Sediment origin and budget in Sepetiba Bay (Brazil) - an approach based on multielemental analysis

C. Barcellos · L. D. de Lacerda · S. Ceradini

Abstract   Sediment origin and transport were determined in a shallow 447 km^2 coastal lagoon in Brazil, using the distribution of major elements in bottom and suspended sediments. Applying multivariate analysis, the sum of normalized concentrations of Ti, Fe, and Al in sediments was selected to trace the terrigenous influence in bottom sediments, whereas Ca, Si, and K were used as indicators of marine influence. Sepetiba Bay bottom sediments are dominated by up to 80% terrigenous inputs. The open bay sediments are enriched in P, Mg, K, and Ca because of the intensive water column primary production. The inner bay forms an independent circulation cell with a predominance of terrigenous sediments. The results suggest a long residence time for particles in the bay, demonstrated by the magnitude of resuspension flux compared to the total sediment input to the bay.

Key words   Estuaries · Sedimentation · Resuspension · Sediment traps

Introduction

Sediments are a medium of transport, accumulation and storage of pollutants, indicators of environmental quality, and an agent of biota damage. In estuaries where sediments from different sources are mixed, knowing the origin of sediments is especially helpful in identifying the fate of pollutants and nutrients and tracing the possible cycles of particulate matter in the estuarine environment. Sepetiba Bay is a semienclosed lagoon (447 km^2) located 60 km West of Rio de Janeiro, Brazil. There are 1.2 million inhabitants and an important industrial park with over 400 industrial outlets in its drainage basin (2065 km^2). Water depth ranges from 2 m in the inner zone to 20 m near the ocean entrance. A clockwise circulation pattern promotes the permanent exchange of water with the sea (Signorini 1980). Water quality studies, using salinity, suspended matter and nutrient concentrations, have shown the absence of vertical stratification, but demonstrated the influence of strong horizontal gradients (Azevedo and others 1996). The main sources of water, sediments and organic matter are the tidal input of marine water, an average fluvial water input of 200 m^3 s^{-1}, the intensive water column primary production, and an extensive mangrove vegetation, which covers 35% of the bay's perimeter (Barcellos and Lacerda 1993).

Sepetiba Bay is severely contaminated with heavy metals, in particular Zn and Cd, due to large chemical and metallurgical plants located in the basin (Barcellos and Lacerda 1994). The dispersion and distribution patterns of these metals are controlled by sediment fluxes (Barcellos 1995). The study of sediment origin and dynamics in the bay is a fundamental step in understanding metal pollution in the area.

Large differences can be observed between the deposition and the final burial of sediments in shallow estuaries (Sanford 1992). In this work, the deposition of sediments was measured by means of sediment traps and the sedimentation (burial) was assessed from a review of existent data obtained in the bay by several methodologies, including dated sediment cores. The aim of this study was to identify the sediment sources of settling (trapped sediments) and deposited (bottom sediments) particulate matter in the bay by using elemental composition data and exploratory multivariate statistical analysis.

Materials and methods

The general location of Sepetiba Bay is shown in Fig. 1a. Sediment sampling sites and the location of sediment traps in Sepetiba Bay are shown in Fig. 1b. The sampling sites were distributed along the northern shore of the

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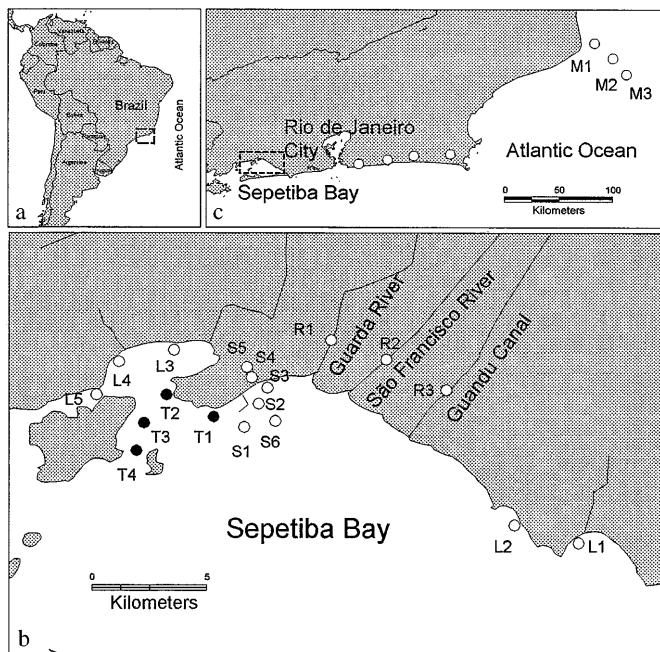Rio de Janeiro, RJ 21045-900, Brazil

Fig. 1
Location maps of **a** the Rio de Janeiro coast, **b** Sepetiba Bay
with the sampling sites and **c** marine sediment sampling sites

bay, where intensive sedimentation has occured during
the last decades (Nogueira 1982). Other bottom sediment
samples were collected along the coast of Rio de Janeiro
and considered as representative of typical marine sedi-
ments of this part of Brazilian coast (Fig. 1c). Sediment
traps are used to evaluate the primary production and
long range transport of sediments in the ocean. In shal-
low waters, the contribution of resuspension must be
evaluated due to the predominance of bed sediments in
the total trapped material (Håkanson and others 1984).
The sediment traps (85 mm diameter and 420 mm height)
were deployed at four stations in the bay's transition
zone between marine and riverine influences (T1, T2, T3,
and T4) for 4 days during the austral summers of 1993
and 1994. Particulate matter in the traps was separated
by centrifugation at 3000 rpm for 10 min.
Bottom sediment samples were collected from the upper
5 cm of mud deposits along the bay shore (L1, L2, L3, L4,
and L5) and from deep (more than 3 m) sites (S1, S2, S3,
S4, S5, and S6) in the mixing zone of river and marine
waters along the northwest coast of the bay. Fluvial bot-
tom sediments (R1, R2, and R3) were collected in the
major tributary rivers of the bay. Marine sediment sam-
ples (M1, M2, M3) were obtained from the continental
shelf (water depth greater than 100 m) off the Rio de Ja-
neiro coast. All sediment samples were immediately wet
sieved (63 μm) and dried at 50 °C for 48 h.
Macro element concentrations in the sediments were ob-
tained by X-ray fluorescence technique using lithium te-
traborate fusion and secondary regional certified samples
as reference standards. At least 2 replicates were used for
the standards, analytical blanks and samples, presenting

reproducibility errors of 2–5%. Phosphorus was deter-
mined by the ammonium molybdate colorimetric meth-
od. Dilution and standard addition test were performed
in order to evaluate potential matrix interferences. Or-
ganic matter was estimated by gravimetry after heating
the samples at 500 °C for 12 h.

Sediment composition and origin

Origin and transport of the sediments were investigated
by using concentration data of the major components as
natural mineralogical tracers (Salomons and Mook 1987).
Concentration values in the marine (M1, M2, and M3),
riverine (R1, R2, and R3), shore (L1, L2, L3, L4, and L5),
bay bottom sediment (S1, S2, S3, S4, S5, and S6) and
trapped (T1, T2, T3, and T4) materials are presented in
Table 1.
The range of major element concentrations indicates a
dominance of the clay aluminum-silicate matrix. Varia-
tions in the major element concentrations suggest the ex-
istence of diverse sources of particulate matter and their
mixture in the coastal region of the bay. Marine sedi-
ments contained lower Al and Fe concentrations than bay
samples. Higher Al and K and considerably lower Ca
concentrations were observed in respect to other estuar-
ine sediments such as in the Rhine and Meuse Estuary
sediments, which are under the influence of North Sea
sediment deposition and dredging (Nolting and others
1990).
Correlation analysis, performed by using major elements
data, showed significant positive relationships among Ca,
K, and Si, and between Al and Ti. Iron exhibited a nega-
tive correlation with the first group of elements. These
groups of elements have the main weight in two vectors
of factor analysis and explain 73% of the sediment com-
position variance. Table 2 presents the obtained varimax
rotate factors for major elements. These two groups of el-
ements have also been used with success to trace terres-
trial and marine sediments along other sectors of the
southeast Brazilian coast (Carvalho and others 1993).
The first factor (1) has a predominance of biogenic and
marine origin elements (Ca, K and Si) and the negative
influence of Fe. The second factor (2), which is controlled
by Al and Ti concentrations, was identified as a tracer of
terrigenous sediments from riverine influence. The third
factor (3), due to the weight of P and Mn, is probably af-
fected by the reworking of sediments and environmental
redox condition changes at the sediment-water interface.
The first two factors, which explain 60% of sediment
composition variance, are possibly related to the origin of
sediments, while only 13% (from the third factor) of sedi-
ment quality variance is due to post-depositional proc-
esses. Higher Mn, Mg and P concentrations (factor 3) are
observed in the inner bay sediments (L1 and L2) when
compared to riverine and marine endmembers.
Factor analysis was used in this work as an exploratory
tool in order to define tracers of marine, continental, and

Table 1
Major element and organic matter (*OM*) concentrations in the sediments from Sepetiba Bay, Rio de Janeiro (values in % with the exception of Mn and P in $\mu g\ g^{-1}$, dry weight; *nd* not detectable)
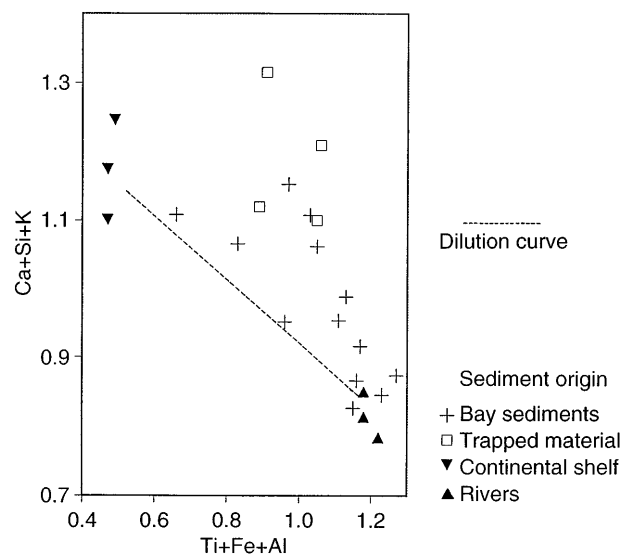
Sample	Fe	Mn	Ti	Ca	K	Si	Al	Mg	P	OM
R1	4.9	790	0.60	0.30	1.07	19.0	8.0	0.79	nd	13.2
R2	5.4	910	0.62	0.31	1.11	15.2	8.4	0.82	310	16.6
R3	4.3	700	0.82	0.34	1.67	18.4	6.4	0.61	240	8.9
L1	4.4	2330	0.66	0.50	1.38	18.5	6.5	1.66	400	14.3
L2	4.7	3310	0.63	0.39	1.38	17.6	7.4	1.23	620	14.2
L3	3.7	460	0.68	0.50	1.67	17.1	6.7	1.33	460	15.8
L4	3.6	370	0.63	0.50	1.74	19.1	6.5	1.35	360	13.6
L5	3.1	310	0.57	0.44	1.66	18.0	5.2	0.79	190	15.7
S1	5.2	520	0.76	0.30	1.30	19.1	8.4	0.84	nd	12.7
S2	4.5	380	0.77	0.28	1.31	18.6	7.8	0.82	nd	13.0
S3	3.9	320	0.61	0.31	1.51	20.9	6.1	1.32	nd	10.1
S4	7.3	320	0.56	0.32	1.16	16.3	5.6	1.29	340	12.3
S5	6.3	280	0.67	0.30	1.33	16.9	6.9	1.16	100	12.7
S6	4.5	450	0.75	0.35	1.34	18.4	7.8	0.81	210	14.5
T1	3.4	770	0.55	0.50	1.56	19.7	6.0	1.23	580	15.3
T2	3.9	570	0.67	0.39	1.79	21.1	7.1	1.12	650	12.6
T3	3.5	440	0.56	0.52	2.17	21.4	6.1	0.98	740	11.6
T4	4.8	590	0.62	0.57	1.64	20.0	6.4	0.92	450	17.2
M1	1.6	390	0.37	0.44	1.54	31.3	3.0	0.30	160	2.9
M2	1.5	350	0.43	0.35	1.13	32.9	2.4	0.23	230	2.4
M3	1.8	400	0.78	0.42	0.91	32.7	1.9	0.29	120	2.7

Table 2
Factor components for major elements of Sepetiba Bay sediments after varimax rotation

Factor	1	2	3
Fe	−**0.88**	−0.02	0.06
Mn	0.03	−0.01	**0.84**
Ti	0.02	**0.82**	−0.08
Ca	**0.70**	−0.54	0.18
K	**0.85**	−0.24	−0.21
P	−0.28	−0.11	**0.74**
Si	**0.79**	0.00	−0.10
Al	−0.29	**0.79**	0.38
Mg	0.07	−**0.67**	0.40

Fig. 2
Relation between continental and marine indicators. Normalized element concentrations were summed for each sample. *Squares* represent the sediment trap samples

authigenic sediments. A normalization of factors was obtained by summing the concentration of two groups of the three major elements (Ca, Si, and K as factor 1; Ti, Fe, and Al as factor 2) divided by their respective mean. Figure 2 shows the plots of factors 1 and 2 for the sediments of Sepetiba Bay. A hypothetical dilution curve linking the marine (M samples) and riverine (R samples) endmembers is drawn. The majority of sediment samples lie above the expected dilution curve. This enrichment is due to the incorporation of K and Ca into the particulate matter and can be considered as biogenic. Higher enrichments are observed for trapped materials (*squares* in Fig. 2). The compositional similarity between trapped sediment samples and bottom sediments, as well as their proximity to the western shore (as shown in Fig. 1b) may indicate the predominance of resuspended sediments in

this area and the minor importance of primary production on sediment composition.

The biogenic enrichment of each element in the bay sediment samples were calculated from the difference between the observed concentrations and those predicted from the dilution curve, linking the marine and continental endmembers. The Sepetiba Bay bottom sediments are enriched in P (5-fold), Mg (1.5-fold), K (1.4-fold), and Ca

(1.3-fold). Other elements, such as Si, Fe, Mn, Ti, and Al are well fitted to the expected dilution curve and have little or no enrichment due to primary production. From the vertical deposition profile of elements in ocean traps, Al and K were characterized as refractory; Si, Ca, and Mg as biogenic; and Fe and Mn as scavenged elements (Brewer and others 1980). The behavior of Si in the bay is in agreement with the observed conservative trend verified in other estuaries as reviewed in Boyle and others (1974). In this case, the presence of Si acts predominantly as a diluter of terrigenous elements, despite the fact that it has an importance to some living organisms (for example diatoms).

The sum of the relative elemental increase due to the biogenic component represents 4.4% of the bulk sediment mass in Sepetiba Bay. Other elements such as C, S, and N, which have large participation in the total mass of biological materials, were not analyzed because of methodological restrictions. Organic carbon has a mean ratio to P from 30:1 to 40:1 in organic-rich sediments (Sundby and others 1992). Other works showed that Sepetiba Bay bottom sediments contain around 10% organic carbon (Rezende 1993).

The distribution ratios between marine and continental, as well as between biogenic and lithogenic materials in Sepetiba Bay sediments (shown in Table 3) were calculated based on the distance between the observed element concentrations and those expected from the dilution curve of endmembers.

Continental origin of sediments is largely predominant in the inner Sepetiba Bay, where river sediments are deposited due to shore parallel currents. The transport of riverine sediments along the eastern shore was observed by means of remote sensing (Argento and Vieira 1989). The existence of an almost independent hydrodynamic cell in the eastern part of the bay was pointed out by Bronniman and others (1981) which enlarges the water residence time and promotes the sedimentation of river-transported particles. The marine influence on bottom sediment composition is higher for the open western area. The predominance of marine-derived particles in bottom sediments has been pointed out in other well-studied estuaries such as the Savannah (Mulholland and Olsen 1992) and Elbe (Schoer 1990) Rivers. In the Rhine-Meuse Estuary, however, between 55 and 65% of the inorganic sediments are of terrigenous origin (Salomons and Mook 1987). The "inverse estuaries", which trap all the conti-

nental sediment input and a large fraction of marine-transported sediments, are commonly found in coastal embayments with small freshwater input (Biggs and Howell 1984). Sepetiba Bay is likely to be this sort of estuary and has a large sediment trapping efficiency. The participation of the estimated organic matter (biogenic) fraction (between 8 and 10% of bottom sediment, dry weight) is in agreement with the measured content of organic matter in the Sepetiba Bay bottom sediments (about 13%, Table 1). Considerable quantities of accumulated organic matter can also be a result of the input of particulate organic matter by rivers. In the inner area, where river-transported sediments are predominant, biogenic elements represent less than 10% of sediment total weight. The persistence of continental originated organic matter in the Sepetiba Bay sediments was verified by using organic tracers (Rezende 1993).

The authigenic origin of a portion in the total deposited organic matter is reinforced by the observed enrichment of P, Mg, K and Ca in respect to marine and riverine sources of sediments. The suspended and benthic biota were pointed out as a main component in the "biologically mediated sedimentation" due to its filtering capacity which sometimes exceeds the water input of the estuaries (Biggs and Howell 1984).

Sedimentation, resuspension and deposition

Sediment deposition rates, measured by means of sediment traps, varied from 5 (in the westernmost open bay site) to 50 mg cm^{-2} day^{-1} (at the northern shore). Figure 3 shows the deposition rates related to the height above the bay's bottom. The higher sediment deposition rates were measured in an embayment with noncompacted sediment bed, exposed to wave action and with
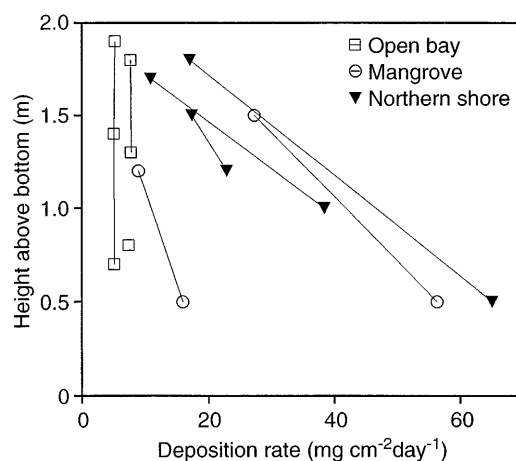
Table 3
Estimated mean fraction of continental, marine, biogenic and lithogenic of Sepetiba Bay sediments (in percentage of total mass)

	Continental	Marine	Biogenic	Lithogenic
Inner bay	79	21	8	92
Open bay	50	50	10	90
Trapped material	64	36	20	80

Fig. 3
Deposition rates at different heights in Sepetiba Bay as measured by sediment traps

Table 4
Sedimentation and deposition rates in Sepetiba Bay compared to other coastal regions

	Sedimentation rate		Deposition rate (mg cm^{-2} day^{-1})
	(cm year^{-1})	(mg cm^{-2} day^{-1})	
Sepetiba Bay			
Open bay	0[a]	0	2700[b]
Northern Shore	1.2[c]	720[d]	7500[b]
Mangrove	0.8–1.0[e]	400–600[d]	4400[b]
River delta	3–5[a]	3300[d]	–
Engenho bay	1.3[f]	650[f]	–
Inner area	0.5[a]	300[d]	–
Other regions			
Guanabara Bay	0.9[g]	–	–
Hong Kong Bay	0.3–0.6[h]	–	–
Rio de Janeiro coast	–	–	36–475[i]
Japan Sea	–	1.7[j]	5.1

Remarks and references
[a] Bathimetric map comparison (Leitão Filho 1995)
[b] Based on sediment trap measurements, this study
[c] Pesticide record (Japenga and others 1988)
[d] Assuming a bulk sediment density of 0.5 g cm^{-3}
[e] Heavy metal record (Quevauviller and others 1992)
[f] Heavy metal record (Barcellos and others 1991)
[g] Bathimetric map comparison (Amador 1988)
[h] Lo and Fung (1992)
[i] Knoppers and Pollehne (1991)
[j] Masuzawa and others (1989)

high sedimentation rates. The presence of vertical gradients of deposition rates in shore traps demonstrates a local resuspension of sediments, where bottom sediments are fine grained. Conversely, where bottom sediments are sandy (open bay samples), the deposition rates are almost constant throughout the water column. A baseline level of deposition rate is observed between 5 and 8 mg cm^{-2} d^{-1}, which can be due both to the long-range transport of particles and the primary production in the bay water. Table 4 presents the reported sedimentation and deposition rates in selected areas of Sepetiba Bay. These values are compared to other coastal regions. Sedimentation rates in the bay were estimated by previous works leading to a range of 0.8–1.3 cm year^{-1}. These values are high when compared to other coastal environments. The highest sedimentation rates were found in the major river estuaries along the northern shore of the bay, where shoreline transgression has been observed. On the other hand, erosion and shoreline transgression have been verified in the southern regions of the bay (Nogueira 1982).
Based on the observed sedimentation rate range, an average particle burial flux of 400–700 mg cm^{-2} year^{-1} is calculated assuming 0.4–0.6 g cm^{-3} for the bulk sediment density for noncompacted clay sediments (Håkanson and others 1984; Barcellos and others 1991). The order of magnitude difference between sediment deposition and burial rates is probably due to frequent resuspension episodes and the intensive sediment production in the water column. This means that particles settle and are resuspended about 10 times before their final burial. This cycling characterizes Sepetiba Bay as a highly active estuary (Sanford 1992).

River sediment inputs were measured by Watts (1990) and Rezende (1993) as 0.30–0.59 × 10^6 tons year^{-1}, respectively. These figures are underestimated according to Argento and Vieira (1989) because they reflect only dry weather periods. Assuming a quadratic relation between solid and dissolved river flows, sediment input increases 4 times for a doubling of river flow rate (Linsley and others 1975). During the wet season (summer), sediment transport can reach up to 1.8 × 10^6 tons year^{-1}.
A sediment mass balance was estimated based on the measured riverine input and mixing rates between continental/marine and biogenic/lithogenic sources as discussed above. Internal fluxes, such as resuspension and deposition, were measured by means of sediment traps. Figure 4 shows the estimated sediment fluxes in Sepetiba Bay.
The calculated total input of particulate matter is in good agreement with the verified mean sedimentation consid-
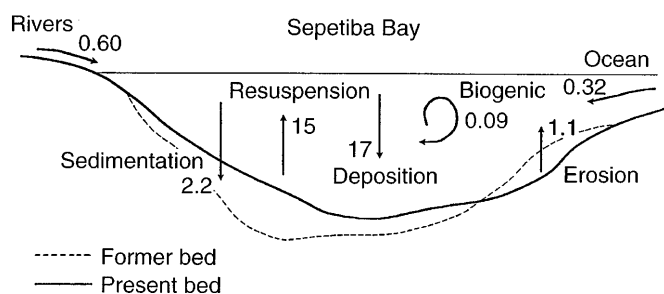
Fig. 4
Estimated mass sediment fluxes in Sepetiba Bay (in 10^6 tons year^{-1})

ering the bathimetric map evolution (Leitão Filho 1995). Differences between sedimentation and erosion, as well as between resuspension and deposition are due to the external sediment inputs to the bay, leading to a convergent value about 1×10^6 tons year^{-1}. Resuspension and deposition fluxes of sediments (15 and 17×10^6 tons year^{-1}, respectively) overcome the sum of sediment inputs by one order of magnitude (around 1×10^6 tons year^{-1}) which indicates the long residence time of sediments in the bay waters.

The mean settling velocity for open bay particles was estimated between 1 and 4 m day^{-1} (Barcellos 1995). Considering the bay dimensions and the advectional currents, particles can travel widely before deposition and sinking. Resuspension episodes thus have an important role in the internal redistribution of sediments. On the other hand, resuspension can be responsible for the release of particles linked to heavy metals, which is a great concern in this bay (Barcellos and Lacerda 1993).

Conclusions

Sedimentation in the Sepetiba Bay is controlled by the mixture of riverine, marine and autochthonous sediments. River-transported sediments are predominant in the bay and are deposited mainly in the eastern region of the bay. Marine sediment contribution is only observed in the western shore deposits. A small fraction of shore sedimentation is a consequence of the intensive local primary production, which is indicated by the enrichment of P, Mg, K and Ca in bottom and suspended sediments. The high sedimentation rates (around 1 cm year^{-1}), reported for some areas in the bay, are explained by riverine input. Vertical internal fluxes, represented by resuspension and deposition of sediments, overcome (by a factor of 15) the external inputs promoting a remobilization of fine particles in the bay and are responsible for an enrichment of K and Mn in suspended particles. The frequent resuspension episodes and the long-range transport of heavy metal-rich suspended matter promote metal remobilization and dispersion in the bay. The long residence time of contaminated particles in the bay should concern the monitoring of long-term effects of heavy metal pollution.

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