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An integrated environmental assessment of the Red Sea coast of Saudi Arabia

ANDREW R.G. PRICE[1]*, GUY JOBBINS[1], ALEC R. DAWSON SHEPHERD[2] AND RUPERT F.G. ORMOND[2]

[1]*Ecosystems Analysis and Management Group, Department of Biological Sciences, University of Warwick, Coventry 4 7AL, UK,* [2]*Tropical Marine Research Unit, Department of Biology, University of York, York Y01 5DD, UK*

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Summary

The Red Sea is a large marine ecosystem in which biological research has been considerable but integrated environmental assessment insubstantial. Approximately 1400 coastal and offshore (i.e. island) sites in the Saudi Arabian Red Sea were examined and an analysis of ordinal data on the abundance of ecosystems and magnitude of human uses/environmental impacts was conducted. Mangroves, seagrasses, other floral groups and terrestrial mammals were significantly more abundant at the coastal sites than offshore. The coastal sites were also impacted most heavily,while reefs, birds, turtles and marine mammals were significantly more abundant in offshore areas. Latitudinal trends include significantly increased abundance of mangroves and seagrasses (and other flora) towards the southern Red Sea, and a decrease in abundance of reefs. Significantly higher levels of beach oil were encountered towards the northern Red Sea, probably reflecting its greater proximity to the Gulf of Suez. Cluster analysis using all biological data revealed distinctive groupings which separated according to latitude. The biogeographic patterns are comparable to those observed in previous studies for seagrasses and other communities.

Using a relational database, applications of the findings to coastal management include creation of environmental profiles for particular sites or sectors, identification of resource-use conflict areas, and selection of representative sites for protected areas. Comparison with data from a complementary investigation in the Arabian Gulf indicates that the Red Sea is less perturbed by human activities than the Arabian Gulf. However, it is also evident that the Red Sea is no longer a pristine environment.

Keywords: ecosystems, impacts, Red Sea, Saudi Arabia, environmental assessment

Introduction

Studies in the Red Sea have examined the ecology of coral reefs, mangroves, seagrasses and other ecosystems (reviews by Edwards & Head 1987; Sheppard *et al*. 1992). Assessments have also been made of environmental pressures and coastal management requirements, mostly in the form of regional reviews (Sheppard *et al*. 1992; Halim *et al*. 1998). However, integrated environmental understanding of this large marine ecosystem (LME; Sherman 1994) is more limited.

In Saudi Arabia, the importance of coastal resources of both the Red Sea and Arabian Gulf for socioeconomic development is becoming increasinglyrecognized (IUCN/MEPA [World Conservation Union/Meteorology & Environmental Protection Agency] 1987*a*, *b*, *c*; Sheppard *et al*. 1992). However, it is recognized that there are limits to resource exploitation, a principle also embedded in Islam (Child & Grainger 1990). Within this context, development is guided by national development plans and various environmental agreements (Price 1996). Upholding these commitments is particularly important in the Red Sea, where trans-boundary resources constitute a 'regional commons' shared by nine countries and utilized by many others.

Environmental assessments can be undertaken at a range of intensities and scales. These span from those based on high resolution quantitative data of generally-limited spatial coverage, to those derived from lower resolution data (e.g. ranked/ordinal or binary) which would generally be collected over larger areas, including entire oceans. The present study is a broad-scale assessment of the Red Sea, based on collection and analysis of ranked/ordinal environmental data.

The main aims of the study were (1) to examine variations in the Red Sea's natural systems over large spatial scales, infer possible determinants of the patterns found, and make biogeographic comparisons with previous studies on selected ecosystems and species; and (2) to provide a mechanism for identifying resource-use conflicts, as an indication of where targeted management interventions, such as protected areas, might be most beneficial. The survey formed part of a major coastal-resource appraisal of the Saudi Arabian Red Sea coast (IUCN 1984*a*, *b*, 1985*a*, *b;* Al-Gain *et al.* 1987; IUCN/MEPA 1987*a*, *b*).

Methods

Environmental setting and study area

Compared with the Indian Ocean, environmental conditions of the Red Sea are more extreme, but less so than in the Arabian Gulf (Sheppard *et al*. 1992); thus surface salinity is

*Correspondence: Dr Andrew Price Tel: +44 1203 524457 Fax: +44 1203 524619 e-mail: argp@oikos.warwick.ac.uk

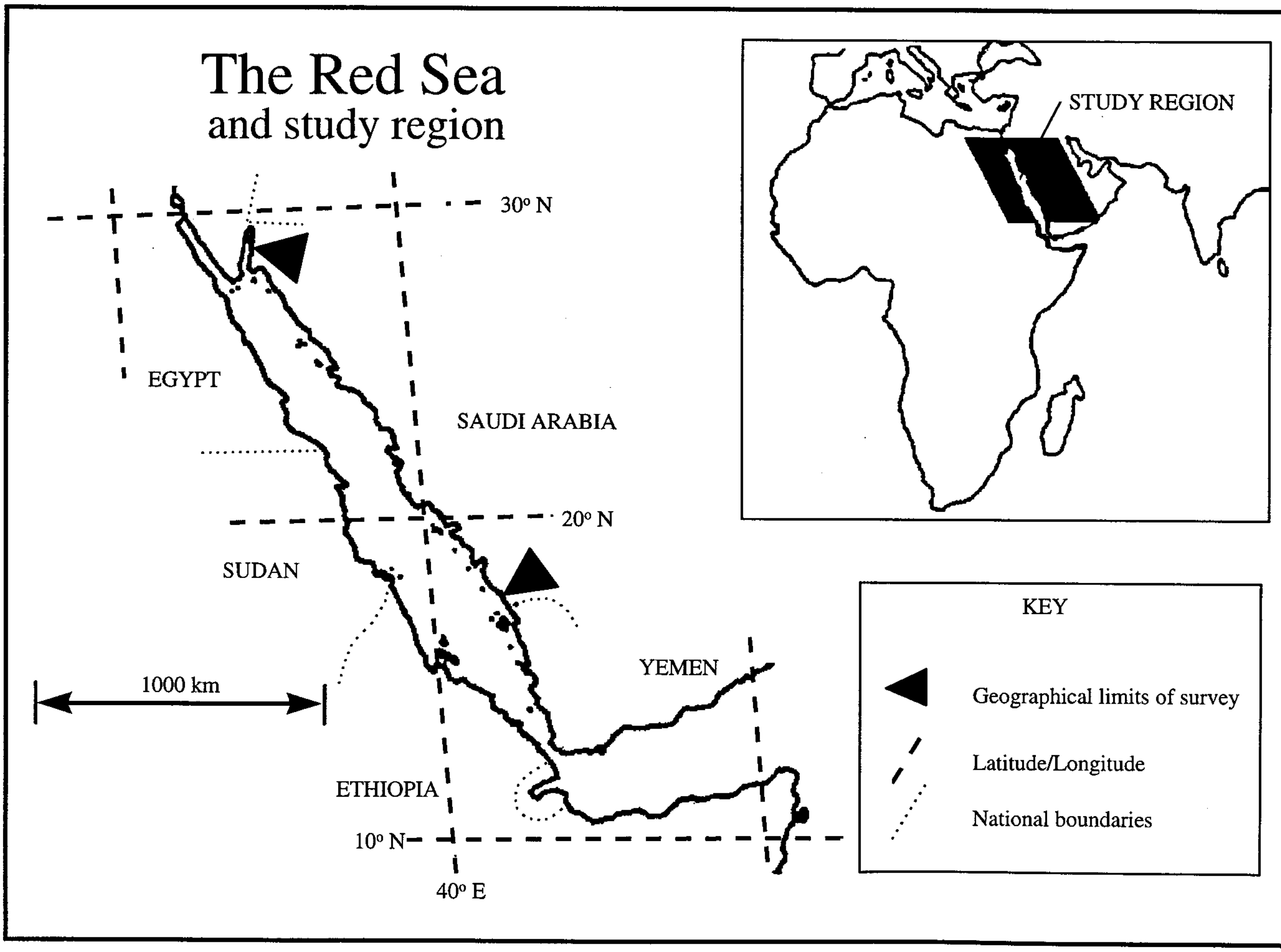

Figure 1 Map of Saudi Arabian Red Sea showing extent of the study area.

generally high, increasing from 36–37 ‰ in the Gulf of Aden to *c*. 41 ‰ in the northern Red Sea, while mean annual sea-surface temperature increases from 22°C in the north to a maximum of 28°C in the south, but seasonal changes are greater in the north.

A wide range of intertidal and offshore ecosystems are represented in the Red Sea. Coral reefs attain greatest diversity in the central part, whereas soft-bottom communities are best developed in southern regions. These include *sharm* (shallow bays) and *mersa* (lagoons), which probably represent extinct estuarinal or *wadi* (river gulley) outwash areas (IUCN 1984*a*; Al-Gain *et al*. 1987). Many bays are colonized by mangroves

Table 1 Ecosystems, species groups, uses and impacts examined at coastal and offshore/island sites along the Saudi Arabian Red Sea coast. [a] Counts of empty nesting pits were included in estimates of turtle breeding, since information on nesting locations as well as seasons is important for management.

Ecosystems/Species *Flora*	*Fauna*	*Human uses/Impacts*
Seagrasses	Reefs/corals	Oil
Algae	Birds	Human litter (plastics, metals, other solid waste & pollution)
Halophytes	Turtles [a]	Driftwood and wood litter
Mangroves	Mammals	Construction/development
Freshwater vegetation	Fish	Fishing
	Invertebrates	

Table 2 Original semi-logarithmic ordinal scale of 0–6 used for estimates of abundance of coastal ecosystems (flora and reefs; areal extent) and species groups (fauna; no. of individuals) during survey of Red Sea. A 0–6 scale was also used as a relative measure of the magnitude of fishing and construction (0: none, 6: greatest); the magnitude of oil, other uses/impacts and driftwood was estimated in the field using a 0–10 scale (see also Methods and Table 3 for further details).

Ranked abundance/ magnitude score (semi-log scale)	*Areal extent (m^2) or No. of individuals (equivalent arithmetic range)*	*Geometric mean*
0	0	0
1	1–9	3
2	10–99	31
3	100–999	316
4	1000–29 999	5477
5	30 000–99 999	54 772
6	100 000 +	–

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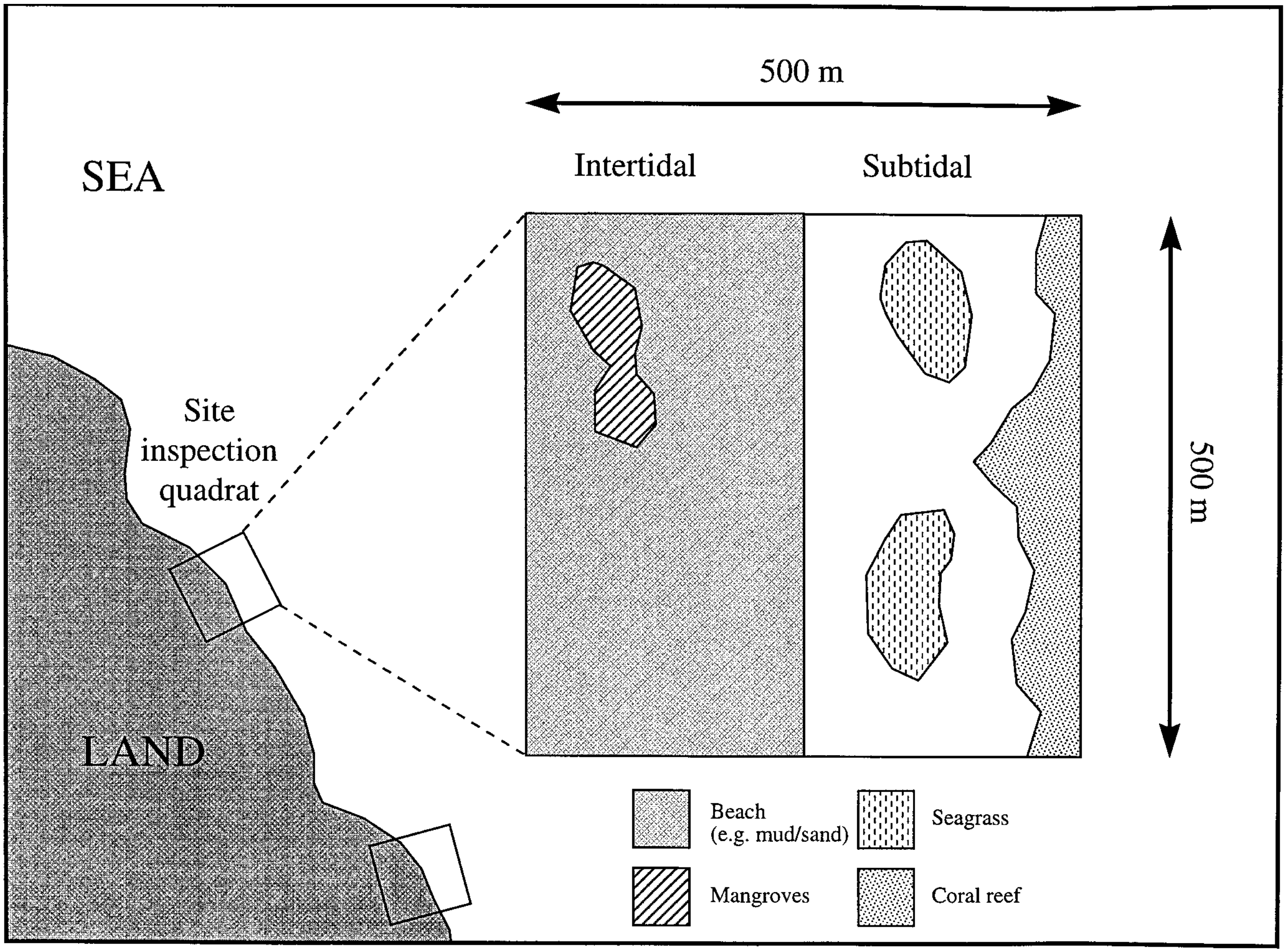

Figure 2 Schematic diagram showing configuration and dimensions of the 'site inspection quadrats' used in environmental assessment of the Saudi Arabian Red Sea coast. At each site, estimates were made of the abundance of key ecosystems, species groups and human uses/environmental impacts, within 250 000 m^2 (i.e., 500 m × 500 m; see also Methods).

Table 3 Modified, logarithmic ordinal scale of 0–6 used for abundance of coastal ecosystems (flora and reefs; areal extent) and species groups (fauna; no. of invididuals). The same scale was also used as a relative measure of the magnitude of fishing and construction (0: none, 6: greatest), and of oil, other uses/impacts and driftwood following transformation from a 0–10 scale. Abundance values of 4 and 5 in the original, semi-logarithmic scale (Table 2) did not need to be transformed, since their geometric means fall within their respective arithmetic ranges of the fully-logarithmic scale (see also Methods and Table 2 for further details).

Ranked abundance/ magnitude score (log scale)	*Areal extent (m^2) or No. of individuals (equivalent arithmetic range)*	*Geometric mean*
0	0	0
1	1–9	3
2	10–99	31
3	100–999	316
4	1000–9999	3162
5	10 000–99 999	31 663
6	100 000 +	–

and seagrasses. These systems are often highly productive, supporting large populations of birds, young fish and shrimp, and are of conservation importance. However, since bays are natural harbours, easy to infill and develop, they are also targets for urban and industrial development. Although the Red Sea coast of Saudi Arabia is less developed than the Gulf, large-scale construction has occurred in Yanbu, Jeddah, Sharm Obhur and Jizan as well as some other areas (IUCN/MEPA 1987*a*, *b*). Reviews of the ecology and environmental conditions of the Red Sea are available (e.g. Bemert & Ormond 1981; IUCN/UNEP 1985; Edwards & Head 1987; Price *et al*. 1988; Sheppard *et al*. 1992).

The survey area extended 1840 km along the Saudi Arabian coast from Haql near the Jordanian border to south of Oreste Point near the border with Yemen (Fig. 1). Observations were undertaken at *c*. 1400 mainland and offshore (i.e. island) sites between 1982 and 1984.

Survey approach and methodology

Unpublished accounts of the methodology are already available (IUCN 1984*a*, 1985*a*; IUCN/MEPA 1987*a*; Jobbins

1996), while published works include details of the original methodology, preliminary findings (Dawson Shepherd & Ormond 1987), and analysis of seagrass communities (Price *et al*. 1988).

Observations were made within geographically-discrete 'site inspection quadrats' distributed at intervals of *c*. 10 km along the mainland coast and on offshore islands. Each coastal site comprised a quadrat *c*. 500 m × 500 m bisecting the beach, extending 250 m up the shore and 250 m down into the subtidal zone (Fig. 2); the latter was examined while snorkelling. Within each quadrat, the abundance of ecosystems and species groups, and magnitude of uses and impacts (Table 1), were estimated and recorded (see below). Physical features recorded included details of the shore profile, substratum type, surface temperature and salinity, the latter using a hand-held refractometer. In addition, qualitative notes on the environment were made.

Ecosystems, flora and fauna

A scale of 0–6 (Table 2) was used for field estimates of the abundance of ecosystems and species groups. In the case of flora (and reefs), scores are based on estimates of areal extent (m^2), while for fauna they are based on the estimated number of individuals, both within each 250 000 m^2 (500 m × 500 m) sample area. For assessment of both flora and fauna, the scale used was semi-logarithmic, but the data were subsequently tranformed to fully logarithmic data (see below).

Human uses and impacts

A scale of 0–6 (Table 2) was also used to assess the magnitude of fishing, construction or development (e.g., ports, jetties). For oil, other impacts and driftwood, a scale of finer resolution (0–10) was adopted during the surveys and the data subsequently transformed to a scale of 0–6 (see below). Recorded scores simply represent the estimated relative magnitude of each use or impact (where 0 indicates no impact and 6 or 10 indicates the greatest impact). In instances where attributes were not, or could not be, quantified, a binary scale was used, namely either '0' (absent) or '+' (present).

Data transformations

The rapid assessment technique developed in the Red Sea (this study) has also been adopted in subsequent surveys, in particular in the Arabian Gulf (Price 1990; Price & Coles 1992; Price *et al*. 1993*a*). However, in these later studies, two changes have been made to the methodology, namely (1) a fully-logarithmic scale (Table 3) replaced the original semi-logarithmic scale (Table 2) and (2) a 0–6 scale was used instead of a 0–10 scale for estimates of the relative magnitude of oil, other impacts and driftwood. Hence a 0–6 scale was used for all attributes in the Arabian Gulf work (ecosystems and uses/impacts; Table 3). These modifications were made to ensure complementarity between the scales of biological and use/impact data, and thereby facilitated statistical analysis.

In accordance with the modifications described above, data transformations were made *post-hoc* to the floral and faunal abundance scores of 4 and 5 recorded during the present Red Sea coastal assessment (Tables 2 and 3) as described below. Similarly, the original 0–10 scale for field estimates of the relative magnitude of oil, other impacts and driftwood were transformed to a 0–6 scale. This ensured greater internal conformity of data and enhanced comparability with data from subsequent coastal surveys using the modified methodology (see above). In some instances, it was also possible to transform presence/absence data for several categories to ranked data and otherwise modify the data, thereby increasing the size of the quantitative data set, in the ways summarized below (further details in Jobbins 1996).

(1) The original use/impact scale (0–10) was transformed to the modified (0–6) scale by multiplying values by 0.6 and rounding to the nearest integer.

(2) Construction/development, at sites where it was not recorded quantitatively but merely in qualitative terms, was converted to a quantitative index using the same values given for similar developments elsewhere in the dataset (i.e. at other sites) as follows: presence of wall, grave or post = 1; shack, hut, jetty or house = 2; coastguard station, road or minor sand-fill = 3; corniche (large coastal road, usually in-fill) = 4; industrial/desalination plant = 5; and town or major port = 6. To give an example, the textual entry at some sites for construction/development was 'desalination plant', but recorded only as present; the record was subsequently transformed to a value of 5, since at other sites a quantitative score of 5 was given for a desalination plant.

(3) At a few sites where there were no, or incomplete, records for construction/development, estimates were taken from information recorded during a complementary survey of coral reefs, based on REEFWATCH, at the same locations (see Roberts *et al*. 1988). Under this scheme, a ranked qualitative scale using five categories was used to assess the magnitude of construction/development. These qualitative categories, together with the numerical value judged as appropriate for use in the present data set, are as follows: no construction or development = 0; possible/little = 1; definite/some = 2; moderate = 3; and extensive/severe = 5. Since there are only four categories of construction/development (the fifth being no construction/development), the categories did not fall directly within a scale of 0–6. Assigning moderate construction or development a value of 3 (rather than 4) and extensive/severe construction or development a value of 5 (rather than 6) was therefore somewhat arbitrary, but also based on the frequency distribution of construction/development values (0–6) actually recorded in the present survey (Jobbins 1996).

(4) Where possible, presence records for fishing were converted to quantitative indices by summing the lengths of

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boats and nets recorded to give a yardstick of fishing effort, and simply ranking the data uniformly into a 0–6 scale (where 0 indicates no boats or nets, and 6 indicates the maximum value of lengths of boats + nets recorded during the survey).

(5) Coral reefs, where indicated as present, could be converted to a quantitative value in some instances by assigning an abundance estimate to commonly-used textual descriptions, as follows: 'well-defined' and 'moderately-defined fringing reefs' = 4, and 'poorly-defined fringing reefs' = 3. In other instances coral reef abundance was already recorded quantitatively, or could not be converted from presence data.

(6) No abundance values of 4 (1000–29 999) and 5 (30 000–99 999) in the original semi-logarithmic scale (Table 2) needed to be transformed, since their geometric means (5477 & 54 772) fell within their respective arithmetic ranges of the fully-logarithmic scale (1000–9999 and 10 000–99 999; Table 3). This assumes reasonably that, within any rank, values were log/semi-logarithmic and normally distributed about the geometric mean of the range.

(7) Overall abundance values of ecosystems/species groups, when not indicated in the original data, were estimated by summing the geometric means of the ranks given for individual species, if these were given; otherwise, the 'presence' designation was retained. An estimate could then be made of overall log abundance. For example, at one site (reference code SAMM12F15) the recorded 0–6 scale abundances of algal taxa were 4 (1000–29 999), 3 (100–999) and 4 (1000–29 999). The summed geometric means were 316 + (2 × 5477) = 11 270. This falls within the range of rank 4 (1000–9 999) on the logarithmic scale, which could then be assigned as the overall algal abundance value.

Appendix 1 summarizes the data quality, in terms of the extent of binary data and of quantitative data following the transformations/extrapolations made. In total, 14.6% of data entries were transformed. While records for some attributes have had minimal transformation (e.g. mangroves, halophytes, freshwater vegetation), records for others underwent more extensive modification (e.g. algae, invertebrates, fishing). Full details of which data were transformed, and on the nature of the transformations, are given by Jobbins (1996).

Database and data analysis

A relational database was created using Microsoft Access, to facilitate data storage, access, manipulation and analysis. 'Average' abundance values (ecosystems, species groups) and magnitude values (human uses/impacts) were expressed by the median, as the data were ordinal. For comparison between two groups (e.g, coastal versus offshore) the Mann-Whitney *U*-test was used. Scores for the two groups were ranked together, and *z* values computed from *U* (corrected for ties), since $n > 20$ (Siegel 1956). The degree of association between two variables was determined using Spearman's rank correlation coefficient (R_s) corrected for ties. Because of the relatively large number of variables tested in some datasets, the level of statistical significance was set at $p \leq 0.01$, to help avoid the occurrence of Type I errors (Siegel 1956; Price 1990; Brown & Rothery 1993).

Multivariate procedures were used to determine structure and patterns in the biological data and included factor analysis and cluster analysis. The latter, although not a statistical test, is a valuable interpretive tool. It was used here to compare, separate and classify sites into groupings according to the environmental attributes recorded at each site. The Bray Curtis similarity coefficient was used for this purpose, and is the most commonly-adopted quantitative index (Sheppard 1987). The weighted pair group average method was used for clustering (Sheppard *et al.* 1995). The resulting dendrogram graphically depicts groupings of the different sites and their affinities with each other. Factor analysis was used to help resolve complex environmental relationships into the interaction of fewer and simpler factors. It aims to express covariation in terms of *k* underlying factors that explain a large part of the variance and covariance of the original variables, *v*, where $k < v$ (Sokal & Rohlf 1995). Statsoft (1991) provides a full description of the methodology and was used for the analysis.

By interrogating the database it was possible to identify and list all sites with particular ecosystems and/or species groups at specified abundance values (0–6). Similarly, sites

Table 4 Prevalence (% occurrence) of ecosystems, species groups, uses and impacts at coastal mainland and offshore sites in the Saudi Arabian Red Sea.

	Occurrence (%):		
Attribute	*Mainland*	*Offshore*	*Combined*
Ecosystems and species			
Mangroves	32.3	19.5	28.9
Seagrasses	63.6	22.8	51.8
Halophytes	80.8	55.6	73.5
Algae	77.3	68.8	74.9
Freshwater vegetation	13.4	5.4	11.1
Reefs	56.6	81.3	53.6
Birds	45.3	57.5	48.8
Bird nesting	2.1	32.9	10.7
Turtles	2.2	18.0	6.7
Turtle nesting	1.9	25.3	8.5
Terrestrial mammals	19.1	0.7	13.9
Marine mammals	1.2	9.4	3.5
Fish	80.1	92.9	84.5
Invertebrates	88.6	78.9	85.3
Uses/impacts			
Construction	27.0	12.7	22.9
Fishing	38.6	39.8	39.0
Beach oil	46.2	43.5	45.3
Human litter	73.7	52.9	67.6
Wood litter	69.2	48.3	62.7

associated with human uses/impacts of a specified magnitude (0–6) were identified.

Results

The prevalence of different ecosystems, species groups and human uses/impacts examined is shown in Table 4 for coastal and offshore sites. This is based on the percent occurrence of each biological and physical attribute, and provides a broad-scale, qualitative assessment of the state of the environment. All floral groups were more prevalent at the coastal sites than offshore, as were invertebrates and terrestrial mammals. In contrast, reefs, birds, turtles and marine mammals were more prevalent in offshore areas than at the coast (Table 4). Except for fishing, all human uses/impacts were more common on the coastal sites than offshore (Table 4).

Summary data for the abundance of different ecosystems/species groups, and for the magnitude of different uses/impacts, are shown in Appendix 2. Coastal versus offshore patterns based on quantitative (abundance and magnitude) data are similar to those derived from prevalence (% occurrence) data above. Despite the high occurrence of '0' as the median value, differences between coastal and offshore sites were statistically highly-significant based on the Mann-Whitney *U*-test (Table 5). Tables 5, 6 and 7 (see below) and Appendix 2 are data summaries and provide a semi-quantitative assessment of the overall state of the environment of the Saudi Arabian Red Sea for the period of the surveys (1982–84).

Latitudinal trends and biogeographic patterns

Univariate analyses

The abundance of most ecosystems and species groups increased significantly towards the southern Red Sea, with only reefs and turtle nesting (coastal sites only) showing greater abundance to the north (Table 6). Fish were significantly more abundant towards the south at coastal sites, but the reverse pattern was evident for the offshore sites. Of the human uses and impacts recorded, the magnitude of beach oil was greater in the north, whereas wood litter showed the opposite trend (Table 6). Latitudinal correlations with other uses and impacts were not significant.

Multivariate analyses

Factor analysis indicated two factors with eigenvalues greater than two, namely latitude and mainland versus offshore, which jointly accounted for *c*. 33% of the variance in the data (Table 8).

For cluster analysis, ecosystem and species abundance data from the coastal and offshore sites were pooled using median values for each degree of latitude (Table 7). At a similarity level of 0.43, three groups (I–III) were identified by latitudinal band (Fig. 3). Group I was composed of all northern sites (26–29°N) plus latitude 21°N sites; Group II sites fell within central latitudes (20°N, 22–25°N), and Group III comprised southern Red Sea sites (16–19°N). The environmental diagnostics of each group are shown in Table 9. Group I sites appear to be the most impacted, and Group II sites the least.

Table 5 Comparison of abundance/magnitude values for ecosystems, species groups, uses and impacts at coastal and offshore sites in the Saudi Arabian Red Sea using the Mann-Whitney *U*-test. n = number of observations; *p* = level of significance; NS = not significant.

Attribute	*Mainland:* *Median*	*n*	*Offshore:* *Median*	*n*	*p-level for adjusted z*	*Combined (mainland/offshore): Median*	*n*
Ecosystems and species							
Mangrove	0	689	0	280	<0.001	0	969
Seagrasses	3	632	0	254	<0.001	0	886
Halophytes	3	661	0	202	<0.001	2	863
Algae	3	415	0	125	<0.001	3	540
Freshwater vegetation	0	641	0	264	<0.001	0	904
Reefs	2	627	4	241	<0.001	3	868
Birds	0	629	1	235	<0.001	0	864
Bird nesting	0	657	0	247	<0.001	0	904
Turtles	0	683	0	252	<0.001	0	935
Turtle nesting	0	671	0	226	<0.001	0	897
Terrestrial mammals	0	591	0	274	<0.001	0	865
Marine mammals	0	685	0	275	<0.001	0	960
Fish	1	139	2.5	32	NS	1	171
Invertebrates	5	249	0	69	<0.001	4	318
Uses/impacts							
Construction	0	677	0	269	<0.001	0	946
Fishing	0	617	0	249	NS	0	866
Beach oil	0	477	0	209	NS	0	686
Human litter	1	467	0	199	<0.001	1	666
Wood litter	1	435	0	201	<0.01	1	636

Table 6 Correlations between latitude and abundance/magnitude of ecosystems, species groups, uses and impacts in the Saudi Arabian Red Sea using the Spearman's rank correlation coefficient (R_s); p = level of significance; NS = not significant.

	Mainland sites:		*Mainland and offshore (island) sites combined:*	
Attribute	R_s	p	R_s	p
Ecosystems and species				
Mangrove	−0.44	<0.001	−0.26	<0.001
Seagrasses	−0.14	<0.001	−0.01	NS
Halophytes	−0.03	NS	0.08	NS
Algae	−0.53	<0.001	−0.46	<0.001
Freshwater vegetation	0.01	NS	0.03	NS
Reef	0.41	<0.001	0.29	<0.001
Birds	−0.58	<0.001	−0.48	<0.001
Bird nesting	−0.07	NS	−0.13	<0.001
Turtles	−0.13	<0.001	−0.14	<0.001
Turtle nesting	0.12	<0.001	0.07	NS
Terrestrial mammals	−0.27	<0.001	−0.2	<0.001
Marine mammals	−0.12	<0.001	−0.19	<0.001
Fish	−0.28	<0.001	0.4	<0.001
Invertebrates	−0.74	<0.001	−0.74	<0.001
Uses/impacts				
Construction	0.02	NS	0.04	NS
Fishing	−0.07	NS	−0.07	NS
Beach oil	0.28	<0.001	0.24	<0.001
Human litter	−0.08	NS	−0.05	NS
Wood litter	−0.13	<0.01	−0.1	<0.01

Identification of resource-use conflicts

The database which we have set up can be interrogated to define the principal environmental features of a site or region. Of particular significance are the locations of areas where biological resources did and did not overlap with resource-uses/impacts. Overlapping areas denote locations of actual or potential conflicts, where management may be needed urgently. Non-overlapping areas signify resource-use compatibilities, and hence locations where there may be openings for further resource use and coastal development.

A simple illustration of this application is given in Table 10, which lists all sites associated with high coral abundance (value >3), intensive levels of construction (>4) and/or high levels of beach oil (>4). All of the 24 sites listed are in the central or northern Red Sea (18–26°N), and most are in the vicinity of Jeddah (21°N; Table 10). The listing of sites may be underestimated due to the high occurrence of zero records for beach oil. More complex assessments can be made and specifications set (for example, resource abundance and use/impact magnitude) at the level of sensitivity required by the manager. More generally, the database can be used to generate a snapshot of environmental conditions in a particular area, for example as a precursor to a more comprehensive environmental assessment.

Table 7 Median values of biological data for all sites grouped by latitude for use in cluster analysis. [a] Attributes shown here, but data not used in cluster analysis due to occurrence of median values of zero for all latitudes.

	Median values by latitude (°N):													
Attribute	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*
Mangrove	2.5	0	0	1	0	0	0	0	0	0	0	0	0	0
Seagrasses	4	0	0	0	2	0	3	3	2	3	2	1	1	2
Halophytes	0	0	0	3	3	1	3	3	2	3	2	1	1	3
Algae	5	4	4	2.5	0	4	3	3	0	0	0	0	0	2
Freshwater vegetation [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reefs	0	0	3	3	0	4	2	0	3	3	4	4	4	4
Birds	2	2	2	1	1	0	0	0	0	0	0	1	0	0
Bird nesting [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turtles [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turtles nesting [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Terrestrial mammals [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marine mammals [a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fish	3	2	1	1	1	0	0	0	0	0	2	2	1.5	–
Invertebrates	6	6	6	5	2.5	1	2.5	1	0	3	0	0	0	2

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Table 8 Results of factor analysis of biological data from Saudi Arabian Red Sea, to determine the sources of a large part of the variance and covariance of the original variables (see Table 1 and Appendix 2).

Variable	*Mainland*	*Latitude*
Communality	1	1
Factor	1	2
Eigenvalue	2.21255	2.01961
% of variance explained	17	15.5
Cumulative % of variance explained	17	32.6

Discussion

The relative merits and shortcomings of rapid coastal assessment and fully quantitative techniques have been reviewed extensively (e.g. Dawson Shepherd & Ormond 1987; Price 1990; Price *et al*. 1988, 1993*a*; Price & Firaq 1996). Inevitably, there are trade-offs between low-resolution data collected from many sites using low-cost methodologies, and higher-resolution data from fewer sites which have generally involved more costly methodologies. A combination of approaches may be required, depending on the precise assessment objectives, funding and logistical constraints. In the present context, the rapid assessment procedure adopted is seen as appropriate for broad-scale assessment (*c*. 2000 km) of coastal systems. The study also provided extensive baseline data as a foundation for assessing coastal environmental change.

Transformations were made to 14.6% of the data entries, resulting in a more extensive quantitative dataset. This facilitated statistical analysis, and allowed more direct comparison between the Red Sea and other regions assessed using the (slightly modified) methodology described. Use of an extensive dataset is particularly important when cluster analysis using quantitative indices (e.g., Bray Curtis) is performed. If a value for a single attribute is not recorded, the entire row (i.e., site) is omitted from the cluster analysis. Hence, if missing data records are all or mostly from different sites, a substantial loss of data and geographical coverage can result, thus rendering the cluster analysis unrepresentative. The benefits of an extensive dataset are considered to more than outweigh possible bias introduced into the dataset from data transformations or extrapolations. An example of possible bias is the use of data on construction/development collected during a complementary assessment of coral reefs using REEFWATCH at the same locations examined in the present study. REEFWATCH distinguished five categories of intensity of construction/development, from which the data were adopted for the present study which utilized a seven-point scale (0–6). Fishing effort was particularly difficult to assess, and the reliability of the data may be questionable. However, the occurrence of biological assemblages separating clearly according to latitude (rather than randomly), and the fact that the same phenomenon was observed for Red Sea seagrass communities using the same methodology (Price *et al*. 1988), add support to its overall utility and robustness.

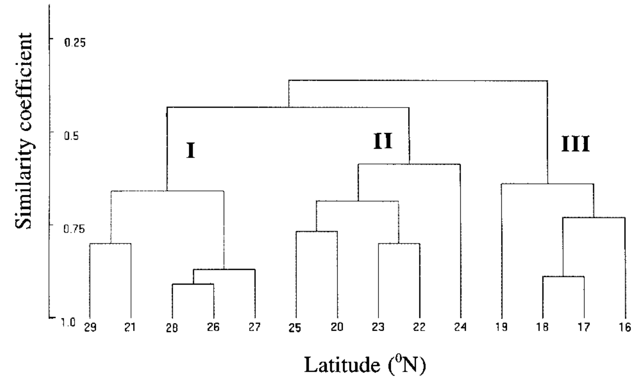

Figure 3 Cluster analysis of biological resource data for coastal and offshore sites.

The reasons for the greater prevalence and abundance of floral groups observed at coastal rather than offshore sites are not completely clear. The pattern probably reflects a complex interaction of physical factors (e.g., groundwater availability, substratum suitability, temperature, salinity, and oxygen levels) and biological factors (e.g., grazing and competition) (IUCN/MEPA 1987*a*; Sheppard *et al*. 1992). The more extensive vegetation coastally might also partly explain the greater coastal (i.e., mainland) prevalence and abundance of terrestrial mammals (e.g. camels), which are herbivorous. However, remoteness and relative inaccessibility are undoubtedly also limiting factors for the presence of terrestrial mammals on offshore islands. Reasons for the greater abundance of invertebrates observed at coastal sites compared with offshore sites are not fully understood. The association may partly reflect the cryptic nature of many invertebrates on coral reefs (Sheppard 1983), which are the predominant offshore habitat (Table 5). Hence, invertebrates would be less

Table 9 Environmental diagnostics of the three groupings derived from cluster analysis of biological data in the Saudi Arabian Red Sea (see also Fig. 3). Median values for mangroves, freshwater vegetation, birds, bird nesting, turtles, turtle nesting, terrestrial mammals, marine mammals, construction and fishing were 0, and are not shown.

Variables	*Median values for sites:*		
	Group I	*Group II*	*Group III*
Ecosystems and species (factors used in cluster analysis)			
Seagrasses	0	2	0
Halophytes	2	3	1
Algae	0	0	4
Reefs	4	2	0
Fish	0	0	2
Invertebrates	0.5	1	6
Uses/impacts (factors not used in cluster analysis)			
Beach oil	1	0	0
Human litter	2	0	1
Wood litter	1	0	1

Table 10 Illustration of use of the database for identifying sites associated with actual or potential resource-use conflicts in the Saudi Arabian Red Sea. Using a 0–6 scale, the example lists all coral reef sites associated with high coral abundance (>3), intensive levels of construction (>4), and/or high levels of beach oil (>4). All of the 24 sites listed (see Jobbins 1996 for details) are in the central or northern Red Sea (approximate latitude 18–26°N), and mostly in the vicinity of Jeddah (approximate latitude 21°N see also Methods). NR = no record.

		Abundance/magnitude value:		
Site reference	*Latitude (°N)*	*Reefs/Corals*	*Construction*	*Beach oil*
12d15	18° 12.6′	4	5	0
01g02	28° 28.8′	4	6	NR
01g08	28° 27′	4	6	NR
03a05	27° 22.2′	4	5	NR
03a06	27° 20.4′	4	5	1
04a07	26° 13.8′	4	5	1
04a08	26° 14.4′	4	6	NR
04b01	26° 13.8′	4	5	NR
04b05	26° 9′	4	1	5
05e17	24° 42.6′	4	0	5
06a04	24° 16.2′	4	5	NR
06e06	24° 4.8′	4	6	NR
06h02	23° 57′	4	5	+
07i03	22° 34.2′	4	6	NR
08c10	22° 7.2′	4	5	NR
08c12	22° 6′	4	5	NR
08d08	21° 48′	4	5	NR
08d14	21° 43.2′	4	5	NR
08e02	21° 43.2′	4	5	NR
08e07	21° 40.8′	4	5	1
08e08	21° 40.2′	4	5	NR
08e09	21° 39′	4	5	NR
08e10	21° 38.4′	4	5	0
08e11	21° 36′	4	5	NR

likely to be recorded at the offshore sites. Birds and most larger marine fauna (e.g., nesting turtles) were more prevalent and abundant offshore, probably reflecting the reduced human predation/impact on these animals and their breeding populations at offshore islands and reefs.

The higher levels of construction/development, human litter and wood litter along the coast relative to offshore sites reflect high population pressure at the coast. However, wind, in particular, can also influence the transport and fate of surface wastes and pollutants (Reynolds 1993; Al-Rabeh *et al.* 1993). Significant coastal/offshore differences were not evident for levels of beach tar, which originates mainly from tanker and ship traffic (Dicks 1987; Sheppard *et al.* 1992).

The increasing abundance of mangroves and seagrasses (and other flora) in the southern Red Sea mirrors the reverse trend shown by coral reefs; a pattern also reported elsewhere (Price *et al.* 1987, 1988; Sheppard *et al.* 1992). This is explained mainly by the wider and shallower shelf, as well as the greater prevalence of unconsolidated sediments, which characterize the southern Red Sea. These conditions favour development of soft-substratum communities but limit coral reef development (Sheppard *et al.* 1992). Primary productivity is also highest in the southern Red Sea (Sheppard *et al.* 1992), which may partly account for the observed higher abundance of invertebrates compared with northern regions.

The higher coastal fish-abundances which were observed in the south (Table 6) are in accordance with a geographical pattern of higher fishery catches (IUCN/MEPA 1987*a*). Offshore, fish abundance increased towards the north, probably reflecting the high fish abundances known for reefs (Sheppard *et al.* 1992), and the fact that reefs increase in development from the south towards the central and northern Red Sea, as described above.

It is important to recognize that significant correlations do not necessarily imply causality. Bird migration and breeding in the Red Sea are highly seasonal, making the dates of observations important. Northern areas were examined in October and November, and the central part from February to May and again from June to September. Southern areas were examined from March to July, and again from August to November. The greatest numbers of birds nesting were recorded during June–July. It is therefore possible that observed spatial abundance-patterns for birds (i.e., the significant increase in bird populations towards the south) are influenced by seasonal effects of sampling, but space/time interactions in the data cannot easily be differentiated. Other database variables displayed less pronounced seasonality. With the exception of nektonic fauna, other species groups are also less mobile than birds. Hence, for most species groups and all ecosystems recorded, season is unlikely to be a major confounding factor. The occurrence of biological

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assemblages separating very strongly according to geographically related factors adds further support to this contention.

Increasing levels of beach oil towards the northern Red Sea are probably a reflection of greater proximity to the Gulf of Suez, which is a major oil-producing area (Dicks 1987). Floating oil is likely to be transported some distance southwards, i.e., into the northern Red Sea, by winds, which are predominantly northerly (Edwards 1987). Levels of beach and wood litter were higher towards the south, probably reflecting the geographic distribution of litter inputs and the influence of the predominant wind.

Cluster analysis using all biological data revealed three clear biogeographic groupings which, at the coastal sites in particular, separated according to latitude-related factors. Of these groupings, Group I sites appeared to be the most impacted, and Group II sites the least (Table 3). It is noted that Jeddah, a heavily-developed coastal area, is situated at *c*. 21˚N which may partly explain the absence of latitude 21˚N sites from Group II and their inclusion in Group I (Fig. 3). The overall biogeographic pattern discerned from this study is similar to that observed for seagrass communities (Price *et al*. 1988) and other biological groups (IUCN 1984*a*, *b*; Sheppard 1985), demonstrating that biological features of the Red Sea are not uniform. Results from this investigation (Fig. 3) and reef-fish studies (Roberts 1991; Roberts *et al*. 1992; Sheppard *et al*. 1992) suggest major differences in the assemblage structures north and south of *c*. 19–20˚N, probably linked with changes in habitat (e.g., decreasing coral-reef development south of this latitude) and/or water quality (e.g., increasing turbidity south of this latitude (Sheppard *et al.* 1992). These findings have major implications for coastal management. For example, representativeness of habitats and species is recognized as an important criterion in the selection of marine protected areas (Gubbay 1995).

The database constructed is useful for creating an environmental profile of particular areas of the Red Sea, as well as for identifying areas with key resources, heavy uses, impacts and resource-use conflicts. Such information is a critical input to coastal management (IUCN/MEPA 1987*c*; Price *et al*. 1993*b*). Comparisons can also be made with other areas investigated using the same methodology (Price 1990; Price *et al.* 1993*a*). During a survey of 53 sites along the Saudi Arabian Gulf coast in 1986, median values of beach oil, other forms of pollution (i.e., human litter) and driftwood (i.e. wood litter) were 2, 3 and 2, respectively (Appendix; Price 1990). Comparison with the median values for these variables in Table 5 suggests that the Gulf coast is more impacted than the Red Sea, in terms of oil and solid waste. Similarly, construction was recorded at 23% of the sites in the Red Sea compared with 28% in the Gulf, although the median value for construction was 0 in both regions. From the baseline data collected in the Gulf in 1986, it was possible to determine changes in the magnitude of oil and other environmental impacts following the 1991 Gulf War (Price *et al*. 1993*a*, *c*). Data collected during the present survey in the Red Sea can also be used for determining the extent of coastal environmental change. Results from the present surveys undertaken during the 1980s and other studies (Sheppard *et al*. 1992) suggest that the Red Sea is no longer the pristine environment it appeared to be about 25 years ago.

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Appendix 1

Summary of data quality, showing numbers of binary and quantitative records following data transformations.

Attribute	*Total no. of data entries/attribute (binary and ranked)*	*No. of binary data entries*	*No. of rank abundance data entries*	*No. of data transformations*	*No. of no records (NR)*
Ecosystems and species					
Mangroves	976	7	969	3	3
Seagrasses	921	35	886	88	58
Halophytes	971	108	863	13	8
Algae	885	345	540	209	94
Freshwater vegetation	957	53	904	10	22
Reef	943	75	868	146	36
Birds	938	74	864	158	41
Bird nesting	915	11	904	0	64
Turtles	955	20	935	41	24
Turtle nesting	932	35	897	0	47
Terrestrial mammals	962	97	865	27	17
Marine mammals	962	2	960	32	17
Fish	490	319	171	62	489
Invertebrates	593	275	318	201	386
Uses/impacts					
Construction	965	19	946	123	14
Fishing	942	76	866	292	37
Beach oil	719	33	686	686	260
Human litter	755	89	666	666	224
Driftwood/wood litter	676	40	636	636	303
Totals	16 457			2403	

Appendix 2

Summary abundance/magnitude data for ecosystems, species groups, uses and impacts at coastal and offshore sites in the Saudi Arabian Red Sea.

Attributes	*Frequency of abundance/magnitude score:*															
	Mainland coast								*Offshore*							
Ecosystems and species	0	+	1	2	3	4	5	6	0	+	1	2	3	4	5	6
Mangroves	470	5	30	34	61	66	26	2	227	2	3	5	11	25	9	0
Seagrasses	238	22	7	58	136	123	68	2	206	13	0	8	17	12	11	0
Halophytes	133	31	52	137	167	147	23	2	124	1	1	9	32	32	3	1
Algae	144	220	23	55	85	86	16	16	78	125	1	3	14	14	11	4
Freshwater vegetation	588	38	6	11	13	16	6	1	263	16	0	0	0	0	0	0
Reefs	293	48	9	45	74	204	2	0	50	27	2	14	43	112	17	3
Birds	367	42	91	121	49	1	0	0	113	32	24	39	50	7	2	0
Bird nesting	646	3	10	1	0	0	0	0	171	8	20	13	38	3	2	0
Turtles	668	0	15	0	0	0	0	0	223	20	28	1	0	0	0	0
Turtle nesting	658	0	11	1	1	0	0	0	195	35	16	15	0	0	0	0
Terrestrial mammals	555	95	24	11	0	1	0	0	274	2	0	0	0	0	0	0
Marine mammals	678	1	6	1	0	0	0	0	250	1	18	7	0	0	0	0
Fish	64	182	12	17	21	13	6	6	12	137	2	2	1	7	4	4
Invertebrates	45	145	7	13	26	16	27	115	42	130	4	3	5	1	3	11
Uses/impacts																
Construction	504	13	30	21	51	30	29	12	240	6	21	7	1	0	0	0
Fishing	413	56	105	54	16	21	6	2	162	20	63	22	0	2	0	0
Beach oil	267	19	105	79	14	9	3	0	126	14	38	36	6	3	0	0
Human litter	140	65	117	111	47	42	10	0	105	24	28	41	12	9	4	0
Wood litter	144	32	103	105	30	48	5	0	108	8	25	23	14	27	4	0

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