direction from environmental predictions may indicate an effect of catch or habitat variation. If, in the future, the management of the King George whiting fishery becomes quota based, it may be possible to vary the allowed quota on the basis of prediction of fish available based on environmental parameters.

Information in this report also further supports the importance of habitat in underpinning the King George whiting fishery. The ENSO cycle affected both the habitat and the catch, and the effect on catch is likely to be mediated by habitat in some way (for example, increased food production). Moreover, long-term trends in catch seem to be related to habitat. The decline in seagrass cover and corresponding catch of King George whiting in Western Port beginning in the 1970's is well established. We found that in Port Phillip Bay there has been either a steady or increased cover of seagrass at all sites examined, and at a site known to be a major settlement area for King George whiting larvae there has been a major increase in seagrass cover since the 1950's. This increase in cover has corresponded to an increase in both catch and CPUE of King George whiting. Thus, the research reported here adds further weight to arguments for the preservation of shallow vegetated habitat in bays and inlets because it appears to be of major importance to the sustainability of the King George whiting fishery.

Further Development

The results of this report suggest that transport of larvae is not a significant factor in the variation in larval settlement and fishery recruitment because models of larval transport failed to predict catch. However, the factual basis of the assumptions upon which the models are based needs to be improved. For example, information on spawning areas and times that are input to the models could be greatly improved if a study of gonad development of King George whiting were undertaken along the Victorian coast (Hyndes et al. 1998, Fowler et al. 1999).

If indeed the transport hypothesis can be rejected then the most likely reason for variation in larval settlement is variation in planktonic productivity. A prediction from this hypothesis would be that larval growth rates would be higher in years of high larval settlement and catch five years later. We have collected newly-settled larvae of King George whiting in Port Phillip Bay for the past 9 years. Therefore, the larval growth rates of individuals collected in years of low and high settlement could be estimated using otolith daily increments, providing a test of the planktonic productivity hypothesis. Furthermore, such biological processes could be incorporated into transport models, giving a more realistic model that includes both physical and biological processes (Heath & Gallego 1998).

Although we can use environmental variables affecting the larval stage to estimate settlement and subsequent catch five years later, we may obtain more accurate predictions by directly measuring settlement each year. We have been monitoring settlement of King George whiting larvae in Port Phillip Bay for approximately 9 years and indications are that this is a strong indicator of lagged catch. However, the time-series is still too short to test the statistical adequacy of this technique, and monitoring into the future would be highly desirable.

A significant proportion of the unexplained variation in catch after accounting for environmental variables is likely to be due to variation in the relationship between catch and the actual population level. Until refined measures of effort that include a number of variables measuring type and frequency of gear deployment, efficiency of gear under different conditions, changes in fisherman's behaviour and fish catchability are available, a significant proportion of the variation in catch will remain unexplained. Research into the area of effort variables could be fruitful in this respect.

Conclusion

This research has shown that the environment has a large influence on the catch of King George whiting in bays and inlets in Victoria. Strong westerly winds during the larval stage result in increased catch approximately 5 years later, probably mediated by higher larval settlement. Moreover, La Niña conditions during the juvenile stage appears to have a positive effect on habitat or food production, leading to larger catches. Years that could potentially yield large catches can be negatively affected by strong westerly wind conditions. The work emphasises the possible influence of climate change on King George whiting catches, long-term changes in wind fields or the ENSO cycle would be expected to affect catches. The work also emphasises the importance of juvenile habitat in underpinning this fishery. Anthropogenic affects that result in habitat loss, such as the seagrass loss in Western Port, has the potential to have major negative effects on the fishery. It will be possible to make predictions of King George whiting catch. A prediction of catch can be made 5 years ahead based on zonal westerlies. This prediction can subsequently be refined a year ahead by including the effect of the ENSO cycle.

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Appendix 1: Intellectual Property

No patentable inventions or processes have been developed as part of this project. All results will be published in relevant scientific articles and other public domain literature.

Appendix 2: Staff

Dr Greg Jenkins	Principal Investigator (MAFRI)
Mr David Hatton	Project Scientist (MAFRI)
Mr Sean Moran	Project Scientist (MAFRI)
Dr Kerry Black	Co-investigator (University of Waikato)