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Integrating Vulnerability Into Estuarine Conservation Planning: Does the Data Treatment Method Matter?

Mohammad Reza Shokri & William Gladstone

Abstract Protected areas will more efficiently protect biodiversity if threats to the persistence of populations are addressed. Seagrass meadows are globally regarded as critical habitats because of their ecosystem services, human use values, and their diminishing extent. While selecting priority areas for conservation of seagrass meadows is largely aimed at maximizing the protection of their biodiversity, little attention is paid to consider simultaneously the representation of biodiversity and the minimization of threats. This study developed and tested an approach for integrating vulnerability of seagrass meadows to anthropogenic disturbance with the selection of estuarine-protected areas. Vulnerability was measured by data on different land use types in subcatchments. Conservation value was measured by irreplaceability, diversity indices, and rarity of macroinvertebrate species in seagrass meadows. Vulnerability was incorporated into conservation planning by plotting grid cell scores for conservation value versus their scores for vulnerability. The results showed that the performance of the model for the integration of vulnerability into estuarine conservation planning was sensitive to the data treatment. The vulnerability of seagrass meadows and accordingly the

arrangement of priority areas for conservation and management attention may change if more information is incorporated into the measurement of vulnerability.

Keywords Conservation measure · Vulnerability measure · Seagrass · Human use · Irreplaceability · Reserve selection

Introduction

Effective conservation areas should represent biodiversity and ensure its persistence (Pimm and Lawton 1998; Williams 1998; Margules and Pressey 2000). Biodiversity persistence is ensured by increasing the size of populations within individual reserves (Rodrigues et al. 2000) or across networks of reserves (Margules et al. 1994). It is also ensured by managing uses in reserves and in surrounding areas (Margules and Pressey 2000). The basic role of conservation areas to segregate biodiversity from the factors and processes that peril its existence requires that the threatening factors be directly addressed in the reserve selection processes (Margules and Pressey 2000; Gaston et al. 2002; Lawler et al. 2003). The effectiveness of conservation planning will be enhanced when both representation and persistence can be incorporated.

Vulnerability is the likelihood or proximity of attributes (e.g., species, areas, regions, and countries) to destruction and perturbation (Pressey et al. 1996). Wilson et al. (2005) extended this definition by distinguishing three dimensions of vulnerability: exposure, intensity, and impact. Exposure and intensity apply to areas and consequently to the attributes they contain, whereas impact applies only to attributes. Using vulnerability information, conservation planners can make decisions on both the degree of protection necessary and the urgency of that protection (Pressey and Taffs 2001). A number of

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researchers have suggested that integrating representation and vulnerability will enhance the effectiveness of conservation planning (Margules and Pressey 2000; Pressey and Taffs 2001). Incorporating measures of vulnerability into the reserve selection process gives planners more options to select from among sites with similar conservation value, so that sites facing greater threats can be prioritized to receive more immediate attention (Lawler et al. 2003). The main issues for integrating vulnerability into conservation planning are the methods of measuring vulnerability and the means of incorporating these measures of vulnerability in the reserve selection process.

Vulnerability is not as objectively computable as conservation value (Pressey et al. 2000). Sisk et al. (1994) used an index of human population pressure in combination with an index of forest loss as a vulnerability measure. Pressey and Taffs (2001) estimated the vulnerability of land systems from previous assessments of their suitability for clearing or cropping. Noss et al. (2002) assessed vulnerability on the basis of expert opinion about the extent of the threats faced by a site. Lawler et al. (2003) measured vulnerability as the percentage of a site dedicated to agriculture, urban and suburban development, and to open mines.

Assessing vulnerability in aquatic systems has mostly been conducted by using an index of environmental sensitivity following procedures developed for responding to natural hazards such as cyclones, tsunamis, flooding (Cutter 1996; Clark et al. 1998), human-induced events, and impacts such as oil spills (Gundlach and Hayes 1978; Hanna 1995) and drainage leakage (Hatt et al. 2004). Pethick and Crooks (2000) measured shoreline vulnerability by relating disturbance event frequency to relaxation time. Zacharias and Gregr (2005) proposed three steps to identify vulnerable marine areas including identification and mapping of valued ecological features, identification of sensitivities and vulnerabilities of valued ecological features, and prediction of vulnerable marine areas. The conclusion from these studies is that there is no explicit way to measure vulnerability and its measurement is largely dependent on the availability of data and an arbitrary selection of factors that may be relevant to this issue.

Integrating vulnerability and conservation value has generally taken place by a graphical approach that includes a plot of the values of irreplaceability versus vulnerability (Sisk et al. 1994; Pressey et al. 1996; Pressey and Taffs 2001; Noss et al. 2002; Fig. 1). Two approaches have been used to identify high-priority areas for conservation in these plots (Sisk et al. 1994; Pressey et al. 1996; Pressey and Taffs 2001; Noss et al. 2002). Sisk et al. (1994) identified areas which occurred within the upper quartile on each axis. They suggested the areas in the upper right quartile had a high priority for conservation because they have both high

Fig. 1 A matrix for identifying priority conservation areas by integration of two measures of vulnerability and irreplaceability (adapted from Margules and Pressey (2000)). Irreplaceability is the extent to which an area is required as part of a reserve network to achieve a specific goal, and the vulnerability is the likelihood of an area being disturbed

irreplaceability and high vulnerability values. Noss et al. (2002) gave the higher priority to sites in the upper left quadrant over the lower right quartile. They argued that sites with high irreplaceability value deserved more conservation action even if they are not presently at high risk. Pressey et al. (1996) and Pressey and Taffs (2001) used a diagonal to delineate the top right of the plot. However, some authors have suggested a different approach in which priority should be given to sites with high representation and low vulnerability because they believe that these areas are in the best condition and thus can ensure species persistence if planners are obliged to deal with very small number of areas (Davis et al. 1996).

Integrating vulnerability and conservation values might be sensitive to the methods by which data for these measures are treated before integration. Earlier studies used either untreated raw data (Sisk et al. 1994; Noss et al. 2002) or ranked data (Pressey et al. 1994; Lawler et al. 2003) when mapping irreplaceability and vulnerability. We are not aware of any studies of the effects of different data treatments on the outcomes of graphical approaches that relate conservation value and vulnerability.

The present study aims to explore the integration of reserve selection and vulnerability using biological and physical data on seagrass meadows in southeast Australia. In particular, this study aims to (1) quantify conservation value and vulnerability in an estuary; (2) apply an approach from terrestrial environments that uses measures of conservation value and vulnerability to select estuarine protected areas; and (3) to explore the consequences of different analytical approaches and data treatments when integrating conservation value and vulnerability for estuarine conservation planning.

Methods

Study Area

This study was undertaken in seagrass meadows (*Zostera capricorni*) in Brisbane Water Estuary (33°28'S, 151°20'E) in southeast Australia. Brisbane Water is a shallow estuary with an area of 27 km² and length of 13 km that is connected to the Pacific Ocean through a narrow channel (Gosford City Council 1995). The estuary drains a catchment of 185 km², the principal tributaries being Narara Creek in the northwest, and Erina and Kincumber creeks in the northeast. Habitats occurring within Brisbane Water Estuary include (1) mangrove (*Avicennia marina*), (2) seagrass (*Z. capricorni*), (3) intertidal rocky shores, (4) intertidal mud, and (5) subtidal unvegetated

habitat (Gosford City Council 1995). The total area of the estuary was divided into 36 grid cells of 1 km² in order to provide a uniform degree of sampling resolution (Fig. 1). Three distinctive systems were captured by this division: marine–estuarine (grid cells, 28–33), creeks draining into the estuary (grid cells, 34–36), and the estuarine system (all remaining grid cells). We selected seagrass meadows because they occurred throughout the estuary, they typically contain a high diversity of organisms, and they and their associated fauna are negatively impacted by a range of anthropogenic stressors (Short and Wyllie-Echeverria 1996; Duarte 2002; Orth et al. 2006). The total area of the estuary was divided into 36 grid cells of 1 km² in order to provide a uniform degree of sampling resolution (Fig. 2). Three distinctive systems were captured by this division: marine–estuarine

Fig. 2 Location of grid cells used for sampling in Brisbane Water Estuary. Reproduced from source map (Gosford City Council 1995), location of grid cells with the highest values for summed-irreplaceability, total number of spatially and numerically rare species, Shannon index, Pielou's evenness and conservation value, and location of grid cells with the highest values for impervious rate, different land use types, and vulnerability

(grid cells, 28–33), creeks draining into the estuary (grid cells, 34–36), and the estuarine system (all remaining grid cells). The Brisbane Water Catchment was broken up into subcatchments based on hydrological considera-

tions (Cardno Lawson Treloar 2008).

Biological Sampling

Biological sampling was carried out from May to December 2005 in 31 grid cells known to contain *Z. capricorni* seagrass meadows. Sampling occurred in two replicate sites located approximately 100 m apart. The optimal number of replicate samples was determined following previous study (Shokri et al. 2009). Macroinvertebrates were sampled by inserting a 10 cm wide × 10 cm deep PVC corer (N06) into the sediment in water from 20 to 50 cm deep and then sieving the sediment sample through a 1-mm mesh. Sediments were rewashed in the laboratory over a 1-mm mesh sieve and retained sediments, leaf litter and wrack were separated. Sediments were preserved in 5–7 % formalin, followed by 70 % ethanol with rose bengal for further sorting. Identification of macroinvertebrates was pursued in the laboratory and the identifications were checked by the assistance of experts at the Australian Museum.

Assessment of Conservation Value

Several measures were used to assess the conservation value of each grid cell: summed irreplaceability, diversity, and the number of numerically and spatially rare species. The basis for this strategy was to ensure that major goals for conservation planning were met.

The conservation planning software C-Plan (New South Wales National Parks and Wildlife Service; Pressey 1998, 1999) was used to quantify the summed irreplaceability value of each grid cell for the conservation goal of each species being represented at least once in a reserve. Summed irreplaceability was used as the quantitative measure of each grid cell's contribution to the conservation goal. Irreplaceability is a measure of the likelihood that a grid cell will be required to achieve the conservation goal (Pressey 1999). Summed irreplaceability is the sum of the irreplaceability values for each species occurring in each grid cell (Ferrier et al. 2000). Summed irreplaceability values were calculated for each grid cell from the matrix of species presence-absence.

The Shannon index H' (Shannon and Weaver 1949) and Pielou's evenness measure J' (Pielou 1976) were used as heterogeneity measures that emphasize the species richness component of diversity. The indices were calculated using the following formulae:

1. The Shannon index H' (Shannon and Weaver 1949):

$$H' = - \sum_{i=1}^S p_i \ln p_i$$

where S is total number of species, and $p_i = n_i/N$ where n_i = number of individuals of the i th species and N = total number of individuals.

2. Pielou's evenness measure J' (Pielou 1976):

$$J' = \frac{H'}{\ln S}$$

where H' is the Shannon index and S total number of species.

Rarity was used as another measure of conservation value. Rarity hot spots were identified as grid cells containing numerically and spatially rare species. Using the definition of Gaston (1994) on rarity, spatially rare species were defined as those whose range size (i.e., the number of grid cells in which the species was recorded) fell in the lower quartile of the frequency distribution of range sizes. Numerically, rare species had a maximum abundance that fell in the lower quartile of the frequency distribution of maximum abundance of all species. It was assumed that grid cells with a high number of numerically and spatially rare species had high conservation value.

The conservation value of each grid cell was quantified by summing the values for summed irreplaceability, Shannon index, Pielou's evenness measure, and the total number of spatially and numerically rare species.

Measuring Vulnerability

A suite of indicators of human impact on seagrass meadows and their associated fauna were selected to assess the vulnerability of each grid cell. Data for the vulnerability indicators were derived from existing reports (Gosford City Council 1995; Thomson 2007). The Brisbane Water Catchment was initially broken up into subcatchments based on hydrological considerations. The Council GIS layer of subcatchments was used as a template for the catchment delineation. These hydrological catchments were then divided up based on their land use (such as residential, commercial, industrial, rural, and sewage uses).

Clearing natural vegetation and development of urban and rural land uses in catchments increases the flow of pollutants into estuaries and results in degradation of seagrass beds and their associated fauna (Arnold and Gibbons 1996; Deeley and Paling 1999; Edgar and Barrett 2000; Ralph et al. 2006). Urbanization impact is closely related to catchment impervious surface coverage (Arnold and Gibbons 1996). An index of catchment imperviousness was calculated for each grid cell by using values for

catchment impervious surface coverage and area (hectare) of subcatchments adjoining each grid cell by the following equation:

where I is imperviousness index, C is number of subcatchments adjoining a grid cell, I_i is the impervious percentage of each subcatchment adjoining a grid cell, and A_i is area (hectare) of each subcatchment adjoining a grid cell. Area (hectare) of subcatchments dedicated to different land use type (i.e., residential, commercial, industrial, rural, and sewage uses) was also selected as indicators of vulnerability.

In opposition to vulnerability, a measure of resistance (the ability to withstand human disturbances) was calculated for each grid cell. Some areas of wetlands of Brisbane Water have been set aside as National Parks and nature reserves because they are wildlife feeding and breeding habitats (Gosford City Council 1995). These areas have been given full protection from development, pollution from adjoining developments, and disturbance from recreational and other human activities. A measure of resistance was calculated for each grid cell if it was adjacent to any National Park. The area (hectare) of National Park and or nature reserves adjacent to a grid cell was selected as the indicator of resistance. Data for resistance were derived from existing sources (Gosford City Council 1995).

It is generally accepted that larger protected areas will increase the likelihood of species' persistence (Gaston et al. 2002). In terms of habitats, larger habitats are more likely to remain in a stable state (White and Bratton 1980; Pethick and Crooks 2000; Gaston et al. 2002). Thus, this study incorporated the total area of seagrass meadows within each grid cell as a factor-modifying vulnerability of seagrass meadows.

Vulnerability (V) of each grid cell containing seagrass meadows was calculated by the following equation:

$$V = \frac{IR + RE + CO + IN + RU + SE - NP}{4 + SG}$$

where IR is imperviousness index, RE is the area (hectare) of subcatchments dedicated to residential use, CO is the area (hectare) of subcatchments dedicated to commercial use, IN is the area (hectare) of subcatchments dedicated to industrial use, RU is the area (hectare) of subcatchments dedicated to rural use, SE is the area (hectare) of subcatchments dedicated to sewage use, NP is the area (hectare) of subcatchments dedicated to National Park and or nature reserves, and SG is the area (hectare) of seagrass meadows in a grid cell.

Incorporating Vulnerability into Conservation Planning

Vulnerability was incorporated into conservation planning by plotting grid cell scores for conservation value versus creation of a plot in which the Y-axis was conservation value and the X-axis was vulnerability. Using this plot, high-priority areas for conservation were selected according to the approach suggested by Margules and Pressey (2000) in which the area of plot was divided into four quadrants and priority was given to grid cells in the top right of the plot which are the areas most likely to be lost and with fewest replacements. Grid cells in the top left of the plot face lower present risk and have high irreplaceability. Grid cells in the lower right of the plot are areas vulnerable to loss but with more replacements. Grid cells in the lower left of the plot are likely to be stable and require least intervention.

Maps of conservation and vulnerability were plotted by four scenarios that differed principally according to how the variables were treated. In scenario 1, the actual values of different variables were summed and used to create a plot of conservation and vulnerability. In scenario 2, the values of different variables used to measure conservation and vulnerability were ranked and then summed before creating the plot. In scenario 3, variables were first standardized (by subtracting the mean and dividing by the standard deviation) and then summed to quantify the conservation and vulnerability of grid cells. In scenario 4, the standardized variables were first ranked and then summed before creating the plot.

Results

Biodiversity of Seagrass Macroinvertebrates

A total of 188 species of macroinvertebrates were recorded from *Z. capricorni* seagrass meadow in 31 grid cells with an average 40.0 ± 1.68 (mean $\pm$ SE species) per grid cell. The greatest number of species was recorded in grid cells 18 and 30 (56 species) and the least number of species was recorded in grid cell 34 (21 species). Assemblages consisted of molluscs (88 species), polychaetes (57 species), crustaceans (32 species), echinoderms (4 species), nematodes (2 species) and sponge, platyhelminthes, nemertean, other annelids and sipunculans (1 species each). The five species occurring in the greatest density in the study area were *Barantolla lepta* (657.9 ± 70.52) and *Capitella* sp. (446.4 ± 104.78 ; Polychaeta: Capitellidae), *Simplisetia aequisetis* (229.7 ± 64.06 ; Polychaeta: Nereididae), *Aricidea* sp. (159.9 ± 104.03 ; Polychaeta: Paronoidae), and *Spirorbidae* sp. (143.4 ± 45.43 ; Polychaeta: Spirorbidae).

Conservation Value

The average summed irreplaceability value per grid cell was 11.6 ± 0.76 with the highest value recorded in grid cell 30 (26.4) located at the lower reach of the estuary (Table 1, Fig. 2). Spatially rare species (i.e., species whose range size fell in the lower quartile of the frequency distribution of range sizes) were defined as those recorded in ≤ 2 grid cells. The average number of spatially rare species per grid cell was 7.2 ± 1.99 . The greatest number of spatially rare species (12 species) was recorded in grid cell 30. Numerically rare species had maximum abundance of ≤ 32 individuals in the estuary. The average number of numerically rare species

was 6.9 ± 2.0 per grid cell. The greatest number of numerically rare species (11 species) was recorded in grid cell 30. The average number of combined spatially and numerically rare species was 4.5 ± 0.77 per grid cell with the greatest number (20 species) recorded in grid cell 30 (Table 1, Fig. 2).

The average Shannon index value was 2.8 ± 0.06 with the greatest value recorded in grid cell 18 (3.33) located at the upper reaches of the estuary (Table 1, Fig. 2). The average Pielou's evenness value was 0.8 ± 0.01 with the greatest value recorded in grid cell 15 (0.87) located at the upper reaches of the estuary (Table 1, Fig. 2).

The average conservation value of grid cells in scenario 1 (actual values) was 19.6 ± 1.48 , with the greatest value

Table 1 Values for summed irreplaceability, total number of spatially and numerically rare species, Shannon index and Pielou's evenness measure in grid cells containing *Z. capricorni* seagrass meadow. Conservation value is the sum of the four values

Grid cell	Summed irreplaceability	Combined number of spatially and numerically rare species	Shannon index	Pielou evenness measure	Conservation value
1	5.65	0	2.77	0.79	9.21
2	7.22	2	2.63	0.71	12.56
3	11.96	7	2.11	0.60	21.67
4	13.47	2	2.94	0.79	19.2
5	11.62	6	3.14	0.80	21.56
6	13.24	4	3.19	0.86	21.29
7	11.13	3	3.01	0.77	17.91
8	10.46	1	2.89	0.74	15.09
9	10.27	3	3.00	0.86	17.13
12	14.87	4	3.04	0.80	22.71
13	18.21	9	2.74	0.70	30.65
15	8.33	0	2.96	0.87	12.16
16	4.93	0	2.64	0.74	8.31
17	10.64	5	2.77	0.72	19.13
18	13.48	1	3.34	0.83	18.65
19	13.08	4	3.11	0.78	20.97
20	9.68	5	2.88	0.78	18.34
21	10.69	7	2.47	0.76	20.92
22	5.13	1	2.50	0.70	9.33
23	9.17	4	1.78	0.54	15.49
24	11.18	5	2.23	0.64	19.05
25	7.28	1	2.74	0.77	11.79
26	12.20	4	2.91	0.81	19.92
27	9.12	0	2.55	0.74	12.41
28	11.13	4	3.17	0.82	19.12
29	17.04	14	2.61	0.68	34.33
30	26.37	20	2.60	0.64	49.61
31	11.19	2	3.03	0.79	17.01
34	9.47	4	2.23	0.73	16.43
35	13.39	7	2.88	0.84	24.11
36	17.04	10	2.80	0.79	30.63
Mean	11.57	4.48	2.76	0.75	19.57
SE	0.76	0.77	0.06	0.01	1.48

recorded in grid cell 30 (49.6) located at the lower reach of the estuary and the smallest value recorded in grid cell 16 (8.3) located at upper reach of the estuary (Table 1 and Fig. 2).

Vulnerability Score

The average imperviousness index was 0.34 ± 0.02 with highest value recorded in grid cell 9 (0.55 ± 0.02) located at the middle reach of the estuary and part of an arm of the estuary (Pelican Island, grid cell 9; Table 2 and Fig. 2). Grid cell 31 located at the seaward boundary of the estuary had the highest subcatchment area dedicated

to residential use (Table 2 and Fig. 2). Grid cell 27 located at the lower reach of the estuary had the highest subcatchment area dedicated to National Park and or nature reserve (Table 2 and Fig. 2). The highest area of *Z. capricorni* seagrass meadow occurred in grid cell 20 (30.33 ha) and was located at the middle reach of the estuary. Grid cell 35, which was the mouth of a creek (Narara Creek) entering the estuary, had the highest subcatchment area dedicated to multiple land uses including commercial, industrial, rural, and sewage uses (Table 2 and Fig. 2). Consequently, this grid cell achieved the highest score for vulnerability (3,101.93; Table 2 and Fig. 2).

Table 2 Actual values for potential indicators of vulnerability, and vulnerability score per grid cells containing *Z. capricorni* seagrass meadow

Grid cell	Imperviousness	Residential use (ha)	Commercial use (ha)	Industrial use (ha)	Rural use (ha)	Sewage (ha)	National Park (ha)	Seagrass (ha)	Vulnerability score
1	0.50	178.00	44.00	49.00	26.00	0.00	0.00	10.76	27.65
2	0.40	148.00	0.00	0.00	0.00	0.00	0.00	3.84	38.68
3	0.38	82.00	0.00	0.00	0.00	0.00	0.00	1.07	76.76
4	0.30	83.00	0.00	0.00	0.00	0.00	0.00	2.83	29.44
5	0.33	103.00	0.00	0.00	0.00	0.00	0.00	0.36	285.84
6	0.26	52.00	0.00	0.00	0.00	0.00	23.00	6.74	4.34
7	0.08	24.00	0.00	0.00	0.00	0.00	117.00	1.22	-76.13
8	0.39	407.00	22.00	0.00	0.00	0.00	43.00	1.76	218.96
9	0.55	66.00	22.00	0.00	0.00	0.00	0.00	24.66	3.59
12	0.36	118.00	0.00	0.00	0.00	0.00	15.00	8.42	12.28
13	0.35	91.00	0.00	0.00	15.00	0.00	0.00	4.03	26.37
15	0.40	104.00	0.00	0.00	0.00	0.00	0.00	0.64	162.41
16	0.31	101.00	0.00	12.00	0.00	0.00	62.00	1.02	50.51
17	0.40	74.00	0.00	0.00	0.00	0.00	0.00	1.90	39.26
18	0.34	189.00	0.00	0.00	0.00	0.00	37.00	2.95	51.57
19	0.37	165.00	0.00	0.00	0.00	0.00	36.00	14.28	9.06
20	0.46	276.00	0.00	0.00	0.00	0.00	0.00	30.33	9.12
21	0.38	157.00	0.00	0.00	0.00	0.00	12.00	11.59	12.54
22	0.18	57.00	0.00	0.00	45.00	0.00	48.00	7.73	7.01
23	0.17	36.00	0.00	0.00	71.00	0.00	0.00	7.73	13.87
24	0.19	142.00	0.00	0.00	90.00	0.00	85.00	14.57	10.10
25	0.10	39.00	0.00	0.00	54.00	0.00	93.00	8.57	0.01
26	0.46	182.00	0.00	0.00	0.00	0.00	0.00	3.92	46.60
27	0.25	104.00	0.00	0.00	0.00	0.00	126.00	3.40	-6.39
28	0.11	59.00	0.00	0.00	0.00	0.00	126.00	7.79	-8.59
29	0.46	146.00	0.00	0.00	0.00	0.00	0.00	1.95	75.23
30	0.35	180.00	0.00	0.00	0.00	0.00	92.00	1.30	67.73
31	0.46	597.00	0.00	0.00	0.00	0.00	0.00	0.41	1,454.18
34	0.31	178.00	0.00	33.00	39.00	0.00	73.00	0.07	2,383.73
35	0.46	31.00	56.00	178.00	213.00	7.00	24.00	0.15	3,101.93
36	0.33	58.00	0.00	14.00	45.00	0.00	0.00	1.70	69.15
Mean	0.34	136.35	4.65	9.23	19.29	0.23	32.65	6.05	264.41
SE	0.02	20.92	2.40	5.95	7.78	0.23	7.63	1.28	128.88

Map of Conservation Value and Vulnerability

The four data-treatment scenarios altered the relative patterns of conservation value and vulnerability among grid cells. In scenario 1 (actual values) four grid cells (13, 36, 29, and 30) in quadrant I have lower vulnerability and higher conservation value. No grid cells fell in quadrant II (high vulnerability, high conservation value). Twenty-four grid cells in quadrant III have lower vulnerability and lower conservation value. Three grid cells (31, 34, and 35) in quadrant IV are highly vulnerable to loss and have lower conservation value (Fig. 3a). Use of ranked actual values in scenario 2 led to an increase in the number of grid cells in each quadrant: eight grid cells (4, 6, 12, 13, 19, 21, 24, and 28) in quadrant I, eight grid cells (3, 5, 17, 26, 29, 30, 35, and 36) in quadrant II, eight grid cells (1, 7, 9, 20, 22, 23, 25, and 27) in quadrant III, and seven grid cells (2, 8, 15, 16, 18, 31, and 34) in quadrant IV (Fig. 3b). Scenario 3 (standardized values) led to three grid cells (6, 28, and 35) in quadrant I, 17 grid cells in quadrant II, two grid cells (22 and 25) in quadrant III, and nine grid cells (1, 2, 3, 8, 16, 23, 24, 27, and 34) in quadrant IV (Fig. 4a). Use of ranked standardized values (scenario 4) led to nine grid cells (6, 12, 19, 26, 28, 29, 31, 35, and 36) in quadrant I, seven grid cells (4, 5, 7, 9, 13, 18, and 30) in quadrant II, seven grid cells (2, 8, 21, 22, 23, 24, and 25) in quadrant III, and eight grid cells (1, 3, 15, 16, 17, 20, 27, and 34) in quadrant IV (Fig. 4b).

Discussion

Measures of Conservation and Vulnerability

In the present study, a combination of measures of species diversity, rarity, and irreplaceability were employed to quantify the conservation value of each grid cell because none of these measures alone can reflect the conservation value of each grid cell. Species diversity measures do not represent other aspects of biotic diversity (Angermeier and Karr 1986) and do not have the capability to include rarity into quantification of conservation value (Angermeier and Winston 1997). Irreplaceability does not take into account numerically rare species. Earlier studies have also proposed a suite of indices that combine species richness, density, and/or rarity into a measurement of conservation value (Winston and Angermeier 1995; Angermeier and Winston 1997; Schmera and Kiss 2004). Several authors have combined richness and rarity measures to quantify conservation value (Dony and Denholm 1985; Angermeier and Winston 1997; Schmera and Kiss 2004). Conservation value was quantified only for a single group of organisms within seagrass beds, the macroinvertebrates. Although this represents only one component of the total biodiversity of this habitat (which

also includes fish, microinvertebrates, and larger mobile invertebrates), the spatial congruency in the biodiversity of macroinvertebrates and other fauna (Edgar et al. 1999) suggests that the conclusions from this study are relevant to other groups of seagrass biota.

Attributes of subcatchments were used measure vulnerability of seagrass meadows in each grid cell, assuming the seagrass meadows were under direct or indirect influence of the adjacent subcatchments (Edgar and Barrett 2000; Gillanders and Kingsford 2002). Catchment imperviousness reflects the extent to which urban and rural areas have been developed around the Brisbane Water Estuary. Urbanization impact is closely attributed to catchment impervious surface coverage (Arnold and Gibbons 1996). The area of subcatchments dedicated to different land use type was used as indicators of vulnerability. Earlier studies have shown seagrass area loss near centers of population in Australia (Kirkman 1978; Cambridge and McComb 1984). The losses have been attributed to discharges of domestic and industrial effluent (Cambridge et al. 1986) that reduce light intensity due to sedimentation and/or increased epiphytes from nutrient enrichment (Kirkman 1997). Others factors such as sediment instability, dredging, and poor catchment management increase the human impact (Kirkman 1997).

While poor catchment management can increase human impacts on seagrass health, intact terrestrial ecosystems in the vicinity of seagrass meadows will maintain the health of seagrass meadows. Intact soil in nature reserves has a natural porosity that reduces the discharges of effluent to an estuary (Lister et al. 2004). Therefore the area of subcatchments dedicated to National Park and nature reserve was used as resistance indicator for seagrass meadows.

Vulnerability of seagrass meadows in each grid cell was quantified using data limited to subcatchments. Other potentially threatening factors (e.g., nutrient loads) were not included in the measurement of the vulnerability because data were not available at the scale of individual grid cells. Thus vulnerability of seagrass meadows in each grid cell may change if more information was incorporated into measurement of vulnerability.

Effect of Data Treatment on Conservation and Vulnerability Maps

The four quadrants in the conservation and vulnerability plots can be used to prioritize and schedule both in situ conservation measures (such as the establishment of conservation reserves) and off-reserve management (such as integrated catchment management; Margules and Pressey 2000). Grid cells in quadrant II have high conservation and vulnerability values and are therefore a priority for management actions that both conserve the site and address the activities that pose a risk to the sites' value. Grid cells in quadrant I have a high conservation value

Fig. 3 Map of conservation and vulnerability scores a based on actual values of different variables and b based on ranked values of conservation value and vulnerability scores of grid cells. Figures in the plot represent identification number of grid cells. Positions of grid cells are shown in Fig. 2

and a low vulnerability and require some form of protection to guard against possible future degradation and monitoring to detect any changes to vulnerability. Grid cells in quadrant III have low vulnerability and conservation values and are a low

Fig. 4 Map of conservation and vulnerability scores a based on standardized values of different variables and b based on ranked standardized values of conservation value and vulnerability score of grid cells. Figures in the plot represent identification number of grid cells. Positions of grid cells are shown in Fig. 2

priority for conservation action. Grid cells in quadrant IV have low conservation value but they are highly vulnerable to loss. Some form of management is required to reduce the risks to these sites as they may constitute a reservoir of replacements in the event of loss of high conservation value sites.

In the present study, major priority was given to grid cells in the top right of the plot (quadrant II). Grid cells in this quadrant have high conservation value and high vulnerability and therefore need management attention. The grid cells in this quadrant have high conservation value and, because of their high summed irreplaceability value, there are no or few replacements for their species and their loss will have the greatest impact on the achievement of conservation targets.

The four scenarios presented different spatial patterns of grid cells in the conservation and vulnerability maps. In scenario 1 that employed actual values, no grid cell fell in quadrant II. However, the results highlighted several grid cells with high conservation and vulnerability values that needed urgent protection and special management attention (Fig. 5). This suggests that the use of raw data for variables

of conservation value and vulnerability does not effectively reflect the actual distribution of values of conservation and vulnerability of grid cells.

Use of ranked actual values in scenario 2 led to expansion of grid cells in the plot. Eight grid cells (3, 5, 17, 26, 29, 30, 35, and 36) in quadrant II achieved highest priority for urgent protection and special management attention (Fig. 6). Of these grid cells, six were among the top 10 grid cells with either highest conservation or vulnerability values.

When standardized values were used, 17 grid cells in quadrant II achieved highest priority for urgent protection and special management attention (Fig. 7). Of these grid cells, seven were among the top 10 grid cells with either highest conservation or vulnerability values.

Using ranked standardized values, seven grid cells (4, 5, 7, 9, 13, 18, and 30) in quadrant II achieved highest priority

Fig. 5 Map of priority areas depicted by actual values of conservation value and vulnerability score for allocation of appropriate protection and/or management measures

Fig. 6 Map of priority areas depicted by ranked actual values of conservation value and vulnerability score for allocation of appropriate protection and/or management measures

for urgent protection and special management attention (Fig. 8). Of these grid cells, three were only among the top 10 grid cells with either highest conservation or vulnerability values. This suggests that this type of data treatment (i.e., ranking standardized data) would not improve the efficacy of conservation and vulnerability maps to reflect the true need of areas for either urgent protection or management attention.

The effects of different methods of data treatment can be appreciated by looking at the number of grid cells that were prioritized to be given both protection and management attention (grid cells in quadrant II). Grid cell 35 (Narara Creek) with the fifth highest conservation value (Table 1) and highest vulnerability (Table 2) score requires both urgent protection and special management attention. This creek is at risk due to the range of human uses currently occurring along its banks and within its catchments

(Gosford City Council 1995; Thomson 2007). Narara Creek also had high conservation value because its species were not widely distributed in the estuary (reflected in its high summed irreplaceability). When ranked values of both conservation and vulnerability were employed to map conservation and vulnerability, Narara Creek was among the five top grid cells that were selected to be given both urgent protection and special management attention (Fig. 6). However, none of other methods of data treatment highlighted Narara Creek to be given both urgent protection and special management attention. For example, when actual values of conservation and vulnerability were used, Narara Creek was highlighted as an area to be given only special management attention (Fig. 5). Using standardized and ranked standardized values, Narara Creek was only given priority for urgent protection (Figs. 7 and 8). This suggests that maps of conservation and vulnerability will better reflect the relative

Fig. 7 Map of priority areas depicted by standardized values of conservation value and vulnerability score for allocation of appropriate protection and/or management measures

importance of sites when they are developed from ranked values of measured variables.

The effects of different methods of data treatment can be further evaluated by looking at the number of grid cells that are prioritized to be given only management attention (grid cells in quadrant IV). The ranked values scenario again outperformed other data treatment methods by including a higher number of grid cells that were among the top 10 grid cells with highest vulnerability values. Another difference (shown in Figs. 5 and 6) is that use of ranked scores (Fig. 6) resulted in fewer grid cells requiring no attention. All the above comparisons suggest that ranking values of conservation and vulnerability is the best data treatment strategy to reflect the true relative values of areas in conservation and vulnerability maps.

The preference for using ranked conservation and vulnerability values arises from the nature of the measures used

to construct each value. Conservation value and vulnerability are based on different parameters that are quantified with different units and different scales (rather than on assigned scores). The outcome of using a graphical approach to plot the combination of conservation and vulnerability values, where the division into quadrants is based on the midpoint of each axis, was that the distribution was affected by a very few grid cells with high values for both that effectively restricted all other grid cells to the lower left quadrant (low conservation value, low vulnerability). Ranking of conservation and vulnerability values restricted each to the same scale (with a maximum set by the number of grid cells) and resulted in a greater dispersion of values across the four quadrants. Ranking is therefore likely to be applicable to other ecosystems where the same or different measures of conservation value and vulnerability are used.

Fig. 8 Map of priority areas depicted by ranked standardized values of conservation value and vulnerability score for allocation of appropriate protection and/or management measures

Protection and Management Implications

The map created using ranked values in scenario 2 (Fig. 6) was used for further suggestions for allocation of protection and/or management planning. Seagrass meadows in eight grid cells (4, 6, 12, 13, 19, 21, 24, and 28) achieved priority for urgent protection because they had high conservation value. These grid cells were located in the upper reaches of the estuary (grid cells 4, 6, 12, and 13), the middle reach of the estuary (grid cells 19 and 21), an arm of the middle reach of the estuary (grid cell 24) and at the lower reach of the estuary (grid cell 28; Fig. 6).

Seagrass meadows in eight grid cells (3, 5, 17, 26, 29, 30, 35, and 36) have a high vulnerability and high conservation value because of their high irreplaceability values. The seagrass in these grid cells require urgent protection by establishing estuarine-protected areas and

also require special management attention. These grid cells were located at upper reach of the estuary (grid cells 3, 5, and 17), the middle reach of the estuary (grid cell 26), the lower reach of the estuary (grid cells 29 and 30) and two creeks entering the estuary (grid cells 35 and 36; Fig. 6). The Narara Creek (grid cell 35) catchment represents the largest proportion of pollutant load delivered to Brisbane Water that is a function of both its proportionally larger subcatchment area, as well as very large areas dedicated to industrial, commercial, rural and sewage uses (Thomson 2007). The Kincumber Creek (grid cell 36) catchment also has a high pollutant intensity of the major subcatchments within Brisbane Water because of the mixture of industrial and residential land-uses in this area (Walker et al. 2005).

Seagrass meadows in eight grid cells (1, 7, 9, 20, 22, 23, 25, and 27) are likely to be stable because they face lower risk.

They also have low conservation value because of their low irreplacability indicating that their features are relatively common in the estuary. Accordingly, seagrass meadows in these grid cells are not in need of urgent protection and/or special management attention indicating that further development in their catchments is allowed provided that constant monitoring is maintained. These grid cells were located at the upper reach of the estuary (grid cell 1), in two opposite arms of the middle reach of the estuary (grid cells 7, 22, 23, and 25), the middle reach of the estuary (grid cells 9 and 20) and at the lower reach of the estuary (grid cell 27; Fig. 6).

Seagrass meadows in seven grid cells (2, 8, 15, 16, 18, 31, and 34) are highly vulnerable to loss but with lower conservation value. Thus, they only need special management attention to minimize the risk. These grid cells were located at upper reach of the estuary (grid cells 2, 15, 16, and 18), in an arm of the middle reach of the estuary (grid cell 8), a creek entering the estuary (grid cell 34), and at the seaward boundary of the estuary (grid cell 31; Fig. 6). Grid cell 31 had the highest subcatchment area dedicated to residential use and the Erina Creek subcatchment (grid cell 34), delivers approximately half the pollutant load of the Narara Creek catchment (Thomson 2007).

Conclusion

The results of the present study revealed that conservation of estuarine seagrass meadows must be based on the objective of maintaining the existing conservation value of areas containing *Z. capricorni* seagrass and managing human uses to minimize changes to features underlying this value (species biodiversity and persistence of macroinvertebrates). The present study used a selection of measures to quantify conservation value and vulnerability and tested the effects of a range of data treatments on the conservation planning outcomes. We showed that the outcomes of an approach that integrates vulnerability into estuarine conservation planning were sensitive to the data treatment. This finding indicates that an explicit justification is required for the selection of attributes used to quantify conservation value and vulnerability.

The present study focused on a single type of estuarine habitat, namely seagrass (i.e., eelgrass) beds. Given the significance of seagrass beds to total estuarine biodiversity, their widespread distribution throughout estuaries, and their susceptibility to anthropogenic disturbance, it is likely that the outcomes of this study are applicable to comprehensive spatial planning exercises in estuaries that include all habitats.

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