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THE IMPACT OF NITROGEN AND PHOSPHORUS RELEASE FROM
A SILICEOUS SEDIMENT ON THE OVERLYING WATER

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ABSTRACT

The release (+) or uptake (-) of ammonia (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^+), phosphate (PO_4^{-3}) and dissolved organic phosphorus, nitrogen and carbon (DOP, DON, DOC) from a subtidal (18.3 m depth) siliceous sediment off La Jolla, California was studied over two years. The mean net exchange values (and the total range of rates obtained) were: NH_4^+ +872 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-47 to +3290); NO_2^- +34 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-5 to +97); NO_3^- -77 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-720 to +647); PO_4^{-3} +77 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-438 to +502); DOP +12 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-28 to +59); DON -75 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-1326 to +1280); and DOC -583 $\mu\text{mol m}^{-2}\text{d}^{-1}$ (-30,800 to +23,800). Using published primary production rates and C:N:P ratios it was calculated that 15,000 $\mu\text{mol N m}^{-2}\text{d}^{-1}$ and 935 $\mu\text{mol P m}^{-2}\text{d}^{-1}$ were taken up by the phytoplankton. The benthos released 786 $\mu\text{mol N m}^{-2}\text{d}^{-1}$ and 90 $\mu\text{mol P m}^{-2}\text{d}^{-1}$ or 5% and 10% of the required N and P. It was shown, however, that sediment exchange released only an insignificant fraction of both N (0.4%) and P (0.5%) already contained in the water. By using a conservative mean net advection rate of 1.5 km d^{-1} it must be presumed that the N and P released into the water at this site was superfluous to the needs of the phytoplankton and was, therefore, exported from the area.

INTRODUCTION

Marine benthic communities receive their organic matter from sinking detritus, sinking organisms and benthic autotrophic production. Metabolism, diffusion and resuspension (27, 17, 18, 25, 6, 7) are the major routes of organic matter loss from the benthos, whereas burial is not considered a loss because the organic matter remains in the sediment.

Metabolism results in the assimilation of a portion of the organic matter, the release of another portion and the mineralization of the remainder. Natural bacterial assemblages metabolizing under aerobic conditions mineralize 8-57% of the total organic carbon taken up (10, 29), the remainder being incorporated into new cell material or partially mineralized and released. Many factors determine the rate at which these metabolic products participate in sediment-water nutrient exchange. Diffusion rate, bioturbation, resuspension, metabolic rate, photosynthetic rate, sorption reactions, redox and pH (2, 8, 19, 14, 15, 5, 6, 7, 16) are the more important of these factors.

In shallow coastal waters benthic nutrient exchange can influence the water nutrient chemistry and thereby the productivity of the overlying water (19, 24, 5). The impact of nutrient regeneration on phytoplankton productivity depends on several factors, including the rate of release of the nutrient from the sediment, the depth of the water, the degree of mixing of the overlying water, the in situ concentration of the nutrient, and the rate of uptake of the nutrient by the phytoplankton.

In deep waters, such as over the Santa Barbara Basin, California, the importance of benthic nitrogen release to the phytoplankton nitrogen requirement in the upper waters was shown to be negligible, providing only 0.4% of the nitrogen required (23). In Doboy Sound, Georgia, which has a mean depth of 2 m at mean high water and a mean tidal amplitude of 2 m, Pomeroy et al. (19) found that the sediment acted to stabilize the phosphate concentration in the overlying water to $1 \mu\text{mol l}^{-1}$. Hale (5) concludes from direct measurements of nitrogen and phosphorus released from Narragansett Bay sediments (a shallow bay, average depth 8.8 m) that in June, 80% of the nitrogen requirement and more than 200% of the phosphorus requirement of Skeletonema costatum (a major component of the phytoplankton community) is released from the bay sediments. In the period of August through November, 780% of the nitrogen requirement was released from bay sediments. Rowe et al. (24) calculated that over the New York Bight benthic nutrient regeneration accounted for more than 200% of the nitrogen required by phytoplankton photosynthesis. The calculations of Rowe et al. (24) were based on many assumptions but show the contribution sediment nutrient regeneration can make even in deeper (80 m) waters.

The purposes of this study were to quantitate the in situ rate of nutrient exchange and to analyze the probable impact this exchange would have on the phytoplankton productivity in the overlying waters.

METHODS

Study Site

The study site (Fig. 1) was located in 18.3 m of water in the La Jolla Bight region off the Scripps Institution of Oceanography (SIO). The extended study area was demarcated by its biological and physical similarity to the study site (11, 4). Water movement within this region has been described in detail (21, 1, 12, 9). The size distribution of the sediments was studied extensively by Inman (11). The phi median diameter at this site was 3.50 to 3.24 phi units (88 to 105 μm) with a phi deviation measure of 0.3 to 0.5 phi units and a phi skewness measurement of -0.15 to +0.05 meaning the particle sizes were skewed towards smaller phi values (larger particle diameters). Sediment organic carbon content of this siliceous sediment was low (0.06% to 0.21%) (7).

Temperature

Bottom water temperature was taken with a mercury thermometer held approximately three cm above the sediment surface. During portions of the study a Ryan model F-15^R recording thermometer was used. Daily surface and five meter deep temperature measurements were recorded by the SIO Aquarium-Museum.

Sediment Nutrient Exchange

In situ net nutrient exchange was ascertained by analyzing the nutrient concentrations contained in a known water volume overlying a measured sediment area enclosed within plastic boxes over a pre-determined time interval. A light and a dark box were used in each experiment to quantitate the exchange rate occurring during the day

and night. Daylength was determined from data recorded on a bimetallic actinograph. To determine the spatial variability of nutrient release replicate light or dark boxes were used on four occasions. The time interval between replicate experiments was one to two months in order to estimate temporal averages over a summer and winter. To calculate exchange rates, nutrient concentration changes inside each box were corrected for the volume of water enclosed, the sediment area enclosed, the hours of incubation (generally 6 hours or less) and the hours of daylight and darkness. Each box measured, on its inside dimensions, 30 cm long x 30 cm wide x 15 cm high and when inserted five cm into sediment enclosed 900 cm^2 of sediment and nine liters of overlying sea water.

The ratio of 10 ml of water to 1 cm^2 of sediment is favorable for detecting nutrient changes in short periods of time. This is especially true in sediments of low organic carbon content where biological activity is low. Hale (5) used chambers of a similar ratio in Narragansett Bay, Rhode Island and incubated them for 2 to 4 hours. In the present study two box types were used, the first box type in the experiments of April 2, 1971 through December 8, 1971 and box type #2 (Fig. 2) in the experiments of January 3, 1972 through February 20, 1973.

To implant the boxes in the sediment several of the silicone stoppers (size #6) were removed and the boxes gently pressed into the sediment to a depth of five cm, taking great care not to disturb the sediment surface. The insertion procedure did not alter nutrient concentrations inside compared to outside the box as long as the

sediment surface was not disturbed, if disturbance was observed the box was relocated. The silicone stoppers were left out and a sample bottle was placed onto the sample port tube.

The sample bottle consisted of a one liter polyethylene bottle, the cap was replaced with a silicone stopper (size #6) through which a piece of silicone tubing (16 mm O.D. x 9.5 mm I.D.) protruded by approximately 15 cm. A small hole was made through the bottom of the sample bottle and plugged with a silicone stopper (size #00). The sampling port consisted of a T-connector on the inside of the box connected to a piece of silicone tubing (16 mm O.D. x 9.5 mm I.D.) and glass tubing (8 cm long) on the outside of the box through a silicone stopper. The openings of the T-connector inside the box were oriented parallel to the top of the box and about two cm beneath it. Both the silicone tubing on the sample bottle and sample port were closed by means of a spring clamp.

Water samples from inside the box were obtained in the following manner: the silicone tubing of the sample bottle was pushed over the glass tubing extension of the sample port. The sample bottle, which immediately before use was flushed with nitrogen gas in the laboratory and at the water surface over the sample site had most of the gas expelled, was almost completely compressed by the nearly two atmospheres of hydrostatic pressure at 18.3 m. The spring clamps were removed from the pieces of tubing and after the sample bottle was one-half full the sample bottle was gently squeezed forcing the water back into the box mixing it completely. Dye experiments in the box showed complete mixing using this sampling procedure.

As the openings of the T-connector were oriented parallel to the top of the box and, therefore, to the sediment surface, gently squeezing water back into the box did not disturb the sediment surface. The sample bottles were then filled until no additional water entered. The small silicone stopper on the bottom of the bottle was removed and again gently squeezing the bottle, the residual nitrogen was voided. The silicone stopper was replaced and the sample bottle completely filled. To remove the sample bottle the two spring clamps were replaced and the sample bottle was retracted from the glass tubing.

When the boxes were first put in position the silicone stoppers in the top were left out allowing the sampled water to be replaced by similar bottom water. After the initial sampling the stoppers were replaced and no new water entered the box. Having the sides of the box sunk five cm assured not only that the boxes were anchored to the bottom but also that outside water would not have time to diffuse into the box or be forced into the box by pressure differentials between the inside and outside of the box created by waves passing overhead. Whereas it is known that waves can cause water movement in submerged sands (28, 22), the degree of movement is dependent on the pressure head (wave height), water depth and the physical properties of the sediments. As these experiments were never performed when wave height was greater than one meter, the amount of "pumping" in these fine sands was not enough to have an effect at a depth of five cm.

The two box types used alternate methods to prevent water entry after the initial sampling. In box type #1, two collapsed polyethylene bags (one inside the other) were placed through one of the box openings, cemented to the box and plugged with a silicone stopper. When taking a subsequent water sample the stopper was removed and the bags filled with water. In box type #2 (Fig. 2), "O"-ring sealed plungers were placed on the sides of the box and during sampling the plungers were pushed into the box to compensate for the water removed.

Controls on the nutrient changes caused solely by the activity of the plankton in the water above the sediment were performed in two-liter glass stoppered bottles. These bottles (a dark and light bottle were used) were filled with bottom water and incubated next to the boxes. During the 17 months these controls were routinely used, their activity was compared to the sediment activity. It was concluded that the plankton activity did not significantly affect the exchange rates measured in the boxes.

A word of caution on a problem encountered at this exposed coastal station may be useful. Surge activity at times was enough to scour the sand away from the edges of the boxes (sunk five cm) allowing free interchange of inside and outside water. By fashioning deflectors to place around the boxes many experiments were saved, however, approximately 25% of attempted experiments were rendered useless after surge activity had scoured away one or more corners.

Chemical Analysis

Ammonia (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), dissolved organic carbon, nitrogen and phosphorus (DOC, DON and DOP) were all analyzed by the methods outlined in Strickland and Parsons (26). All methods were modified to use only 10 ml of sample.

The treatment of the water prior to analysis consisted of filtering the water at a vacuum of 170 mm Hg through combusted (450°C for 2 hr) 2.4 cm ultra-fine glass fiber filters (Reeve Angel 984H) using chromic-acid cleaned and baked (550°C for 4 hr) glass filtration units. Likewise the 250-ml glass-stoppered bottles used for storing the filtrates at -20°C until analysis were all acid cleaned and baked. These precautions were taken to minimize organic contamination.

RESULTS

Temperature

Temperature data from the SIO pier and the experimental site are plotted in Figure 3. It is evident that not only was there a large variation of temperature with season but temperature differences between the surface and bottom waters exhibit large variations. Daily temperature recordings also exhibited variations. In winter there was virtually no change in temperature during a day, while in summer it would rise and fall by as much as 7°C in a single 24 hr period. In the spring and fall bottom water temperature oscillations were between these extremes varying only 1 to 4°C daily.

The large temperature fluctuations observed in the bottom water were due to semidiurnal internal waves and not the heating and

Figure 3

cooling of the bottom water mass (13). During winter conditions (mid-November or December to mid-March) the water column was isothermal.

In summer, although the water column was stratified, internal waves created, semidiurnally, vertical and horizontal acceleration of the bottom water increasing turbulent mixing. For the purposes of this paper it has been assumed that benthic nutrient exchanges were eventually mixed throughout the overlying water column.

Nutrient Exchange

Figures 4, 5, 6, 7, 8, 9 and 10 show the exchange rates for NH_4^+ , NO_3^- , NO_2^- , PO_4^{3-} , DOC, DON and DOP respectively. The mean net

Figures 4, 5, 6,
7, 8, 9, 10

exchange value for each nutrient over the two year period and the respective total ranges of net input (+) or removal (-) of nutrient from the water overlying the sediment are shown in Table 1.

Table 1

Table 2 tabulates the results of the replicate dark and light box experiments respectively. The percent standard deviation about the mean was greater in the light than in the dark for all inorganic nutrients and DON. This probably results from the patchy distribution of benthic microalgae and their uptake and release of inorganic and organic compounds (6).

Table 2

DISCUSSION

The nutrient exchanges measured in the course of this investigation allowed a conservative mean net exchange rate to be calculated over yearly time spans. During quiescent periods the rate of exchange was determined satisfactorily by this short term static approach. In periods of surge activity the nutrients contained in the surface layers of interstitial water were mixed into the bottom

water. Creating a static situation by placement of a box over the sediment during these periods decreased the actual exchange rate to a degree dependent upon the depth to which the sediment was disturbed, the pre-disturbance concentration of nutrient in the interstitial water, the time taken to re-establish this concentration, and the length of time the box was left in place. Although these experiments were performed under varying intensities of surge they could not be performed during periods of high surge intensities due to the problem of scouring (discussed previously). Also, after a period of no surge activity the onset of surge disturbed the sediment and the contained nutrients were released into the bottom water. The static method utilized did not measure this quantity of nutrient. For the reasons mentioned above the net exchange rates measured were considered conservative.

Eppley et al. (3) give the only known values of primary production for this region over an extended (6 months) period. Using their average phytoplankton production rate of $1.2 \text{ gC m}^{-2} \text{ d}^{-1}$ and a C:N uptake ratio of 106:16 (20) the calculated average nitrogen requirement was $0.21 \text{ gN m}^{-2} \text{ d}^{-1}$. Summing the total benthic nitrogen exchanges and assuming that the DON would be mineralized in the water column to a form utilizable by the phytoplankton yields a net input of $0.011 \text{ gN m}^{-2} \text{ d}^{-1}$ into the water column from the benthos. This amounted to 5% of the daily nitrogen requirement of the phytoplankton. This value is increased to 6% if one does not consider organic nitrogen flux.

Using a C:P uptake ratio of 106:1 (20), the average daily requirement of phosphorus by the phytoplankton was $0.029 \text{ gP m}^{-2} \text{ d}^{-1}$. Summing the phosphorus exchanges and assuming that the DOP compounds present were utilized by the phytoplankton yields a net input of phosphorus to the water of $0.0028 \text{ gP m}^{-2} \text{ d}^{-1}$. Therefore, 10% of the daily phytoplankton requirement of phosphorus was released from the benthos. If one considers only inorganic phosphorus exchange this value becomes 8% of the daily phosphorus requirement.

It appears that benthic nutrient exchange of nitrogen and phosphorus provide a significant fraction of the daily phytoplankton requirement. This result would agree with the conclusion of both Hale (5) and Rowe et al. (24). This conclusion, however, may be presumptuous of these data.

If one considers only the water within the La Jolla Bight over the 1.5 km long extended study area and assumes a mean net advection of 1.5 km d^{-1} , which is perhaps a conservative estimate of the actual mean net speed (Dr. Peter W. Hacker, Dept. Earth and Planetary Sciences, Johns Hopkins University), the residence time of water over the study area would be one day. In this region the yearly mean bottom water concentration of $\text{NH}_4^+ + \text{NO}_3^- + \text{NO}_2^- + \text{DON}$ was $10.8 \text{ } \mu\text{M N}$ or in the entire 18.3 m water column overlying one m^2 of sediment the total nitrogen content equaled $2.0 \times 10^5 \text{ } \mu\text{mol NO}_3^-$ and DON each comprised approximately 44% of this, while NH_4^+ and NO_2^- comprised 10% and 2% respectively. The benthic release of $745 \text{ } \mu\text{mol}$ of nitrogen $\text{m}^{-2} \text{ d}^{-1}$, therefore, represented only 0.4% of the nitrogen already in the water. For phosphorus the total water column concentration of PO_4^{-3} plus DOP was $1.8 \times 10^4 \text{ } \mu\text{mol}$ (PO_4^{-3} was 82% of the

total and DOP 18%) and the benthic release of phosphorus was $89 \mu \text{mol m}^{-2} \text{d}^{-1}$ or only 0.5% of the phosphorus already in the water.

The interpretation of these percentages in relation to the impact of benthic nutrient exchange on the overlying water nutrient chemistry and phytoplankton productivity in this region is that the mean yearly nitrogen and phosphorus benthic exchange resulted in an excess release (as regards phytoplankton requirement) of both nitrogen and phosphorus from the sediments, which, although significant as regards the phytoplankton requirement, was insignificant as regards the total content of nitrogen and phosphorus already in the water. It is recognized that the cumulative effect of benthic nutrient exchange over hundreds of kilometers of coastline can be enormous. Nonetheless, in the extended study area discussed here (Fig. 1) benthic nutrient exchange resulted in a net release of both nitrogen and phosphorus at rates exceeding the uptake ability of the phytoplankton in the time available, resulting in a net export of these nutrients from the region. If this station is not an exception, one can only conclude that in regions such as this there is not a close coupling between phytoplankton production, water nutrient chemistry and benthic nutrient exchange.

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Table 1. Nutrient exchange between the marine benthos and the overlying water.

Values given as release (+) or uptake (-) of the nutrient by the benthos.

Nutrient	Mean ($\bar{x}$)	Range ¹
NH_4^+	$+872 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-47 \text{ to } +3290 \mu \text{mol m}^{-2} \text{d}^{-1}$
NO_2^-	$+34 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-5 \text{ to } +97 \mu \text{mol m}^{-2} \text{d}^{-1}$
NO_3^-	$-77 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-720 \text{ to } +647 \mu \text{mol m}^{-2} \text{d}^{-1}$
PO_4^{3-}	$+77 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-438 \text{ to } +502 \mu \text{mol m}^{-2} \text{d}^{-1}$
DOP	$+12 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-28 \text{ to } +59 \mu \text{mol m}^{-2} \text{d}^{-1}$
DON	$-75 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-1326 \text{ to } +1280 \mu \text{mol m}^{-2} \text{d}^{-1}$
DOC	$-583 \mu \text{mol m}^{-2} \text{d}^{-1}$	$-30800 \text{ to } +23800 \mu \text{mol m}^{-2} \text{d}^{-1}$

¹Range - these values represent the highest uptake rates observed and the highest release rates observed.

Table 2. Results of replicate dark and light box experiments one and two (RD-I, II and RL-I, II). Units are $\mu\text{mol m}^{-2}\text{d}^{-1}$ released (+) or taken up (-). The means ($\bar{x}$) and the standard deviation as $\pm$ percent of the mean are given.

	ΔNH_4^+	ΔNO_2^-	ΔNO_3^-	ΔPO_4^{3-}	ΔDON	ΔDOP	ΔDOC
RD-I	+2.78	+0.260	0	+3.00		-0.880	-267
	+1.76	+0.140	0	+5.04	+17.6	+0.660	+ 83
	+3.90	+0.040	0	+3.06	+17.2	-1.10	+ 50
$\bar{x}$	+2.81	+0.147	0	+3.70	+17.4	-0.440	- 45
$\pm$	31%	61%	0	26%	0.1%	178%	230%
RD-II	+49.5	+1.46	+3.00	+11.1	+52.3	+1.48	-640
	+22.2	+0.994	+2.21	+ 3.70	+40.5	0	-563
	+47.8	+1.24	+3.60	+10.2	+27.4	+0.356	-328
$\bar{x}$	+39.8	+1.23	+2.94	+ 8.33	+40.1	+0.612	-510
$\pm$	31%	15%	19%	40%	25%	103%	32%
RL-I	+15.0	+2.05	-1.09	+2.07	+8.51	-0.63	-146
	+11.4	+1.24	-4.87	+3.84	+4.80	+0.17	-128
	+ 4.34	+1.16	-1.53	+1.85	-26.6	-0.59	-473
$\bar{x}$	+10.2	+1.48	-2.50	+2.59	-4.43	-0.35	-249
$\pm$	43%	27%	68%	34%	355%	105%	78%
RL-II	no data	+0.638	-1.30	-0.732	-26.3	+0.788	- 78
		+0.019	-0.56	-1.29	+17.1	+0.788	+532
		+0.638	+4.5	-0.338	-32.1	+0.300	+423
$\bar{x}$		+0.432	+0.83	-0.787	-13.8	+0.625	+292
$\pm$		68%	293%	50%	195%	45%	111%

FIGURE CAPTIONS

Figure 1. Study site (A) and extended study area (B: stippled area). Contour intervals are in feet.

Figure 2. Box type #2 showing "O" ring (A), end stop (B; 7.6 cm diameter clear-acrylic disc, 3.2 mm thick), plunger handle (C; 6.35 mm clear-acrylic rod), outer plunger support (D; clear-acrylic tubing 6.95 cm O.D. x 7.3 cm I.D. x 2.5 cm high, split at a point to allow for O.D. of "O"-ring support), "O"-ring support (E; clear-acrylic tubing, 7.6 cm O.D. x 6.35 cm I.D. x 9.5 cm high) and plunger (F; 6.35 cm O.D. x 5.1 cm I.D. x 19.0 cm long, is made of clear-acrylic tubing; outside machined to allow it to pass through "O"-ring support and to be water tight with use of "O" rings; end stop glued to plunger). Outer support and "O"-ring support glued to box which is made of 9.5 mm clear-acrylic plastic. Silicone stoppers and sample port are not shown. [Box type #1 had two polyethylene bags sealed to the box through one of the top holes instead of plungers.]

Figure 3. Temperature at experimental site ($\diamond$) and at the SIO pier at the surface (o) and 5 meter depth ($\bullet$).

Figure 4. Ammonia release (+) or uptake (-) by the benthos ($\mu\text{mol NH}_4^+ \text{ m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other values used data from light and dark boxes.

Figure 5. Nitrate release (+) or uptake (-) by the benthos ($\mu\text{mol NO}_3^- \text{ m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other values used data from light and dark boxes.

Figure 6. Nitrite release (+) or uptake (-) by the benthos ($\mu \text{ mol NO}_2^- \text{ m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other used data from light and dark boxes.

Figure 7. Phosphate release (+) or uptake (-) by the benthos ($\mu \text{ mol PO}_4^{3-} \text{ m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other values used data from light and dark boxes.

Figure 8. Dissolved organic carbon release (+) or uptake (-) by the benthos ($\mu \text{ mol DOC m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other values used data from light and dark boxes.

Figure 9. Dissolved organic nitrogen release (+) or uptake (-) by the benthos ($\mu \text{ mol DON m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, all other values used data from light and dark boxes.

Figure 10. Dissolved organic phosphorus release (+) or uptake (-) by the benthos ($\mu \text{ mol DOP m}^{-2} \text{ d}^{-1}$), (*) values used data from only dark boxes, (**) values used data from only light boxes, all other values used data from light and dark boxes.

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TOP VIEW

SIDE VIEW