CHAPTER ONE

Use of Feeding Habitat by Migratory Shorebirds in Southern East Coast Estuaries

Summary: A sample of 63 intertidal flats in 9 New South Wales estuaries was censused for feeding migratory shorebirds and measured for 19 habitat variables to determine habitat features which related to shorebird abundance. The purpose was to develop guidelines for protection, provision and assessment of shorebird feeding habitat in southern east coast estuaries (Chapters 2 and 3).

Six species were abundant enough to characterise habitat selection: Bar-tailed Godwits selected large, low-lying feeding flats; Whimbrel favoured mangrove-lined flats in high-sediment regimes; Eastern Curlew and Pacific Golden Plover favoured large complexes of flats. Greenshank frequented feeding areas of any size, provided they were wet, nutrient-rich and mangrove fringed; Tattler were more likely to feed adjacent to mangroves and on flats with some ground cover. The number of species was greatest on extensive, low-lying, mangrove-fringed flats in sediment-rich and/or nutrient-rich environments. Less common species were most likely to feed where the common species were most abundant.

Important habitat features to maintain as correlates of shorebird abundance are extensive complexes of intertidal flats (avoiding fragmentation of habitat), maintenance of both the depositional regime (avoiding change to elevation profile and texture) and the nutrient regime (including peripheral vegetation sources), and preservation of fringing mangrove. Few conflicts of interest among species exist with the protection of these. Once identified, the habitat features, or more correctly, the attributes of habitat, can be quantified for management guidelines (Chapter 2).

Lawler, W. (1996) Guidelines for management of migratory shorebird habitat in southern east coast estuaries. Unpubl. M.Res.Sc. thesis, University of New England, Armidale.

Chapter 1

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Introduction

Coastal development in Eastern Australia is mainly concentrated around estuaries and associated sheltered foreshores (Yapp 1986; Jones 1991), with the nation's greatest growth in the two regions between the Illawarra and Hunter coasts, and the Northern Rivers and Sunshine coasts (ARAC 1992). This concentration creates diverse environmental stresses (Kenchington 1991). Also concentrated in these estuaries and sheltered shores are the populations of most migratory shorebirds, which use the intertidal flats as feeding habitat (Smith 1991; Watkins 1993). Development and human population pressure can adversely affect shorebird habitat (eg., in the region, Elkington 1977; McGill 1972; McGuiness 1988; Williams 1990; Woodall & Watson 1988; and Kinhill 1991; elsewhere Meire 1991; Sutherland & Goss-Custard 1991) and likewise shorebird conservation requirements affect development (Public Works 1991a; Adam 1993; Driscoll 1993a; Wheeler 1994; Straw 1995a,c,d). It is therefore essential to know just what needs to be conserved or provided in estuaries to conserve shorebird populations.

This research offers some initial answers. The research strategy followed from the question: What needs to be conserved? to: What do shorebirds select from the range of habitat available? It identified attributes which could be used to characterise the habitats selected by shorebirds, and it measured their ranges to provide quantified guidelines for the protection and provision of shorebird habitat.

This chapter reports the attributes of intertidal estuarine habitat which could be related to the occurrence of feeding shorebirds. It does this for the six species of shorebird that were most numerous on the study sites, and then examines the co-occurrence of uncommon species with these common species. It also shows the relationships among the habitat attributes.

Plate 2 *Migratory shorebirds (Bar-tailed Godwit) feeding on an intertidal flat in Deception Bay, S.E. Queensland.*

The next chapters (Chapters 2 & 3) report guidelines for habitat protection, provision, and assessment, developed from these results. Because the research was undertaken for this purpose, the results in this chapter are oriented towards their use in Chapters 2 and 3.

Methods

General Method

To identify trends in habitat use and develop the guidelines, shorebirds were counted on a random sample of intertidal flats in nine estuaries along the whole coast of New South Wales (Nicholls 1989). Multiple counts were made (Nicholls 1989), three times in three seasons, all on the bottom of the diurnal low tide (Public Works 1991b). A suite of physical, biological and chemical attributes were measured on the same flats, and trends were investigated in numbers of shorebirds with each of these ("analytical sampling" (Eberhardt & Thomas 1991).

Attributes which showed statistically significant trends with bird numbers were considered important to the birds. The conclusions were tested by measuring attributes and counting shorebirds on a second sample of flats on 13 different estuaries (Chapter 2: Methods).

All shorebird species were counted, but only the six most common species were abundant enough to use for developing the guidelines. These were Bar-tailed Godwit, Eastern Curlew, Whimbrel, Greenshank, Tattler (not identified to species level but probably Grey-tailed in estuaries (Chafer 1995)) and Golden Plover, assumed to be Pacific (Marchant & Higgins 1994; Higgins & Davies 1996). See Appendix I for binomials. The co-occurrence of other species was investigated to determine which common species, if any, might be used to indicate suitable habitat of the less common ones.

Once the important attributes of habitat were identified, the measured values of these were used to develop two types of habitat suitability models (Chapters 2 & 3). Other guidelines were also developed, reported in Chapter 2.

Limitations

There are limitations to this method, considered in greater depth in the Discussion. Briefly, important ones to bear in mind are:

1) It can only identify attributes of habitat which correlate with bird numbers, rather than those which cause the areas to be suitable for shorebirds. There are also assumptions in the concepts of 'habitat requirements', 'habitat selection', and 'habitat quality'.

2) Although the guidelines use the attributes of habitat showing the strongest relationship with bird numbers among related ones, the importance of every individual one is not established independently of every other. In management, it is safer to assume that an attribute which shows a strong trend with bird numbers is important.

3) Only continuous trends within fairly natural systems were used. Values outside the natural range which occurred on the study flats were not assessed. However, no study site could be called pristine, so guidelines are tuned to present conditions, to conserve the present biota*.

4) Populations of migratory species may change due to many external factors. When bird numbers are used as a measure of habitat suitability, these external factors may affect conclusions.

Experimental Design

The sampling units were intertidal flats; the "population" was all intertidal flats greater than 1 hectare in all New South Wales estuaries which contain more than 10 such flats. Thus very small creek mouths and narrow shorelines were not included. Estuaries and flats were identified from air photographs (Land Information Centre (L.I.C.; Good 1978) and the estuaries were stratified into three size classes based on the number of intertidal flats contained. Flats were chosen by this stratified random sample (without replacement) (Hald 1952; Green 1979) to avoid bias towards large estuaries containing many flats.

Sixty three intertidal flats were sampled, seven from each of nine estuaries (three estuaries from each of the three estuary size classes). Sample size was determined using desired error, estimated variance, time needed per sample and total time available (Southwood 1978; Krebs 1989). The adequacy of the sample size was tested after the first field season using known means and variances (Dale *et al.* 1991).

Study Sites

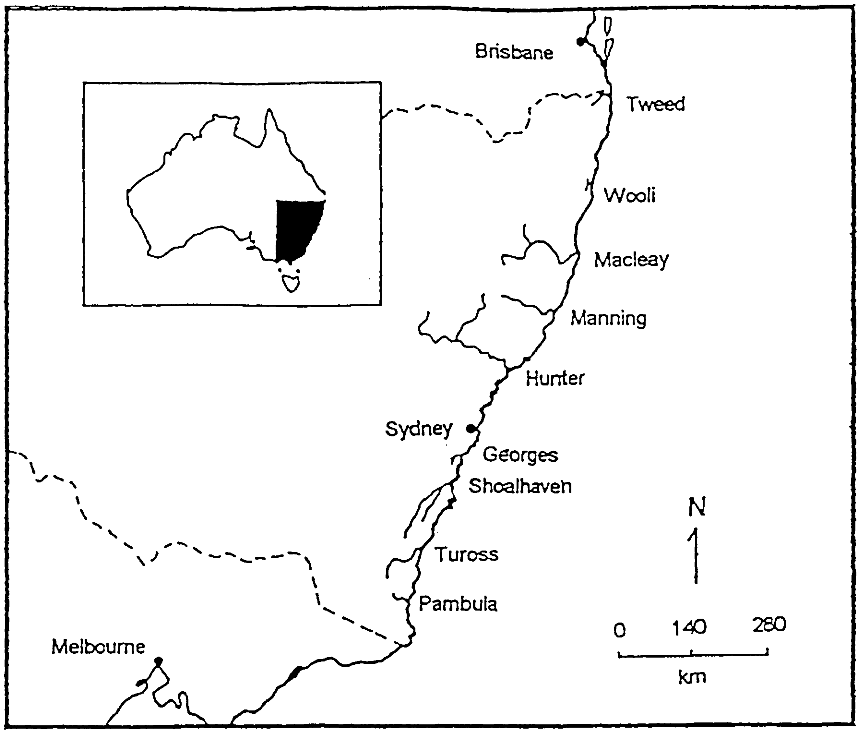
The sampled intertidal flats ranged from dynamic, wave-built sandbars at the mouths of estuaries to alluvial mudflats upstream or in broadwaters. The upstream limit of the study varied from estuary to estuary based primarily on the occurrence of intertidal habitat but also on access. Boundaries of sites were defined by the edge of non-marine vegetation or 100% mangrove canopy (vertical projection), water depth of 150 mm at low tide (at time of census), or a large, distinct change of elevation and substrate texture class where a sandbar abutted a flat (see Habitat Variables).

* Middleton (1985), summarising Bell & Edwards (1980), states that of 137 estuaries and coastal lagoons in New South Wales, only 11 had untouched foreshores and only 4 small waterbodies (each less than 1.5km^2 in area) had low disturbance ratings for both their waters and catchments.

The sample of flats used in this data set were from the estuaries of the Tweed, Wooli, Macleay, Manning (including Old Bar), Hunter, Georges (including Woolooware and Quibray Bays), Shoalhaven/Crookhaven, Tuross and Pambula (including Yowaka) Rivers (Fig. 1.1).

Fig. 1.1

Locations of the sampled estuaries.



Shorebird Counts

All sites were approached from seaward using a small boat (Howes 1989), and birds were counted only on the bottom of low tide (Thomas 1988). Counting was abandoned if there was any sign of prior disturbance, or if neap low tides failed to expose approximately the mean low tide area of the flat (Burger *et al.* 1977). Shorebirds were not flushed during counting*. Counts were made using a tripod mounted 25X telescope. Sites which could not be scanned from one point (vegetated, convoluted or bumpy sites) were traversed on foot, still using the telescope or occasionally using 8X40 binoculars if shorebird density was low and distances short. Thus all counts were total counts (Jaensch 1983; Verner 1985; Baker & Wolff 1987).

* If accidental flushing occurred, the flight and landing of the bird was observed. Normally birds landed on a distant part of the same flat, but if the bird(s) departed in the direction of a site yet to be counted, that site's census was postponed to eliminate observer effect. If shorebirds departed of their own will during the census, they were still included; if birds arrived during the census they were also counted (Prater 1979).

All counts were made between late January and early March as migratory shorebird populations are thought to be most stable in coastal New South Wales in this period (Lane 1987). First counts on the Tweed, Wooli, Georges, Shoalhaven and Pambula estuaries were made in 1992; birds on the remainder were first counted in 1993. All second and third counts were made in 1994. Total counts of the estuaries were also made in each year to check for any large changes in shorebird population size from year to year.

Maximums of the three counts were used in the analysis* (Colwell & Cooper 1993; Gaines & Denny 1993). The maximum number of birds counted on a site was considered to most accurately reflect the potential value of that site to migratory birds (Smith 1987) in a system in which the population is distributed patchily in space and time (Alcorn *et al.* 1994). Population size may be determined elsewhere, causing birds to be distributed patchily in a partially filled habitat (Goss-Custard & Durell 1990; Baillie & Peach 1992; H. Recher pers. comm.).

Habitat Variables

Nineteen attributes of the intertidal flats were measured for potential use in the models. They were chosen as indicators of ecological processes affecting feeding behaviour and food availability for shorebirds, suitable for rapid assessment techniques available to managers. .

The habitat variables measured and a summary of their purpose is given below. Measurement techniques are detailed in Appendix II.

Variable	Reason	Reference(s)	Technique
Size, Shape and Position Variables			
• Area of Flat (ha):	amount of contiguous habitat may affect habitat suitability	(Temple & Wolcox 1986; Storey *et al.* 1993; Dann 1994)	air photographs.
• Area of Surrounding Flats within 1 km:	habitat availability in vicinity may affect habitat suitability	(Laudenslayer 1986)	air photographs
• Total Area of Intertidal Flat within 1 km:	habitat availability		sum of previous two.
• Perimeter Length:	amount of shoreline (water's edge) may affect habitat suitability	(Recher 1966)	air photographs.
• % Open water surrounding flat:	degree of enclosure, position in relation to tide flow may affect or reflect habitat suitability	(Congdon & McComb 1980; Roy 1984; Carne 1989)	air photographs

* Density (numbers per unit area) and relative abundance were not used, because of the conservation management bias of the modelling. The conservation value of a site is not assessed on a per unit area basis, or according to the proportion of species, but on its total worth. Area was considered to be an important habitat variable in its own right. Derived variables can have unpredictable distributions (Atchley *et al.* 1976; Sokal & Rohlf 1981) and may be biased towards small sites.

Variable	Reason	Reference(s)	Technique
Vegetation Variables			
• % Surrounding Mangrove	may affect or indicate habitat suitability through nutrient and organic input	(Clarke 1983; Davie 1984; Briggs 1977; Adam 1994), food (Hutchings & Recher 1982) innate response (Thompson 1991)	air photographs and visual estimation
• % Mangrove Cover on flat	feeding conditions, security	(Metcalfe 1984), prey habitat (Hutchings & Recher 1982)	visual estimation of foliage projection cover (MDBC 1993)
• % Seagrass Cover	feeding conditions	(Moriarty & Boon 1989; Thompson 1991)	visual estimation
	prey habitat	(Larkum & West 1982; Whitten *et al.* 1988a; Poiner *et al.* 1992)	
For Tattler (after preliminary analysis):	More detailed suite of eight	Determined by analysis	Visual estimates of
• Mangrove Area,	additional ground cover		area and proportion
• Seagrass Area,	measures to explore habitat		
• Area(ha) & % Pneumatophores (mangrove aerial roots)	attributes of flats used by Tattler of flats affected		
• Area & % Oyster encrusted ground, rocks and oyster-farming structures,	by cover types		
• Area & % Total Gound Cover			
• % Adjoining Mangroves	as mangrove variables above, another aspect of cover		visual estimate and air photo measurement
Substrate Properties			
• Northcote Texture Class	feeding conditions	(Quammen 1982)	manipulation of bolus according to Northcote (1979) (Appendix II Table 1).
	prey habitat	(Anderson *et al.* 1981; Burger 1984; Leadbitter 1987)	
	organic level	(Northcote 1979)	
• Mean Surface Hardness (kg/cm^2)	feeding conditions, prey habitat .	(Gerritsen & van Heezik 1985)	penetrometer
• Microrelief Variance (mm)	feeding conditions, prey habitat, security	(Grant 1984; Metcalfe 1984)	measurement against straightedge

Variable	Reason	Reference(s)	Technique
Elevation Profile (Modified from Recher (1966))			
• % Area Dry at Low Tide	feeding conditions, prey habitat	(Helmers 1993; Withers & Chapman 1993)	visual estimation.
• % Area Wet at Low Tide	as above		
• % Area < 50mm Deep at Low Tide			
• % Area 50mm to 150mm Deep at Low Tide			
Water Properties			
• Mean Conductivity (mS/cm)	prey habitat tidal regime	Crawford 1975; Halse *et al.* 1993 (Anderson & Storey 1981; Pollard 1994)	mean of high and low tide electrical conductivity measurements of salinity of associated water (Norris & Georges 1986; MDBC 1993
• Secchi Transparency (m)	sedimentation regime, nutrient input, prey habitat	(Baas-Becking 1959), (Fichez *et al.* 1992)	Secchi disc readings of adjacent waters (Wetzel, 1975).
• Suspended Solids (g/L)	sedimentation regime	(Hart 1974; Anderson & Storey 1981)	photometer readings of prepared water sample (Hach undated).
• Orthophosphate (mg/L)	nutrient level, prey habitat	(Allen & Kramer 1972; Congdon & McComb 1980; Storey *et al.* 1993)	spectrophotometer reading of prepared water sample (Hach undated; Allen *et al.* 1974; Cosser 1989).

Estuary Descriptors

Three variables measuring estuary attributes were included in the analysis to aid understanding of shorebird distribution, but were not used in the coast-wide models in Chapter 2:

Variable	Reason	Reference(s)	Technique
• Latitude (degrees, minutes (decimalised))	geographic distribution of non-breeding shorebirds and habitat attributes:		geographic co-ordinates, topographic maps (L.I.C.).
• Total Intertidal Area (Ha)	Amount of potential feeding area, estuary size:		air photos.
• % Basic Volcanics in Catchment	general nutrient potential of catchment and therefore estuary:	(Packham 1969; Anon 1975)	surface geology maps (L.I.C.).

Wind speed and wave height were also measured for maximums and used in guidelines were appropriate, but were not included in the modelling analysis.

Analysis

Distribution and probability plots were made of all data sets using Minitab (Minitab Inc. 1991) to assess normality. Normal distributions were determined by correlations between data and normal probability values according to Minitab Inc (1991). Count data were logten transformed and ratio data were arcsine transformed to obtain normal distributions (Blem 1984), and then rechecked. Some measured variables were also log transformed when tests for normality indicated the need. This was to satisfy the assumption of regression that the *y*-variable, and of correlation that both variables, be normally distributed (Bailey 1979; Sokal & Rohlf 1981; Fowler & Cohen undated).

Bivariate plots were drawn and single linear or quadratic least squares regression* was used to determine which physical variables significantly related to shorebird numbers, for each of the six common species and for species number. Treating the variables singly is an artificial approach adopted for the intended use in subsequent models (see Methods in Chapters 2 & 3). Although interactions between habitat variables are of ecological importance, managers need a suite of stand alone attributes which can each be quantified and prescribed for individual management (Hurley 1986). Simple linear regression was also more conservative and meaningful than pattern analysis, providing significance levels over the whole data set (Bolter & Meyer 1986; Johnson 1981). (See Chapter 3 Methods for a discussion of other methods tried and rejected.)

Significance Level

The significance level of $P = 0.05$ was used in the interpretation after tests using regression on the random data set produced a <6% incidence of significant relation between variables. This indicated that $P = 0.05$ was adequate at the expected probability of Type I error. However, because relating bird number to each variable constituted a family of hypotheses (Beal & Khamis 1991) an adjusted confidence level calculated by a modified Bonferroni Method (Beal & Khamis 1991) was used in the modelling to improve confidence in the use of the guidelines.

The significance level was determined by dividing the nominated P value of 0.05 by the number of habitat variables (= hypotheses) which were significant at the $P <= 0.05$ level. For example, there were 5 habitat variables significantly related to Bar-tailed Godwit number at the 0.05 level, so the adjusted significance level was 0.05/5 = 0.01. Both significance levels are reported, so that the likelihood of both Type I and Type II error can be gauged (Type I error = risk of concluding there is a relationship when there isn't one; Type II error = in effect, risk of assuming there is not a relationship when there is). Only variables significant at the

* Tests with random data of similar sample size, number of variables, distributions, means and standard deviations, generated on Minitab, indicated that parametric regression was a more reliable and conservative measure of this central tendancy than non-parametric Spearman ranked correlation coefficients. Use of polynomials (Meents et al. 1983) made little difference to the results so results reported are all linear.

adjusted significance levels were used for interpretation, and as main guide values and predictors in the models (Chapters 2 & 3).

Estuary Effect

Regression lines of each variable were plotted for each estuary, and generalised linear models incorporating estuary were calculated to explore estuary differences and determine if ANCOVA or a generalised linear model might be appropriate. One-way ANOVA was also used to check between-estuary significances for each variable. This analysis determined that estuary differences in the variables were not consistent and that, overall, the data set could be used to characterise habitat without reference to estuaries (see note on outliers below).

Relationships between Variables

All transformed habitat variables were plotted against each other singly to determine cross-correlation (Legendre 1993), and a Pearson product-moment correlation matrix was produced to report interrelationships (Table 1.2). Significance of correlations between pairs of habitat variables was accepted at $P <= 0.05$ (two-tailed) for the interpretation and modelling, because Type II error (unwittingly using correlated habitat attributes - see ***Significance Level***, above) was considered the most important consideration (Fairweather 1991; Forbes 1990; Jackson & Somers 1991).

Outliers

Outlying data points identified by regression diagnostics (Minitab Inc. 1991; Nicholls 1989) were only removed from the regressions for three sites within Fullerton Cove, Hunter River (described in Hutchings 1983), for the three more abundant species, and one site in Quibray Bay, Botany Bay (Georges River estuary), for Tattler.

Fullerton Cove is recognised as a Wetland of International Importance (Ramsar wetland) (Hines 1994; Jones 1993) because of the very large numbers of migratory shorebirds which use it each summer (van Gessell 1976; Smith 1991; Usback & James 1993). Shorebird numbers on the three sites in Fullerton Cove were often an order of magnitude higher than other sites in the study and produced exaggerated levels of significance in some regressions with numbers of the abundant species. Similarly, they were by far the largest sites and produced exaggerated correlations with area.

To avoid an interpretation of the data biased towards these three sites, and to give a truer impression of the underlying significance levels and therefore the underlying determinants of shorebird habitat quality (Gutzwiller & Anderson 1986; Moyer & Geissler 1991), the data for the three abundant species and for habitat interrelationships have been analysed with and without the Fullerton Cove sites. The data were interpreted and variables were selected for the models by the significance levels without the Fullerton Cove sites, but the relationships shown also applied to these sites (see *Results*), so overall conclusions were not affected (Nicholls 1989). The same is true for the Quibray Bay site, which was treated the same way in the Tattler analysis because exaggerated significance levels were generated by the relatively high number of Tattler and high vegetation cover of this site.

Species Associations

Species associations were determined for as many less common species as possible. To do this, the data in this chapter was combined with the model testing data used in Chapters 2 and 3 to maximise sample size (n = 106). Counts of all species which occurred on more than 4 flats, and species number, were used. Because count distributions of the less common species could not be normalised, a Spearman ranked correlation matrix was produced (Minitab Inc. 1991) for comparison of coefficients. This test is 90% as powerful as the parametric test for the 3 abundant species and species number (Zar 1984).

Significant associations were accepted at $P<=0.0005$ (one-tailed positive associations: species A increasing in number with increasing numbers of species B) as an approximation of Bonferroni adjustment (11 x 12 = 132 simultaneous hypotheses - see *Significant Level*, above). Strong correlations were used because Type I error was the most important consideration when using the associations to infer habitat needs of the less abundant species. Significance was determined from critical values of the correlation coefficient (r) because the sample size was greater than 100 (Zar 1984).

Results

The Estuarine Environment

This section describes the intertidal environment for feeding shorebirds by examining firstly the ranges of the habitat attributes measured in the study; and then the relationships between the attributes.

Ranges of the habitat attributes.

The actual measurements are given in Table 1.1. The areas of the sampled intertidal flats ranged from the minimum study site size (1 hectare) to very large expanses, but most were

Table 1.1

Characteristics of the habitat variables used in the study.

Variable Name	Min. Value	Max. Value	Mean Value	Stand. Deviat.	Unit of Measure	Data Type
Area of Site	1.1	99.1	13.1	18.1	hectare	ratio
Surround. Habitat	5.0	138.8	34.1	24.1	"	"
Total Area	8.5	196.5	47.2	38.7	"	"
Perim. Length	494	8552	2377	1374	metre	"
Open Water adjoin. flat	0	92	43.9	23.4	percent	proportion
Surround. Mangrove	0.25	99.5	60.2	29.5	"	"
Mangrove Cover	0	20.0	2.8	8.8	"	"
Seagrass Cover	0	88.6	13.2	21.6	"	"
Texture Class	1	12	4 (mode)	-	numbered class	ordinal
Mean Hardness	-.566	10.4	1.5	1.8	kg/cm^2	ratio
Microrel-ief Var.	11	1210	204	242	$(mm)^2$	ratio
%Dry	0	97.4	41.9	29.0	percent	proportion
%Wet	1.0	81.0	28.7	21.6	"	"
%<50mm	1.0	80.2	22.0	18.2	"	"
%50-150mm	0	75.0	8.8	13.6	"	"
Mean Cond-uctivity	12.8	52.0	38.8	7.2	mS/cm^2	ratio
Secchi Transp.	0.35	3.5 (arbitrary limit)	1.9	0.8	metres	interval
Supended Solids	0	711	68.2	142	g/L	ratio
Ortho-phosphate	0	1.5	0.2	0.3	mg/L	ratio
Latitude	28-11	36-58	-	-	degrees & mins	interval
Total Inter-tidal Area	112	703	402.4	201.1	hectares	ratio
Basic Volc in Catchment	0	18	5.2	7.1	percent	proportion

cont./...

Table 1.1 (cont.)

Variable Name	Min. Value	Max. Value	Mean Value	Stand. Deviat.	Unit of Measure	Data Type
For Tattler:						
%Adj.Mangr	0	77	30.9	20.7	%	proportion
% Tot. Ground Cover	0	100	26.1	30.4	%	"
% Oyster Structures	0	30	2.7	6.5	%	"
Area Pneum-ophores	0	6.7	0.34	0.9	hectares	ratio
Area Oyster	0	2.7	0.2	0.6	"	"

moderately large - up to about 30 hectares. The total amount of intertidal flat, including the area of surrounding habitat within 1 km, ranged to nearly 200 ha, with most below 90 ha. Their shapes ranged from simple to convoluted, to complexes of fragmented flats, and from banks in mid-channel to almost completely landlocked inlets.

The proportion of fringing mangrove ranged from less than 1 percent to completely surrounding the flat, and most flats had less than 5% mangrove cover. Average seagrass cover was only 13%. The substrate textures ranged from "sand" to "silty clay loam". This ranged from pure beach sand to slimy mud (for particle sizes see Appendix II). The most common class was "light sandy clay loam" which is a light grey, very sandy mud.

Hardness ranged from firm ground (hardness index (kg/cm^2) of 10.4) to -0.5 on the combined scale which, in terms of human mobility, means sinking to one's hips. The most common hardness (1.5 kg/cm^2) was about ankle deep. Microrelief (surface roughness) ranged from flat to having "gilgai"-like hollows and mounds 2-300mm high, although most had irregularities of less than 50mm. An "average intertidal flat" elevation profile is 40% dry. 30% wet, 20% shallow and 10% deeper, but each wetness class ranged very widely.

Conductivity of adjacent water was variable as expected in estuaries and ranged over all measurements from brackish (about 3g/L salinity) to very slightly hypersaline (36 g/L). Salinity changed from low tide to high tide on any one flat. Secchi transparency, as a measure of water turbidity and sediment load, ranged from almost opaque to very clear water. Most readings were between 1.1 and 2.7m of visibility. Orthophosphate levels were very low - most ranging from zero to about 0.3 mg/L. These readings were a comparative index within the study, not accurately comparable to measurements taken by other methods (see Appendix II).

Relationships between habitat attributes

The attributes of habitat measured were different aspects of a whole environment. Many habitat variables correlated statistically with others, both between and within the groups (Table 1.2, Fig. 1.2). The 'strength' of correlations (significance levels) varied, and should be noted when refering to Table 1.2. The following general description of interrelationships is footnoted with significance levels where necessary.

Within Groups

All size variables were interrelated except perimeter length and surrounding area, because surrounding area does not involve the site's size. Open flats tended to be larger and in more extensive intertidal areas than enclosed flats. Vegetation variables were independent of each other except for % surrounding mangrove and % mangrove cover[1]. Sites with high silt or clay content tended to be soft, while sandy sites tended to be hard[1]. Most elevation measures cross-correlated, being complementary components of a whole. Secchi transparency (turbidity) correlated with orthophosphate[3], indicating that the higher the sediment load, the higher the available phosphate levels in the water.

Between Groups

Size and Position

Area of flat and perimeter length were independent of all attributes of habitat outside the size and position group. Larger areas of intertidal flat tended to be in higher salinity regimes[2] (more directly linked to the sea). Conversely, smaller areas tended to be in places with lower salinity regimes, such as upstream or in tidal restrictions. Open flats tended to be harder[1] and courser textured[2], with clearer water[2], and higher in relation to water level[4]; enclosed flats were softer and finer.

Vegetation

The proportion of surrounding mangrove fringe was linked with elevation profile, turbidity, orthophosphate level and substrate texture and hardness. Greater amounts of fringing mangroves tended to occur with higher levels of water orthophosphate[3] (indication

[1] $P <= 0.05$; [2] 0.01; [3] 0.001; [4] 0.0005 (see Table 1.2)

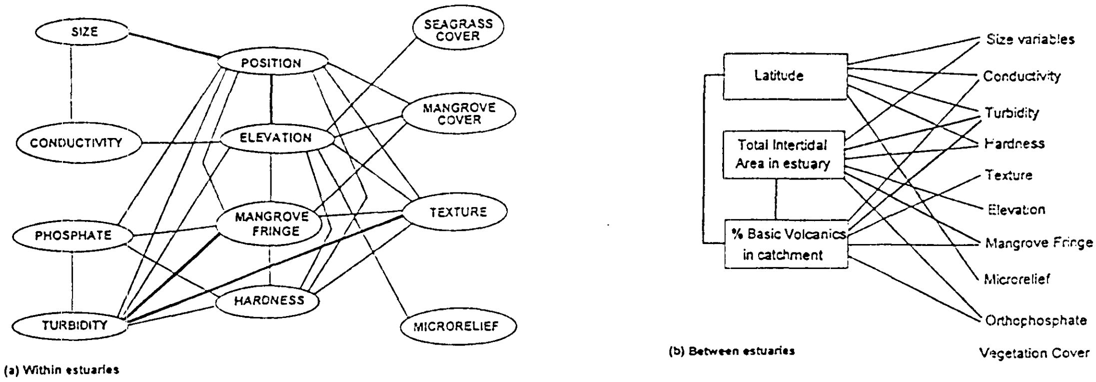
Table 1.2

Correlations between the habitat variables. Significance levels of Pearson correlation coefficients are indicated by *P<=0.05; **<=0.01; ***<=0.001; ****<=0.0005. ns = not significant at P = 0.05. Bonferroni adjusted significance level is 0.0001 (see *Methods: Significance Levels*). Bracketted symbols are with the influential Fullerton Cove sites included, and are shown only if the significance status changes. Modelling was based on correlations without these sites (see *Methods: Outliers*).

	Area Surround.	Total Area	Perim. Length	%Open Water	Mangr. Fringe	Mangr. Cover	Seagr Cover	Text. Grade	Mean Hardn.	Micro Relief	%Dry	%Wet	%<50mm	%50-150mm	Mean Conduct.	Secchi Transp.	Susp. Solids	Ortho phosph.	Latit-ude	Tot.Int-tid. Area	%Basic Volcanics	
Site Area	+ ** (+ ***)	+****	+***	+* (ns)	ns	ns	ns	ns	ns (- *)	ns	ns (- *)	ns	ns	ns	+ * (ns)	ns	ns (+**)	ns (+**)	+ * (ns)	ns (+**)	ns	Site Area
Area Surrounding		+****	ns (+*)	+**** (ns)	ns (+***)	ns	ns	ns	ns (- *)	ns	ns (-**)	ns	ns	ns	+ ** (+*)	ns (-**)	ns (+***)	+ * (+***)	ns	+ ** (+***)	ns (+*)	Area Surround.
Total Area			+ * (+***)	+**** (+**)	ns (+**)	ns	ns	ns	ns (-*)	ns	ns	ns	ns	ns	+ **	ns (-*)	ns (+***)	ns (+***)	ns	+ * (+***)	ns (ns)	Total Area <1km
Perimeter Length				ns	ns (+*)	ns	ns	ns (+*)	ns	ns	ns (-**)	ns	ns (+*)	ns	ns	ns (- **)	ns (+*)	ns (+*)	ns	+ * (+**)	+ ** (+***)	Perim. Length
% Open water surrounding flat					- **	- **	ns	- **	+ *	ns	+****	- *	- ** (-***)	ns	ns	+ ** (+ **)	ns	ns	ns	ns	ns	% Open Water
Mangrove Fringe						+ * (ns)	ns	+ **	- **	ns	- * (-**)	ns (+ *)	ns (+*)	+ * (ns)	ns	-****	+ ** (+***)	+***	ns	+****	+ * (+***)	Mangrove Fringe
Mangrove Cover							ns (+*)	ns	ns	ns	ns	+ * (ns)	ns	ns	ns	ns	ns	ns	ns	ns	ns	Mangrove Cover
Seagrass Cover								ns	ns	ns (+*)	- ** (-*)	ns	+****	+**	ns	ns	ns	ns	ns	ns	ns	Seagrass Cover
Texture Grade									- * (-**)	ns	- * (-***)	ns	(ns)	+** (+*)	ns	-****	+ * (+***)	ns (+***)	ns	ns (+*)	+ * (+**)	Texture Grade
Mean Hardness										ns	+***	- **	- *	ns	ns	+ * (+**)	- *	- * (+**)	-**	- * (-**)	ns	Mean Hardness
Micro Relief											+ * (+**)	ns (-*)	ns	ns	ns	ns	ns (-**)	ns (-*)	- *	ns (-*)	ns	Micro Relief
%Dry												-****	-****	- * (ns)	ns	+ * (+***)	ns (-**)	ns (-***)	ns	- ** (-***)	ns	%Dry
													ns	ns	- ** (-*)	ns (-**)	ns (+*)	ns (+**)	ns	ns (+*)	ns	%Wet
														ns	ns	ns (-**)	ns	ns	ns	+ * (+**)	ns	%<50mm
															ns	ns	ns	ns	ns	+ * (ns)	ns	%50-150mm
																ns	ns	ns	+ *	ns	- ** (- *)	Mean Conduct.
																	-***	-***	+** (+*)	-****	-****	Secchi Transp.
																		+***	ns	+ * (+***)	+ ** (+***)	Susp. Solids
																			ns	+***	+***	Orthophosphate
																				ns	-****	Latitude
																					+****	Total Intertidal Area

Fig. 1.2

Web of interrelationships between the measured estuarine habitat attributes or groups. Connecting lines indicate a statistically significant trend of one attribute with another. Bold lines indicate strong links (based on significance levels adjusted for number of simultaneous comparisons - see *Methods*). Some attribute groups had more than one aspect (variable) measured, not all of which were related to other attributes outside the group.



of nutrient levels) and suspended solids[2], lower Secchi transparency[4], and softer and finer-textured substrates (higher silt and clay content)[2].

More mangroves tended to fringe low intertidal flats which had shallow water remaining at low tide, or smaller relative amounts of ground left high and dry at low tide[1]. Mangrove cover *on* the flats had a similar relationship with flat elevation[1]. Seagrass cover only related to the relative proportions of shallow water[4]. *Zostera capricorni* grows in the intertidal zone to about 0.5m below spring low tide (West 1983) so sites without a gradual slope to deeper water tended to have less seagrass cover. There was no correlation of seagrass cover with mangrove cover on the sites.

Substrate

Flats with finer, softer substrates tended to form flatter, lower profiles than those with courser, firmer substrates[1-2]. Silt and clay content of the substrate were linked with turbidity of the associated water through texture[4] and hardness[1], and uneven surfaces created more dry ground[1], determined by the "lumpiness" measure (microrelief variance) and % dry ground.

Elevation

The elevation profile measures correlated with more habitat variables than did any other group. Proportion of open water bordering the flat, mangrove fringe, seagrass cover and

[1] $P <= 0.05$; [2] 0.01; [3] 0.001; [4] 0.0005 (see Table 1.2)

substrate texture and hardness all significantly correlated with one or more elevation measure, as detailed above. Low levels of fine sediment in the water (clear water) occurred near high and dry flats, and greater fine sediment content (turbid water) occurred adjacent to low flats which remained soggy or shallowly covered at low tide[1].

Flats where the tidal flush was closely associated with the sea and therefore of high salinity were generally not sites with a lot of low soggy ground[2]. The trend was for high sites to be in open positions in the main channels and near the mouths of estuaries, and low sites to be upstream and enclosed. This is linked to substrate properties as mentioned above.

Water Properties

These relationships are mentioned under the groupings above.

Estuary-wide Attributes

Water tended to be more turbid[2] and less saline[1] in the north. There was also a tendancy for flats to be firmer[2] and more unevenly surfaced in the north[1]. Larger complexes of intertidal flat tended to be in larger estuaries[1], and although study flat size was not related to estuary size, flats with greater shoreline lengths tended to be in the larger estuaries[1]. Low[1-2], soft[1], mangrove lined[4], sediment[2]- and nutrient-rich[3] flats tended to occur more in larger estuaries.

Proportion of basic volcanic geology in the estuary catchment correlated positively with all variables related to nutrient level: orthophosphate[3], surrounding mangrove[1], turbidity[4] and texture class[1].

Shorebird Use of the Estuarine Environment

Bar-tailed Godwit

Bar-tailed Godwits were the most abundant migratory shorebirds on the study flats (Table 1.3). Three large flats in Fullerton Cove held by far the most, but overall only 5 flats had more than 80. Seventy percent of sites had fewer than 13 godwit and 18 study flats had none.

The habitat variables which significantly related to numbers of Bar-tailed Godwit on the intertidal study flats were:

[1] $P <= 0.05$; [2] 0.01; [3] 0:001; [4] 0.0005 (see Table 1.2)

Table 1.3

Occurrence of the modelled shorebird species, and species number, on the 63 sampled intertidal flats. For less common species not modelled, see Table 1.4.

Species	Total (of max.no. on each flat)	min	max	Mean	Median	StDev	Flats present (n = 63)
Bar-tailed Godwit	1 770	0	450	28.1	8	67.4	45
Whimbrel	379	0	93	6.1	2	15.2	46
Eastern Curlew	599	0	15[illegible]	9.5	3	21.2	57
Greenshank	54	0	14	0.9	0	2.3	17
Tattler	138	0	35	2.2	0	5.5	21
P.Golden Plover	126	0	67	2.0	0	8.9	10
Species No.	15	0	10	3.5	4	2.0	60

Table 1.4

Occurrence of the rarer migratory shorebird species which were not modelled, on the random sample of 63 intertidal flats. These species were not abundant enough for modelling of habitat suitability for each species, but they were included in the species number model. For occurrence of the modelled species, see Table 1.3.

Species	No. of flats	Total No.	Max. No. per flat	Min. No. per flat (where present)	Estuary
Lesser Sand Plover	9	69	28	1	Tweed, Wooli, Manning, Hunter, Shoalhaven, Pambula
Ruddy Turnstone	1	2	2	2	Tweed
Marsh Sandpiper	1	17	17	17	Hunter
Terek Sandpiper	2	20	18	2	Hunter
Black-tailed Godwit	2	138	103	35	Hunter
Sharp-tailed Sandpiper	2	21	20	1	Hunter, Shoalhaven
Red-necked Stint	7	39	20	1	Manning, Hunter, Georges, Shoalhaven, Tuross, Pambula
Curlew Sandpiper	5	269	101	1	Hunter

Table 1.5

Significant ($P<=0.05$) results of linear regression analysis between maximum numbers of feeding Bar-tailed Godwit and habitat variables on the 63 intertidal study flats. Those in brackets are with 3 Fullerton Cove sites included. The adjusted significance level (see Methods - Analysis) is $P<=0.01$.

Habitat Variable	R^2(%)	F	P	Sign
Area of Site	19.1 (32.3)	14.66 (30.64)	.000 (.000)	+ (+)
Area Surrounding Flats <1km.	3.9 (15.5)	3.37 (12.35)	.072(NS) (.001)	+ (+)
Total Area of Flats < 1 km.	11.4 (26.5)	8.48 (23.35)	.005 (.000)	+ (+)
% Open water surrounding flat	5.6 (1.1)	4.45 (1.72)	.039 * (.194)NS	+ (+)
Surrounding Mangrove	2.5 (7.2)	2.51 (5.83)	.119(NS) (.019)	+ (+)
% Dry at Low Tide	10.9 (19.5)	7.87 (15.53)	.007 (.000)	- (-)
% Wet at Low Tide	8.7 (10.1)	6.34 (7.77)	.015 * (.007)	+ (+)
Secchi Transparency	2.4 (9.3)	2.28 (6.64)	.137(NS) (.013	- (-)
Water Orthophosphate	0.3 (10.5)	1.15 (7.49)	.289(NS) (.008)	+ (+)
Total Intertidal Area (in estuary)	15.6 (19.7)	11.73 (16.25)	.001 (.000)	+ (+)
% Basic Volcanics in catchment	2.1 (6.6)	2.25 (5.40)	.139(NS) (.023)	+ (+)

Not significant: As indicated plus perimeter length, mangrove cover, seagrass cover, texture class, mean hardness, microrelief variance, %<50mm at low tide, %50-150mm at low tide, mean conductivity, suspended solids and latitude. *Not significant at the adjusted significance level.

- area measures: area of flat, total area within 1 km, and total intertidal area in estuary; and
- the elevation measure % dry ground at low tide (Table 1.5).

Bar-tailed Godwit tended to occur in large numbers on intertidal flats with large continuous areas. Their density (birds per hectare) was also higher on large flats. They tended to be few on flats which had large proportions of high and dry ground at low tide. There was no significant relation between godwit numbers and vegetation measures or substrate property measures, without Fullerton Cove.

Whimbrel

Whimbrel were far less abundant on the study flats than Bar-tailed Godwit (Table 1.3) and tended to be more solitary and territorial on feeding areas. Although there were 93 on a single very large intertidal flat in Fullerton Cove, only 4 flats had more than 9 Whimbrel. 65% of the flats had fewer than 3 Whimbrel and 27% had none.

Table 1.6

Significant ($P<=.05$) results of linear regression analysis between maximum numbers of feeding Whimbrel and habitat variables on the 63 intertidal study flats. Those in brackets are with 3 Fullerton Cove sites included. The adjusted significance level (see Methods - Analysis) is $P<=0.01$

Habitat Variable	R^2(%)	*F*	*P*	Sign
Area of Flat	3.6 (37.7)	3.19 (38.48)	.079(NS) (.000)	+ (+)
Area Surrounding Flats <1km.	7.6 (38.1)	5.80 (39.16)	.019* (.000)	+ (+)
Total Area of Flats < 1 km.	8.9 (45.3)	6.64 (52.37)	.013* (.000)	+ (+)
Surrounding Mangrove	29.0 (37.1)	24.64 (37.51)	.000 (.000)	+ (+)
% Dry at Low Tide	8.3 (21.0)	6.28 (17.45)	.015* (.000)	- (-)
% Wet at Low Tide	1.3 (8.9)	1.74 (7.05)	.192(NS) (.010)	+ (+)
Secchi Transparency	28.3 (39.9)	21.09 (37.54)	.000 (.000)	- (-)
Suspended Solids	3.1 (25.7)	2.84 (22.46)	.097(NS) (.000)	+ (+)
Water Orthophosphate	4.8 (29.2)	3.55 (23.71)	.065(NS) (.000)	+ (+)
Latitude	15.6 (8.3)	11.87 (6.59)	.001 (.013)	- (-)
Total Intertidal Area	21.6 (30.6)	16.99 (28.33)	.000 (.000)	+ (+)
% Basic Volcanics in catchment	16.6 (26.6)	12.57 (23.50)	.001 (.000)	+ (+)

Not significant: As indicated plus perimeter length, % open water surrounding flat, mangrove cover, seagrass cover, texture class, mean hardness, microrelief variance, %<50mm at low tide, %50-150mm at low tide and mean conductivity.

* Not significant at the adjusted level.

The attributes of habitat significantly linked with Whimbrel number were:

- the proportion of surrounding mangroves;
- the Secchi transparency (turbidity) of adjacent waters; and
- (less strongly) the total area of intertidal flats within 1km; and
- (negatively) the proportion of dry ground on the flat at low tide (Table 1. 6).

More Whimbrel tended to feed on flats which had a high proportion of their surrounding shore fringed by mangroves than flats with little mangrove fringing. Also, sites with heavy fine-sediment regimes (as measured by the turbidity of associated water) tended to have high numbers of feeding Whimbrel. Sites with high proportions of low soggy or shallowly covered ground at low tide tended to have more Whimbrel. These attributes are linked (see *The Estuarine Environment*, above).

The number of Whimbrel feeding on an intertidal flat was not related to the size of that flat, although it was related to the amount of habitat available in the estuary. Whimbrel number was not strongly related to vegetation on the intertidal flat itself. Substrate properties or other water properties did not relate to Whimbrel number.

Eastern Curlew

The Eastern Curlew was the most widespread migratory shorebird on the study flats, although abundance was much lower than Bar-tailed Godwit. Ninety percent of the sites had at least one Eastern Curlew, though only 5 flats had more than 20. Because of the special conservation status of Eastern Curlew in south-eastern estuaries (Lane 1987; Smith 1991), low numbers were given high conservation significance in the management models (Chapters 2 and 3) despite the abundance of the birds on the study flats.

Table 1.7

Significant ($P<=.05$) results of linear regression analysis between maximum numbers of feeding Eastern Curlew and habitat variables on the 63 intertidal study flats. Those in brackets are with 3 Fullerton Cove sites included. The adjusted significance level (see Methods - Analysis) is $P<=0.008$.

Habitat Variable	R^2(%)	F	P	Sign
Total Area of Flats < 1 km.	34.2 (54.6)	31.68 (75.44)	.000 (.000)	+ (+)
Area Surrounding Flats <1km.	23.7 (45.9)	19.3 (53.55)	.000 (.000)	+ (+)
Area of Site	25.8 (45.3)	21.57 (52.42)	.000 (.000)	+ (+)
Perimeter length	9.6 (18.9)	7.24 (15.48)	.009 * (.000)	+ (+)
% Open water surrounding flat	8.5 (2.3)	6.47 (2.47)	.014 * (.122)NS	+ (+)
Mean Conductivity	9.4 (8.6)	7.14 (6.8)	.01* (.011)	+ (+)
Surrounding Mangrove	1.5 (9.7)	1.92 (7.65)	.171(NS) (.008)	+ (+)
% Dry at Low Tide	0.0 (4.9)	0.21 (4.07)	.646(NS) (.048)	- (-)
Suspended Solids	0.0 (7.1)	0.39 (5.76)	.533(NS) (.019)	+ (+)
Water Orthophosphate	0.04 (6.6)	1.23 (4.87)	.273(NS) (.032)	+ (+)
Total Intertidal Area in Estuary	1.0 (8.6)	1.62 (6.87)	.209(NS) (.011)	+ (+)

Not significant: Surrounding mangrove, mangrove cover, seagrass cover, texture class, mean hardness, microrelief variance, % dry at low tide, % wet at low tide, %<50mm at low tide, %50-150mm at low tide, Secchi transparency, suspended solids, orthophos-phate, latitude and % basic volcanics in catchment.

* Not significant at adjusted significance level.

Few habitat variables related to the number of Eastern Curlew using an intertidal flat (Table 1.7). Larger flats were used by more Curlew, and supported higher densities (birds per hectare) than small flats. The same trend existed with flats surrounded by large areas of intertidal flat, regardless of the study flat's area. The strongest relation was with the total amount of habitat within the arbitrary 1 km radius.

Less strongly related were perimeter length, proportion of surrounding open water and the mean conductivity of associated water. These were correlated with site and surrounding habitat area (see *The Estuarine Environment*, above). Neither vegetation, substrate properties, elevation nor other water properties related to Curlew number using the site.

Less Abundant Species

Greenshank, Tattler and Lesser Golden Plover were far less common than Bar-tailed Godwit, Whimbrel and Eastern Curlew. These only occasionally occurred on the sample of intertidal flats, and were absent on flats which had the same habitat attributes as occupied ones.

When unused flats span the range of habitat attributes, regressing bird numbers against a habitat variable gives a slope which reflects the relative likelihood of a species occurring on flats throughout the range of that habitat variable. A significant slope is taken to reflect a real trend in habitat selection by the species.

Greenshank

Greenshank were the least abundant of the species modelled and were present on 27% of the study flats (Table 1.3). They were found equally on both large and small habitat areas (Table 1.8). They occurred more on partially enclosed flats such as in creek mouths and inlets, than on flats in open positions in the estuary.

Greenshank only occurred on flats with much fringing mangrove, though not all such flats had Greenshank. The trend was significant despite these similar flats being unoccupied. More Greenshank used flats with a high proportion of wet ground at low tide than used flats with a lot of high and dry ground, and there was a greater likelihood of them occurring on sites with moderate to high water orthophosphate levels and high water turbidity (Secchi transparency and suspended solids). These attributes of habitat were correlated with mangrove fringe (see *The Estuarine Environment*, above).

Greenshank were also found in less saline coastal lagoons, where *Casaurina* grows as fringing vegetation instead of mangrove (Yassini 1985). The strong relationship between Greenshank and fringing trees also applies in this environment (see Chapters 2 and 3).

Table 1.8

Significant (P<= 05) results of linear regression analysis between maximum numbers of feeding Greenshank and habitat variables on the 63 intertidal study flats. The adjusted significance level (see Methods - Analysis) is P<=0.006.

Habitat Variable	R^2(%)	F	P	Sign
% Open water surrounding flat	7.7	6.15	.016*	-
Surrounding Mangrove	7.8	14.41	.000	+
Mangrove Cover	9.7	7.52	.008*	+
% Dry at Low Tide	2.8	18.99	.000	-
% Wet at Low Tide	32.8	30.71	.000	+
Secchi transparency	8 5	13.52	.001	-
Suspended Solids	2.7	10.02	.002	+
Water Ortho-phosphate	1.7	8 32	.006	+
Total Intertidal Area in estuary	0.0	7.87	.007*	+
% Basic Volcanics in catchment	7 2	5.78	.019*	+

Not significant: Area of flat, area of surrounding habitat, total area of habitat within 1km, perimeter length, seagrass cover, texture class, mean hardness, microrelief variance, %<50mm at low tide, %50-150mm at low tide, mean conductivity and latitude.

* Not significant at adjusted significance level.

There were no trends with substrate property nor salinity (conductivity). The trend with mangrove cover on the flat's surface is created by one site (Ryan's Creek, Shoalhaven River estuary) with 14 Greenshank and extensive mangrove seedlings.

Tattler

Tattlers used one in three intertidal flats (Table 1.3). They were found singly or in small groups up to a maximum of 35 on one flat in Quibray Bay, Georges River mouth (Botany Bay). This flat had exceptional influence so regressions are reported both with and without this flat (Table 1.9). They were more likely to be found on flats in northern estuaries, though Tattler were present on Pambula flats, the most southern in the study.

There were no trends in their use of intertidal flats except with the % cover variables (Table 1.9). Even without the influence of the Quibray Bay site, mangrove cover remained significant. Intertidal flats with some mangrove cover on their surfaces were more likely to be used by feeding Tattlers than bare flats. Further habitat variables were analysed which measured all aspects of flat cover (see Methods - *Habitat Variables*).

Cover comprised mainly mangrove seedlings and bushes, mangrove pneumatophores (aerial roots), seagrass, and oyster-encrusted ground, rocks or oyster-farming structures. Therefore 'cover' as used here refers to ground cover, not cover for birds. Values given are the proportions of the flat generally affected by the ground cover, including interstices. Each component was analysed separately, and also combined as a 'total % ground cover'.

Table 1.9

Significant (*P*<=.05) results of linear regression analysis between maximum numbers of feeding Tattlers and habitat variables on the 63 intertidal study flats. Values in brackets include the Quibray Bay flat. NS = not significant at *P*<=.05. The adjusted significance level (see Methods - Analysis) is *P*<=0.008.

Habitat Variable	R^2(%)	*F*	*P*	Sign
% Mangrove Cover	10.8 (6.0)	8.23 (4.77)	.008 (.033)	+ (+)
% Adjoining Mangroves	20.7 (23.2)	16.9 (19.69)	.000 (.000)	+ (+)
Pneumatophore Area (hectares)	5.6 (22.3)	4.61 (18.83)	.036* (.000)	+ (+)
Oyster Area (hectares)	9.5 (6.6)	7.44 (5.36)	.008 (.024)	+ (+)
% Oyster Cover	16.5 (13.8)	13.28 (10.93)	.001 (.002)	+ (+)
% Total Cover	6.2 (13.0)	5.01 (10.24)	.029* (.002)	+ (+)
Mangrove Area (ha)	0.0 (11.2)	0.03 (8.86)	.866(NS) (.004)	- (+)
Seagrass Cover (ha)	0.0 (5.4)	0.02 (4.52)	.884(NS) (.037)	- (+)
Total Cover (hectares)	0.4 (14.2)	1.27 (11.25)	.264(NS) (.001)	+ (+)
% Seagrass	0.8 (5.3)	1.48 (4.46)	.228(NS) (.039)	+ (+)
Latitude	9.6 (6.0)	7.51 (4.96)	.008 (.030)	- (-)

Not significant: Area of flat, area of surrounding flats, total area of habitat within 1 km, perimeter length, % open water surrounding flat, % surrounding mangrove, texture class, mean hardness, microrelief variance, % dry at low tide, % wet at low tide, %<50mm at low tide, %50-150mm at low tide, mean salinity, Secchi transparency, suspended solids, orthophosphate, % pneumatophore cover, total area of intertidal flat in estuary, and % basic volcanics in catchment.
Not significant without the Quibray Bay flat: mangrove area (ha), seagrass area (ha), total area of cover (ha) and % seagrass cover .
* Not significant at the adjusted level of significance.

Also measured was the proportion of mangroves actually adjoining the flats (distinct from the main variable `% mangrove surrounding the flats', which includes all shores, adjacent or distant, within 360 degrees).

Tattler numbers were most strongly related to the proportion of mangroves adjoining the flat, favouring flats with adjoining mangroves (Table 1.9). Tattler numbers were also positively related to area of pneumatophores, area of oysters (including structures), proportion of flat with oysters, and total proportion of all cover types. Most of these measures of intertidal flat cover were interrelated (Table 1.10). As with the other less abundant species, flats without Tattlers spanned the full ranges of these attributes.

Pacific Golden Plover

Pacific Golden Plovers were the least widespread of the migratory shorebird species modelled, although not the least abundant. Only 16% of the study flats were used by this species (Table 1.3). The small number of sites used by Pacific Golden Plover resulted in a marginal ability to model habitat suitability for this species.

Area of surrounding flats and Total area of flats within 1 km (including study flat) were strongly related to Pacific Golden Plover numbers over all study flats and when only used flats were analysed (Table 1.11). This means Pacific Golden Plover were more likely to occur, and occurred in greater numbers, where there were large areas of intertidal flat. On flats they used, numbers were greater on larger flats. On these 10 used flats, plover were more numerous on soft flats than on flats with hard surfaces.

These trends were present with or without the Fullerton Cove flat which had 67 plover, but were not present in the second (but smaller) model-testing sample (43 flats, 7 used - see Chapter 2). The trends reported for the other species where tested successfully (see Chapter 2).

Species number

Assigning habitat suitability for the maximum number of shorebird species is a different idea to determining habitat of particular species. The premise is that habitat suitable for multiple species has high conservation value. The aim of this analysis was to define the attributes of habitat associated with relatively high numbers of shorebird species, so that values of these attributes could be nominated for conservation management.

Table 1.10

Correlations among the supplementary cover variables used in the Tattler analysis, and between them and the main habitat variables which were significantly related to Tattler numbers. Pearson correlation coefficients (n=62) significant at P<=.05 are emboldened, * = significant at $P <= 0.01$, ** = $P <= 0.001$. Bracketted values are with the Quibray Bay site included (n=63).

	Pneum Area	Oyster Area	Mangr Area	Seagr. Area	T.Cov. Area	%Pneum. Cover	%Oyster Cover	%Adjoin Mangr.	%Total Cover	%Mangr Cover
Oyster Area	-0.028 (-0.047)									
Mangrove Area	0.342* (0.855**)	-0.028 (-0.048)								
Seagrass Area	0.077 (0.614**)	0.178 (0.109)	-0.039 (0.551**)							
Total Cover	0.279 (0.733**)	0.453** (0.286)	0.312 (0.731**)	0.874** (0.930**)						
%Pneum Cover	0.827** (0.578**)	-0.080 (-.087)	0.305 (0.371*)	-0.004 (0.166)	0.139 (0.279)					
%Oyster Cover	-0.066 (-0.079)	0.906** (0.906**)	0.006 (-0.046)	0.120 (0.054)	0.385* (0.227)	-0.106 (-0.117)				
%Adjoining Mngr	0.376* (0.322*)	0.203 (0.193)	0.173 (0.241)	-0.011 (0.109)	0.161 (0.240)	0.421** (0.446**)	0.217 (0.203)			
%Total Cover	0.445** (0.484**)	0.379 (.344*)	0.464** (0.510**)	0.490** (.569**)	0.717** (.711**)	0.532** (.571**)	0.426** (.382*)	0.516** (0.538**)		
%Mangrove Cover	0.503** (0.491**)	-0.018 (-.029)	0.817** (0.661**)	-0.079 (0.149)	0.219 (0.371*)	0.657** (0.683**)	0.013 (-.005)	0.328* (0.363*)	0.601** (0.643**)	
%Seagrass Cov.	0.101 (0.312)	0.080 (0.065)	-0.022 (0.250)	0.746** (0.735**)	0.654** (0.649**)	0.081 (0.153)	0.119 (0.097)	0.290 (0.326*)	0.673** (0.706**)	-0.003 (0.092)
	Pneum Area	Oyster Area	Mangr Area	Seagr. Area	T.Cov. Area	%Pneum. Cover	%Oyster Cover	%Adjoin Mangr.	%Total Cover	%Mangr Cover

Table 1.11

Significant ($P<=.05$) results of linear regression analysis between maximum numbers of feeding Pacific Golden Plover and habitat variables (a) on the 63 intertidal study flats; and (b) on the 10 study intertidal flats used by Lesser Golden Plover. The adjusted significance levels (see Methods -Analysis) are (a) $P<=0.013$, (b) $P<=0.008$.

Habitat Variable	R^2 (%)	*F*	*P*	Sign
(a)				
Area of surrounding flats (<1 km.)	19.5	16.00	.000	+
Total area of flats within 1 km.	11.3	8.87	.004	+
% area < 50mm deep at low tide	5.1	4.19	.045*	-
Suspended Solids	5.6	4.64	.035*	+

Not significant (a): Area of flat, Perimeter length, % Open water surrounding flat, Surrounding mangroves, Mangrove cover, Seagrass cover, Texture class, Mean hardness, Microrelief variance, % Dry at low tide, % Wet at low tide, %50-150mm at low tide, Mean conductivity, Secchi transparency and Orthophosphate.

Habitat Variable	R^2 (%)	*F*	*P*	Sign
(b)				
Area of flat	58.2	13.52	.006	+
Area of surrounding flats (<1 km.)	64.4	17.30	.003	+
Total area of flats within 1 km.	63.5	20.56	.000	+
Mean surface hardness	53.1	11.2	010*	-
Mean conductivity of water	40.8	7.21	028*	+
Water Orthophosphate level	33.9	6.72	.032*	+

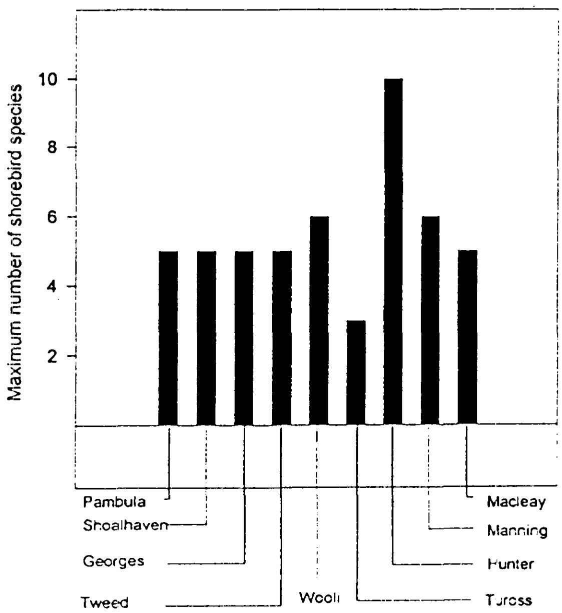
Not significant (b): Perimeter length, % Open water surrounding flat, Surrounding mangroves, Mangrove cover, Seagrass cover, Texture class, Microrelief variance, % Dry at low tide, % Wet low tide, % <50mm at low tide, %50-150mm at low tide, Secchi transparency and Suspended solids.

* Not significant at the adjusted significance level.

This analysis was based on presence or absence of species and gave all species equal conservation importance. It used the cumulative total number of migratory shorebird species recorded over the three censuses on each study flat. Because Fullerton Cove, Hunter estuary, had many more species (Fig. 1.3), the analysis was done with and without this, and reported without (see Methods: *Outliers*).

Fig. 1.3

Highest number of shorebird species counted on any one study flat, in each estuary.



Shorebirds tended to feed together. The number of birds of each species correlated strongly with species number on the flat, except Sharp-tailed Sandpiper, and Greenshank outside Fullerton Cove (Table 1.12). That is, where there were more individuals of each species, there tended to be more species and *vice versa*. The less common species (those not modelled) generally occurred together. The attributes of habitat which were related to the number of shorebird species using intertidal flats were:

- the perimeter length of the intertidal flat at low tide;
- the area of surrounding flats within 1 km and the total area of intertidal flats within 1 km (including study flat);
- the proportion of surrounding mangroves;
- the proportion of shallowly covered (<50mm deep) ground on the flat at low tide; and
- the Secchi transparency (turbidity) of adjacent waters (Table 1.13).

Estuary attributes latitude, total area of intertidal flat, and proportion of basic volcanics in the catchment also related significantly to species number on the flats.

Table 1.12

Matrix of Spearman ranked correlation coefficients among numbers of all migratory shorebird species which occurred on 5 or more of the 106 intertidal flats used in the study. Associations between species significant at P<=0.0005 (one-tailed)(see Methods: *Significane Levels*) are indicated by values >=**0.313** (emboldened), and imply strong trends in co-occurrence, listed in Table 1.14.

	BTG	WBL	ECW	GSK	TAT	PGP	STS	RNS	LSP	TER	CSP
WBL	0.629										
ECW	0.482	0.626									
GSK	0.264	0.334	0.255								
TAT	0.248	0.390	0.272	0.211							
PGP	0.360	0.423	0.278	0.330	0.386						
STS	0.089	0.008	0.023	0.219	0.237	0.285					
RNS	0.220	0.118	0.232	0.269	0.361	0.398	0.462				
LSP	0.326	0.319	0.348	0.302	0.292	0.555	0.334	0.587			
TER	0.219	0.330	0.251	0.408	0.195	0.416	0.292	0.406	0.550		
CSP	0.377	0.410	0.383	0.367	0.209	0.603	0.330	0.441	0.474	0.571	
SppNo	0.650	0.747	0.596	0.481	0.623	0.610	0.300	0.511	0.571	0.360	0.451
	BTG	WBL	ECW	GSK	TAT	PGP	STS	RNS	LSP	TER	CSP

BTG = Bar-tailed Godwit, WBL = Whimbrel, ECW = Eastern Curlew, GSK = Greenshank, TAT = Tattler (probably Grey-tailed), PGP = Pacific Golden Plover, STS = Sharp-tailed Sandpiper, RNS = Red-necked Stint, LSP = Lesser Sand Plover (and possibly Greater Sand Plover (Lane 1995)), TER = Terek Sandpiper, CSP = Curlew Sandpiper, SppNo = cumulative total number of species recorded on the study flat. See Appendix 1for binomials.

Table 1.13

Significant ($P<=.05$) results of linear regress on analysis between maximum numbers of species of feeding migratory shorebirds and habitat variables on the 63 intertidal study flats. Those in brackets are with 3 Fullerton Cove sites included. The adjusted significance level (see Chapter 1 *Methods - Analysis*) is 0.008

Habitat Variable	R^2(%)	F	P	Sign
Area of Flat	3.7 (9.5)	3.25 (7.49)	.077(NS) (.008)	+ (+)
Perimeter Length	16.4 (12.9)	13.17 (9.76)	.001 .003	+ (+)
Area Surrounding Flats <1km.	13.3 (19.4)	10.03 (15.92)	.002 (.000)	+ (+)
Total Area of Flats < 1 km.	12.7 (19.0)	9.57 (15.54)	.003 (.000)	+ (+)
Surrounding Mangrove	18.7 (23.4)	14.55 (19.95)	.000 (.000)	+ (+)
% <50mm deep at Low Tide	8.2 (14.7)	6.12 (11.36)	.016* (.001)	+ (+)
Secchi Transparency	21.6 (26.7)	15.31 (21.08)	.000 (.000)	- (-)
Suspended Solids	1.7 (6.7)	2.02 (5.47)	.160(NS) (.023)	+ (+)
Water Orthophosphate	4.5 (9.5)	3.45 (6.77)	.069(NS) (.012)	+ (+)
Latitude	24.7 (22.5)	20.40 (18.95)	.000 (.000)	- (-)
Total Intertidal Area	21.8 (26.2)	17.41 (2[illegible].00)	.000 (.000)	+ (+)
% Basic Volcanics in catchment	26.1 (30.4)	21.81 (28.08)	.000 (.000)	+ (+)

Not significant: As indicated plus % open water surrounding flat, mangrove cover, seagrass cover, texture class, mean hardness, microrelief variance, %dry at low tide, %wet at low tide, %50-150mm at low tide, and mean conductivity.
* Not significant at the adjusted significance level.

Perimeter length is a function of both size and shape - greater numbers of shorebird species were supported by flats with larger amounts of shoreline than flats with less shoreline. Also, greater numbers of shorebird species used flats which were part of large complexes of intertidal areas than used isolated flats, and those fringed by mangroves had greater numbers of shorebird species than flats with little mangrove fringing. Flats with heavy fine-sediment regimes, as measured by the turbidity of associated water, tended to have many species of feeding shorebird. Mangroves and turbidity are intimately linked (see *The Estuarine Environment*, and the Discussion).

Flats with a lot of shallowly covered ground at low tide (small proportions of dry ground) were slightly more likely to have many shorebird species, but there were a lot of exceptions and the trend was not significant at the higher adjusted significant level. Shorebird species number showed no trends with the position of the flat in relation to land

and open water, vegetation on the flat itself (within the range measured), substrate properties, other aspects of flat elevation, salinity (within the range measured) or water phosphate level without Fullerton Cove.

Species Associations

Habitat requirements have only been determined for six species. Associations on the feeding grounds among the six common species and less common ones were inferred from correlations of occurrence on all censused flats (Table 1.12, above). The associations listed (Table 1.14) are among species occurring on 5 or more sampled flats: Sharp-tailed Sandpiper, Red-necked Stint, Lesser Sand Plover, Terek Sandpiper and Curlew Sandpiper. Shorebirds tended to feed together and there were no clearly defined species groups

Table 1.14

Species which tended to occur on the same study flats, according to strong (P <= 0.0005) correlations of occurrence (see text, Table 1.12). Use with caution to infer habitat conservation needs of less common species based on guidelines for the modelled species which tended to use the same habitat, bearing in mind that each species will have specific habitat requirements at some scale. See Discussion for considerations.

Bar-tailed Godwit	- Whimbrel - Eastern Curlew - Pacific Golden Plover - Lesser Sand Plover - Curlew Sandpiper
Whimbrel	- Bar-tailed Godwit - Eastern Curlew - Greenshank - Tattler - Pacific Golden Plover - Lesser Sand Plover - Terek Sandpiper - Curlew Sandpiper
Eastern Curlew	- Bar-tailed Godwit - Whimbrel - Lesser Sand Plover - Curlew Sandpiper
Greenshank	- Whimbrel - Pacific Golden Plover - Terek Sandpiper - Curlew Sandpiper
Tattler	- Whimbrel - Pacific Golden Plover - Red-necked Stint
Pacific Golden Plover	- Bar-tailed Godwit - Whimbrel - Greenshank - Tattler - Red-necked Stint - Lesser Sand Plover - Terek Sandpiper - Curlew Sandpiper
Sharp-tailed Sandpiper	- Red-necked Stint - Lesser Sand Plover - Curlew Sandpiper
Red-necked Stint	- Tattler - Pacific Golden Plover - Sharp-tailed Sandpiper - Lesser Sand Plover - Terek Sandpiper - Curlew Sandpiper
Mongolian Plover	- Bar-tailed Godwit - Whimbrel - Eastern Curlew - Pacific Golden Plover - Sharp-tailed Sandpiper - Red-necked Stint - Terek Sandpiper - Curlew Sandpiper
Terek Sandpiper	- Whimbrel - Greenshank - Pacific Golden Plover - Lesser Sand Plover - Red-necked Stint - Curlew Sandpiper
Curlew Sandpiper	- Bar-tailed Godwit - Whimbrel - Eastern Curlew - Greenshank - Pacific Golden Plover - Sharp-tailed Sandpiper - Lesser Sand Plover - Red-necked Stint - Terek Sandpiper

There were 32 associations between the 11 species at $P <= 0.0005$ over all 106 study flats (Tables 1.12, 14). In summary, associations between modelled species and others (at this strength of correlation) were:

- Bar-tailed Godwit with Lesser Sand Plover, Curlew Sandpiper;
- Whimbrel with Lesser Sand Plover, Curlew Sandpiper and Terek Sandpiper;
- Eastern Curlew with Lesser Sand Plover, Curlew Sandpiper;
- Greenshank with Curlew Sandpiper, Terek Sandpiper;
- Tattler with Red-necked Stint; and
- Pacific Golden Plover with Lesser S. Plover, Curlew Sandpiper, Terek Sandpiper and Red-necked Stint.

Correlating co-occurrence of the less abundant species (excluding Bar-tailed Godwit, Whimbrel and Eastern Curlew) only where they occurred (37 flats), showed the same associations, at $P >= 0.05$ (Table 1.15). But at the adjusted significance level of 0.015 (to minimise accepting a non-existant trend through chance during multiple comparisons - see *Methods*), no relationship was significant, except Curlew Sandpiper/ Pacific Golden Plover when Fullerton Cove was included. This only means that no very strong trends existed, not that there wasn't co-occurrence (which would be shown by a negative trend (Fig. 1.5 caption)). The potential suitability of a flat to one species may not be accurately assessed by the presence of another of these less abundant species. Better to use a common indicator species; better still to use site specific information if available.

Table 1.15

Matrix of Spearman ranked correlation coefficients among numbers of the less abundant shorebird species which occurred on 5 or more study flats (excluding Bar-tailed Godwit, Whimbrel and Eastern Curlew). Only flats with one or more species present were used. Associations between species significant at $P <= 0.05$ are indicated by r_s values >= 0.325 ($n = 37$) and >= 0.362 ($n = 30$) (emboldened). Associations significant at the adjusted level of $P >= 0.015$ (see text) are indicated by values of approximately >= 0.402 ($n = 37$) and >= 0.446 ($n = 30$) The negative value indicates significant lack of association (eg. Greenshank and Tattler tended to use different flats).

Including Fullerton Cove (n=37)

	GSK	TAT	PGP	LSP	RNS
TAT	**-0.338**				
PGP	0.056	- 0.047			
LSP	0.028	-0.308	**0.336**		
RNS	-0.141	-0.113	0.132	**0.392**	
CSP	0.178	-0.280	**0.429**	0.185	0.175

Excluding Hunter Estuary (n=30)

	GSK	TAT	PGP	LSP
TAT	**-0.435**			
PGP	**-0.400**	0.058		
LSP	-0.156	-0.267	0.341	
RNS	-0.360	-0.189	0.027	**0.418**

GSK = Greenshank, TAT = Tattler, PGP = Pacific Golden Plover, LSP = Lesser Sand Plover (and possibly Greater Sand Plover), RNS = Red-necked Stint, CSP = Curlew Sandpiper.

Discussion

The Estuarine Environment

The interrelationships among the attributes of habitat indicate a gradient between two extreme types of tidal flat characterised by elevation profile, substrate, sediment regime, and nutrient level. At one end of the gradient are low lying, soft, muddy flats of high nutrient content (as reflected by water phosphate levels and surrounding mangrove fringe), in areas of high water sediment load. These flats can be of any size. Smaller ones tend to be enclosed in inlets; large ones tend to be in semi-open positions, but with relatively low salinity regimes. This places large flats of this type in the upstream part of an estuary where the river current meets the tidal current.

At the other end of the gradient are more built-up flats or banks which dry to firm sand at low tide in open positions. These may have lower levels of nutrients and organic matter, reflected by less seagrass cover, mangrove cover and fringing mangrove, and are in areas of low water sediment load. These may also be of any size, but larger ones are in high salinity areas - they tend to be at the mouths of estuaries.

The low, soft, mangrove lined, nutrient-rich flats in sediment-rich waters tend to occur more in larger estuaries, which have extensive intertidal area, and in estuaries with basic volcanic catchments of high fertility. Estuary size stratification (see *Methods - Experimental Design*) masked any trend of size with latitude, but larger New South Wales estuaries tend to be north of about 34 degrees of latitude where the coastal strip broadens (the exception being the Shoalhaven/ Crookhaven estuary, fed by a catchment which is parallel to the coast).

The volcanic surface geology (predominantly basalt) in the river catchments is also found north of the Hunter River (about 33 degrees), in highland areas (Galloway 1967; Packham 1969; Ollier 1978; Harriman & Clifford 1987). This misses the smaller estuaries with either southern (Tuross and Pambula) or lower (Wooli) catchments, and points to a nutrient and fine sediment input available to extensive estuarine wetlands (more likely to occur in larger estuaries with larger, higher catchments), which is not available to tidal flats with smaller, lower catchments.

Those catchments rich in clay minerals and fine grained material produce the most extensive mudflats (Bird 1968). Physical landform and resultant soil conditions determine in large part estuary plant distribution (Carne 1989). Estuaries act as nutrient traps where essential elements are concentrated and recycled (Odum 1970), their presence affecting the vegetation (Adam (1994) and animal community (summarised by Hobbie 1977). Australian estuaries tend to have about twice the phosphate levels of the marine environment, and about 80 times the nitrate levels (Hart 1974). Mangroves, saltmarsh, seagrass etc show very high primary production. Mangrove litter fall on Hinchinbrook Island was found to be up to 20 tonnes per hectare per annum, with a mean of nearly 10 tonnes, about 60% from leaves (Duke *et al.* 1981). Seagrasses have high biomasses and fast growth rates, and organic matter production has been found to be amongst the highest for temperate primary producers (West 1983).

Secondary production is high. The standing crop of invertebrates on estuarine mudflat can be 10 times higher than in adjoining deep marine waters (Odum 1970). Higher diversity and density of infauna has been found in seagrass compared with bare areas, caused by both direct herbivory and provision of habitat (West 1983). Weate (1975) found *high densities of infauna near mangroves in the Myall River, and discusses the general function and importance of mangroves further.*

Shorebird Use of the Estuarine Environment

In the estuaries studied, the number of shorebird species was greatest on extensive, low-lying, mangrove-fringed tidal flats in sediment-rich and/or nutrient-rich waters, and the abundances of each species analysed were correlated with some combination of these attributes of the tidal flats.

Beyond this generalisation, each species selected a particular suite of attributes. Bar-tailed Godwits selected large, low-lying feeding flats; Whimbrel favoured mangrove-lined flats in high-sediment regimes; Eastern Curlew were more catholic, but favoured sites within large complexes of flats. Greenshank frequented large or small flats, provided they were wet, nurient-rich and mangrove fringed; Tattler were more likely to feed adjacent to mangroves, and on flats of any size as long as there was some ground cover; Pacific Golden Plover used extensive intertidal areas.

Species Profiles

Bar-tailed Godwit

The results indicate that Bar-tailed Godwit favour extensive feeding areas. Their flocking behaviour on feeding sites (Lane 1987) may require the selection of flats with sufficient room and resources for the whole flock. Tidal flats of less than several hectares are likely to provide feeding habitat for only small numbers of Bar-tailed Godwit, although small flats may, in total, provide for worthwhile numbers. Very large flats are important to Bar-tailed Godwit because they provide feeding habitat for very large numbers, and because such sites are few. They typically occur in broadwaters or very broad estuaries, and these landforms are uncommon on the east coast south of Moreton Bay.

Black-tailed Godwit are a fairly rare species on these estuaries (Lane 1987). Although not formally analysed, counts of this species during the study imply a similar but more extreme requirement for area. They were only encountered in flocks of 35 or more, and only on very large (> 100 ha) flats in two broadwaters - Fullerton Cove in the Hunter estuary, and Wooloweyah Lake in the Clarence estuary. Conservation of such large intertidal flats appears to be important for this species.

Bar-tailed Godwit were also the most abundant shorebird in the Richmond River estuary during a survey by Dettmann (1989), and likewise in Central Queensland (Driscoll 1995b). McLean (1994) found that Bar-tailed Godwit were associated with extensive areas of mudflat in the Endeavour River. Area is frequently found to be important in habitat selection by wetland birds, eg. Story *et al.* (1993), Nicholls & Baldassarre (1990). Harris (1988) found that on the Parramatta River species diversity also increased with mudflat area. Larger numbers of shorebirds fed on wide shores than narrow shores during a study of the Wash in Britain (Goss-Custard & Yates 1992).

The other attribute of Bar-tailed Godwit feeding habitat shown to be important was the elevation profile of tidal flats, in relation to low tide water level. Flats (in the modelled sample) with mostly wet ground or shallow* water at low tide provided for more Bar-tailed Godwit than those which mostly dried at low tide. As discussed below, the probing behaviour of godwit may be aided by water and soft substrate (Quammen 1982; Gerritsen & van Heezik 1985). Tidal regime (elevation) of the flat may affect density or availability of prey (Andersson 1972; Zwarts & Wanink 1993), determining godwit distribution. Colwell & Landrum (1993) found that the distribution of an amphipod explained nearly a

* less than 150mm deep

quarter of the variation in shorebird distribution in a Californian estuary, and Kalejta & Hockey (1994) found a similar relationship with either density or biomass of prey (depending on species of shorebird) in a South African estuary.

Distribution of shallow water (< 150mm deep) was found to determine densities of shorebirds in a saline swamp in southern India (Sampath & Krishnamurthy 1989), and elevation/water level was also found to be important in a study of migrating shorebirds on Great Plain wetlands, North America (Skagen & Knopf 1994). Hughey (1986) found shorebirds mostly used wet mud or water, from a surface film to 160mm deep, in a coastal lagoon in New Zealand, and on the New Jersey coast, Burger *et al.* (1977) found that most shorebird species exhibited strong preferences for the wettest areas.

In Roebuck Bay, Tulp & de Goeij (1994) found that foraging Bar-tailed Godwits, Great Knot and Tattler kept to the water's edge, sometimes having to fly to keep up with the rapidly retreating water due to the large tidal range there. They speculated that prey organisms may be more active at the water's edge, or (from their Dutch perspective) that it might be cooler in the hot weather. An alternative explanation is that the birds were monitoring the zone where downward migration of benthos was yet to occur (Kalejta & Hockey 1991), and the optimal consistancy of the sediment for prey procurement. Saturated sand becomes more liquid when worked (thixotropic); drier sand becomes firmer when worked (dilatant) (Whitten *et al.* 1988b). Grant (1984) compared high and low portions of mudflat ripples after seeing shorebird probing marks concentrated on the crests, and found no difference in particle size or prey density. But the small crests, being less stable and therefore less compacted, held more water. Due to their thixotropic nature the crests required 50-70% less penetration force than the troughs.

Tidal currents, wave patterns and river flows combine to influence the elevation profiles of tidal flats (Bird 1968). These can be altered by interference with shoreline, bottom and channel shape, and water flow, resulting in changes to intertidal elevation profiles (Butlin 1976; Druery & Curedale 1979; Johnston 1981). Conversely, profiles may be manipulated to enhance feeding habitat (Wilcox 1986; Rehfisch 1994).

Whimbrel

Whimbrel are birds of mangrove shores in the study estuaries. They roosted in mature mangroves at high tide (Chapter 6) and occurred in greatest numbers on tidal flats with extensive fringing mangroves, rarely being found where mangroves were absent. Their feeding flats were either bare or vegetated by mangrove. The link with mangroves may be direct or indirect (see *Habitat Management Needs*, below). The other attributes of habitat which related to Whimbrel number - low elevation and turbidity - suggest a sheltered sediment-rich and organic matter-rich environment which favour both mangroves (West 1985; Whitten *et al.* 1988b) and Whimbrel. Either way, mangrove preservation and Whimbrel habitat conservation are demonstrably linked.

Thompson (1991), when modelling shorebird occurrence in relation to substrate properties in Moreton Bay, identified an association between Whimbrel and muddy substrates, also found in Surinam (Spaans 1978) and California (Gerstenberg 1979). Smith (1991), in a general review, describes Whimbrel habitat on tidal mudflats as "near mangroves". Tidal flats of any size may be used by relatively large numbers of Whimbrel, if they form part of large complexes of suitable habitat. Very large complexes are of high conservation significance to Whimbrel. See also Dann (1993) for a Victorian perspective on similar relationships.

Eastern Curlew

Eastern Curlews appear to be generalists on intertidal habitat. No attribute measured in the study discerned any preferences beyond habitat which provided space. The Curlew's territorial feeding behaviour requires it to disperse on feeding sites (Dann 1987), so it needs extensive habitat within reach of roost sites, even though this is not used at high densities (Driscoll 1995a).

Use of extensive foraging areas by curlew has been documented elsewhere. Dann (1994), examining survey results in coastal Victoria, suggests it is because curlew do not discriminate microhabitats within estuaries as much as other species. Congdon & Catterall (1994), finding the same relationship in Moreton Bay, suggest sites are chosen according to potential foraging area, social facilitation among sexes and age groups, and reduced risk of disturbance. But they caution that not all large areas are used equally - flats in their Moreton Bay study area which had thin sediment overlying hard coral were used less.

Few prescriptions for Eastern Curlew feeding habitat can be made from the results reported here, and a greater understanding of habitat needs probably requires research into each age-group or sex. Eastern Curlew feed on Ghost Shrimps (*Callianassa australiensis*) and small crabs (Dann 1987), and one or other of these prey are available on most intertidal areas of adequate salinity (Chapter 5). The Curlew's long legs and bill allow it to feed in a greater range of water depths and for longer periods either side of low tide, than smaller shorebirds (pers. obs.). Yet its greater body size increases energy efficiency (Calder 1974), needing less feeding time (eg. Kersten & Piersma (1987)). Its greater strength, and bill shape, allows it to probe in a wider range of substrates (Ferns & Siman 1994). So the nature of a tidal flat may be less critical for the Eastern Curlew than the availability of large areas for dispersal and disturbance-free foraging.

Proximity to roosts has been suggested by Thompson (1991) and Congdon & Catterall (1994) to partially determine habitat use by curlews. Energy efficiency appears to be important for migratory shorebirds on non-breeding grounds (Evans 1976; Tulp & de Goeij 1994; Wiersma & Piersma 1994). Despite their ability to fly enormous distances on migration, shorebirds favour areas where maximum feeding habitat is within close reach (Appendix IV).

As with Bar-tailed Godwit and Whimbrel, the results for Eastern Curlew indicate that large tidal flat assemblages are important, and need to be protected. Because curlew disperse widely for feeding, small flats within the large complexes are important in total. Given the dependence of this species on estuaries on the east coast of Australia (Lane 1987), such groups of tidal flats need to be managed with Eastern Curlew conservation in mind and fragmentation avoided (Laudenslayer 1986).

Greenshank

Greenshank, in the study estuaries, are birds of sheltered, sediment- and nutrient-rich intertidal areas characterised by the presence of mangroves. Thirteen of the 17 study flats used by Greenshank were semi-enclosed -- in inlets, creeks and shallow minor passages. These wetland areas have more fringing mangrove and mangrove correlates - low elevation, high turbidity and high nutrient level. They act as sediment traps (Druery & Curedale 1979; Wolanski *et al.* 1980) and nutrient sinks (Odum 1970; Congdon & McComb 1980), and tend to remain saturated at low tide.

Such intertidal areas, of any size, should be managed with Greenshank conservation considered. As with Whimbrel, mangroves are so closely linked to both Greenshank occurrence and other attributes of Greenshank feeding habitat, that protection of mangroves must help protection of Greenshank habitat. Similar prescriptions apply in brackish coastal lagoons (Chapter 3 Discussion).

Tattler

Tattler differ from the other species examined because they are less likely to forage on bare tidal flats. Tattlers were recorded foraging among mangroves and mangrove pneumatophores, on oyster beds, under oyster-farming structures and in seagrass, as well as on bare substrates. They were more likely to feed among all of these types of cover than on bare ground. An association with seagrass has been shown in the Richmond River estuary (Rohweder & Baverstock 1996) and in Moreton Bay and elsewhere (Thompson 1991, J. Thompson pers. comm.). Driscoll (1995b), in a survey of Central Queensland coastal wetlands, found that the species assemblage dominated by Tattler corresponded to semi-enclosed areas with seagrass. Pegler (1981), comparing shorebird use of Port Stephens and Botany Bay, found Tattler "in sites near mangroves and seagrass", Clarke & van Gessel (1982) reported them from mangrove fringes and oyster banks in the Hunter River estuary, and Morris *et al.* (1990) reported them from rocky intertidal shores in the Parramatta River wetlands. Smith (1991) in a review, describes their habitat as "extensive mangroves, flats, amongst mangrove, seagrass, debris, oyster racks".

Cover variables were the only attributes of habitat significantly linked to Tattler numbers. The extent of cover (and adjoining mangrove) may be a more important consideration for Tattlers than any other aspect of intertidal habitat, and may even act as a cue for recognition of suitable foraging sites (Thompson 1991). Tattlers were equally likely to occur on all sizes of flat, all sizes of habitat complex, and regardless of substrate property, profile or water properties, within the ranges encountered in the sample.

Adjoining mangroves were a feature of Tattler feeding habitat. The proportion of adjoining mangrove influences pneumatophore cover and is correlated with mangrove cover on the flat, commonly present as suckers and seedlings. Adjoining mangroves may provide direct resources, eg. refuges and nearby high tide roost sites (Chapter 6). Preservation of fringing mangroves is implicated as important in Tattler habitat management. Preservation of seagrass (notably protection from excess sewage effluent (Thompson 1993) but also other impacts) is also needed for Tattler.

Mangrove colonisation of tidal flats is regarded as detrimental to migratory shorebirds (Buckney 1987; P. Straw, M. Dodkin, D. Geering pers comm.). Dense growth may still be used by Tattler while displacing other shorebird species, creating a conflict in conservation management. This study only included light mangrove cover - no study flat had more than 20% cover, and only 3 flats had more than 10% (Table 1.1). No negative correlations between mangrove cover and shorebird numbers were detected, so there should not be any conflict at these light densities of mangrove colonisation.

Pacific Golden Plover

Low numbers of Pacific Golden Plover made it difficult to characterise the selection of feeding habitat. There were strong positive trends with the measures of surrounding habitat area, but only in the modelled sample. While this trend was not present in the testing sample (Chapter 2), it is retained tentatively because the modelled sample was larger and multiple counts were made.

The same association with extensive habitat was present with Bar-tailed Godwit, Whimbrel and Eastern Curlew, and Pacific Golden Plover co-occurred with godwit and Whimbrel (Table 1.12), so it seems reasonable to use the relationship for a basis for management guidelines. With the low numbers involved, direct inspection of the scatterplots in Chapter 3 (Figs. 3.16, 3.18 and 3.19) gives a useful appeciation of the strengths of the relationships. Thomas (1988) found that Pacific Golden Plover were attracted to seagrass areas in Tasmania, and Morris *et al.* (1990) report them from rocky shores in the Parramatta River estuary. Thompson (1991) was unable to model Pacific Golden Plover and suggested that its unspecialised habitat use (drylands, fresh, brackish and estuarine wetlands, reefs) meant that its innate responses were not so directly tuned to the characteristics of tidal habitat.

Conflicting Habitat Needs

With the differences in habitat use among the species, the management of any one site for all shorebirds might be hampered by conflicts of interest. Comparing the directions of the correlations (positive or negative trends) shows that although the *values* of the attributes of habitat may differ among species, the directions are mostly the same, suggesting that few conflicts of interest exist (Table 1.16).

While Bar-tailed Godwit and Eastern Curlew numbers tend to increase with increased "openness" of a flat, Greenshank numbers tend to diminish along this gradient. Thus a conflict of interest may exist between Greenshank habitat management and that for Curlew and Godwit where, for example, mangrove is separating a tidal flat from open water. Another conflict may arise with control of vegetation or other cover on tidal flats, in which Tattler may be disadvantaged to the benefit of other species. Because both Greenshank and

Table 1.16

Summary and comparison of feeding habitat attributes important to the 6 modelled shorebird species and species number (significantly ($P <= 0.05$) related to numbers of shorebirds on the study flats). Symbols indicate positive or negative relationships: plus implies more is better; minus implies less is better. Conflicts of interest between species exist if + and - symbols occur on the same line.

BTG=Bar-tailed Godwit; WBL=Whimbrel; ECW=Eastern Curlew; GSK=Greenshank; TAT=Tattler; PGP=Pacific Golden Plover; SpNo = species number.

	BTG	WBL	ECW	GSK	TAT	PGP	SpNo
Size, shape and position variables:							
Area of Flat	+	+			+		
Area of Surrounding Flats within 1 km		+	+			+	+
Total Area of Intertidal Flat within 1 km	+	+	+			+	+
Perimeter Length			+				+
% Open Water Surrounding Flat	+		+	-			
Vegetation variables							
% Surrounding Mangrove		+		+			+
% Mangrove Cover on flat				+	+		
% Seagrass Cover							
For Tattler:							
Area Pneumatophores					+		
Area & % Oyster encrusted ground, rocks and oyster-farming structures					+		
Mangrove Area							
Seagrass Area							
% Total Gound Cover					+		
% Adjoining Mangroves					+		
Substrate properties							
Northcote Texture Class							
Mean Surface Hardness						-	
Microrelief Variance							
Elevation profile							
% Area Dry at Low Tide	-	-		-			
% Area Wet at Low Tide	+			+			
% Area < 50mm Deep at Low Tide							+
% Area 50mm to 150mm Deep at Low Tide							
Water quality							
Mean Conductivity	+					+	
Secchi Transparency		-		-			-
Suspended Solids				+			
Orthophosphate				+		+	+
Estuary descriptors							
Latitude (degrees, minutes)		-			-		-
Total Intertidal Area	+	+		+			+
% Basic Volcanics in Catchment		+		+			+
	BTG	WBL	ECW	GSK	TAT	PGP	SpNo

Tattler did occur with other species (Table 1.14), compromise values for the relevant attribute of the habitat should exist.

Species Associations

Associations between the study species and the less common species can only be considered circumstantial evidence for similar habitat selection on the study flats, and little indication of the overall habitat requirements of the species not analysed (Symmonds *et al.* 1984; Block *et al.* 1986). The associations found (Table 1.14) can be used to infer the use of a site by the less common species, based on known use by associated modelled species (or when these are predicted by the keys in Chapter 3). This allows some idea of which less common species are likely to be affected by impacts.

A strong association between Curlew Sandpiper, Great Knot and Black-tailed Godwit was discerned in Moreton Bay by Thompson (1991), but this was driven by the effect of sewage effluent in Bramble Bay. Weaker associations were discerned in more natural habitats, with a mixing of species on feeding flats. Driscoll (1993b, 1995b) similarly inferred species associations in Great Sandy Strait and on the Central Queensland coast from weak patterns, but observed that associations changed with season (see also Warnock & Takekawa (1995)). Co-occurrence may be facilitated simply by an abundance of prey (Withers & Chapman 1993) making associations transient. Table 1.17 summarises species associations inferred by the other studies mentioned, for comparison with the results in Table 1.14.

Habitat Management Needs

Generally, habitat management for the six shorebird species dealt with, will be compatible. The important attributes of habitat to protect are the maintenance of extensive complexes of tidal flats (avoiding fragmentation of habitat), maintenance of the depositional regime (avoiding change to elevation profile and texture) and the nutrient regime (including vegetation sources), and preservation of fringing mangrove.

These attributes may have direct or indirect functions, or they may be simply indicators. For example, mangrove fringe may provide physical shelter, sediment stability (Sato 1984), nutrient input (Lear & Turner 1977; Correll 1978; Harbison 1981; Clough

Table 1.17

Species associations on intertidal flats inferred by shorebird studies elsewhere on the east coast of Australia. Only associations between the six species modelled in this study and species not modelled are shown (associations were also discerned among the six modelled species). Note that species associations were not a focus of the studies and those tabulated here have not been derived from inferential statistics. Those marked with an asterisk (*) were also found in this study.

	Great Sandy Strait (Driscoll 1993b)	**Central Queensland** (Driscoll 1995b)	**Moreton Bay** (Thompson 1991)
Bar-tailed Godwit	Terek Sandpiper	Red-necked Stint sand plover*	
Whimbrel	Terek Sandpiper*	Red-necked Stint sand plover*	
Eastern Curlew	Terek Sandpiper	Red-necked Stint sand plover*	
Greenshank	Terek Sandpiper*		
Tattler	Terek Sandpiper		Red-necked Stint* sand plover
Pacific Golden Plover			Sharp-tailed Sandpiper Marsh Sandpiper

1982; Clarke 1983) and/or be a co-feature of an environment which has the food availability required by shorebirds (Carne 1989; Clarke & Myerscough 1993) (Chapter 5).

The identified attributes of habitat are discussed in more detail in Chapter 2: General Discussion: *The Guide Values*. Potential impacts on them are considered in Appendix III, along with some management strategies.

Guidelines

An understanding of general habitat needs is important to wildlife conservation, but in the face of estuarine development, more specific and quantitative information is needed. In the climate of compromise and trade-offs which unfortunately exists in east coast estuarine resource management, resource managers need to know the limits of compromise. The trends in habitat suitability identified in this chapter are quantified in the following chapter (Chapter 2) to provide guidelines for the management of estuarine intertidal flats as shorebird feeding habitat.

Limitations of the Study

There are limitations to this research which must be borne in mind when using the conclusions for conservation management:

1) It only identifies the attributes of habitat which correlate with bird numbers, rather than those which cause the areas to be suitable for shorebirds (Romesburg 1981; Noon 1986; Mentis 1988; Eberhardt & Thomas 1991). External influences can be important. For example, conservation of the recommended attributes on the feeding areas may not be enough if the nutrient regime of catchment flows is changed.

There are also assumptions in the concepts of 'habitat requirements' (Gray & Craig 1991), 'habitat selection' (Rosenzweig 1985; Lunney 1986), and 'habitat quality' (van Horne 1983a). Gray & Craig (1991) contend that there are historical elements to bird behaviour which may affect assessments of current habitat use. They point out that birds' needs may change (and may be changed as a part of conservation management eg., relocation of a shorebird roost lost by development), and current habits may not be optimal. The use of bird abundance may be misleading if the age or sex structure of a species shows that sites with greatest numbers are not the "best" habitat. Thompson (1990) found 3.7 times the normal density of Bar-tailed Godwits at sewage outfalls in Moreton Bay but there was a high proportion of juveniles, suggesting that the habitat may have been sub-optimal for adults (though perhaps it functioned as a "wader nursery", as coined by Lane (1992)).

Abundance is also affected by territorial behaviour and temporary population increases (van Horne 1983b). Migratory species may have highly fluctuating numbers at a site. For example Gosper (1981) observed a temporary increase in Red Knot numbers on the Hunter estuary of "several thousand" between late September and early December. High habitat quality is defined by habitat where survival rate and/or reproduction rate is high relative to other habitats (van Horne 1983b), factors difficult to quantify for migratory shorebirds.

Competition within or between species will also affect species abundance independently of attributes of habitat (Diehl 1986), as will predation, disease, parasites, weather, and single high-impact (stochastic) events (O'Neil & Carey 1986). Wolff (1991), when comparing shorebird density with prey biomass (an integrator of habitat quality) in Europe and North Africa, found that bird densities were not necessarily related to food density at the flyway level. Best & Stauffer (1983), while conducting a wide-ranging Habitat Suitability Index study of terrestrial birds, also identified five confounding influences in modelling: incomplete sampling along gradients, non-linear relationships, variability in species responses, coarseness of measurements, and scale. Brandt *et al.* (1995) found that important aspects of habitat associations became apparent only at certain scales while studying habitat selection of nesting seabirds.

However, in the words of Salwasser (1986) "without suitable habitats populations cease to exist. So we should always be able to explain something about populations from knowledge of habitat variables".

2) The estuarine ecosystem is also an interrelated web of attributes. This research and the resulting guidelines used the attributes of habitat showing the strongest relationship with bird numbers among related ones. The models in Chapter 2 give supplementary guide values for attributes allied with the main ones, but the importance of every individual one is not established independently of every other. In management, it is safer to assume that an attribute of habitat which shows a strong trend with bird numbers is important, because it is likely to at least represent one aspect of an important environmental condition (Chalk 1986; Hargrove & Pickering 1992).

3) Only continuous trends were used. Step-functions could not be identified with the method used because no environmental extremes were sampled (Gaines & Denny 1993). For example, water salinity regime may become unsuitable at an extremely high or low value, but all of the moderate salinities encountered during the study may be suitable for shorebird habitat. Values outside the natural range which occurred on the study flats were not assessed.

4) Populations of migratory species may change due to external factors. Shorebirds are vulnerable to weather conditions, predators, and prey availability on the breeding grounds (Tomkovich 1995), hunting on the flyway (Johnson *et al.* 1992), and habitat loss (Parish 1985; Straw 1995c). Local populations can fluctuate with rainfall and resultant habitat availability in Australia (Maher 1991; Kingsford & Porter 1993). For example Chafer (1991) recorded large numbers of Sharp-tailed Sandpiper at Lake Illawarra during an inland drought. As discussed above, when numbers are used as a measure of habitat suitability, these external factors may affect conclusions (Holmes 1981).

For the above reasons this research does not replace intensive ecological investigations on smaller scales, especially field experiments, which can complement regional findings (Hargrove & Pickering 1992, see also *Research Recommendations*, below). Models which describe relationships are valuable tools in management but are not replacements for research identifying cause and effect (James & McCulloch 1985). Descriptive models describe the present, but do not predict the future (Bradbury *et al.* 1984). They help manage environmental changes within the tolerances of the present system, but Bradbury *et al.* (1984) warn that studies of present ecosystem structure fail to predict the effect of change which pushes the system beyond its (unknown) edge, citing as an example the much-celebrated fishery management models which did not predict the collapse of the North Sea herring fishery.

Similar disasters have befallen shorebirds in other parts of the world, such as the damming of the Oosterschelde estuary in the Netherlands, which, coupled to excessive offtake of cockles, caused the "disappearance" of an estimated 10 000 oystercatchers (Meire 1991, Sutherland & Goss-Custard 1991). The incremental loss and degradation of habitat in southern east coast estuaries may have as much potential.

Research Recommendations

Many recommendations for shorebird research can be found in Smith (1990), Thompson (1991), Watkins (1993) and Congdon & Catterall (1994). Discussions with shorebird researchers and estuary managers add the following specific, if difficult, topics:

1) Ecological-demographic study investigating which habitats or other factors are limiting shorebird populations, particularly the species with smaller, more restricted population distributions. Specific questions to answer are: Is intertidal habitat in southern east coast estuaries at carrying capacity? leading to: Do densities of feeding shorebirds change with distance from roosts? Are relationships between prey densities and bird densities constant over space and time? What effect do shorebirds have on invertebrate populations, and are they sustainable through summer? When habitat is lost, does density of shorebirds increase on adjacent habitat, short term and long term? If so, what effect does increased density have on food intake, ability to migrate and mortality? a question requiring understanding of shorebird energetics and population structure. These answers are important in environmental impact assessment and habitat loss mitigation plans.

2) Ecological-behavioural study investigating the effect of roost loss on shorebird populations. Specific questions to answer are: As above, do densities of feeding shorebirds

change with distance from roosts independently of prey densities and habitat factors? Does roost loss affect shorebird species density on adjacent feeding habitat? This will lead into the above questions regarding loss of feeding habitat. How flexible is shorebird roosting behaviour when faced with roosting habitat changes and loss? What is the effect on mortality and ability to migrate of sub-optimal or disturbed roosts? also a question requiring understanding of shorebird energetics and population structure.

3) Biochemical-ecological study investigating contamination of shorebirds. Specific questions to answer are: What are the ranges of contaminant levels in shorebird tissues (eg. the many petroleum hydrocarbons, heavy metals, organic compounds)? What are the sources of these contaminants, and how much are they magnified through the trophic levels? What effect do the levels of contamination have on shorebird mortality, ability to migrate and ability to reproduce? Some questions may need the study of resident species, initially at least.

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