Mangroves protected villages and reduced death toll during Indian super cyclone

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Protection against coastal disasters has been identified as an important service of mangrove ecosystems. Empirical studies on this service have been criticized, however, for using small samples and inadequately controlling for confounding factors. We used data on several hundred villages to test the impact of mangroves on human deaths during a 1999 super cyclone that struck Orissa, India. We found that villages with wider mangroves between them and the coast experienced significantly fewer deaths than ones with narrower or no mangroves. This finding was robust to the inclusion of a wide range of other variables to our statistical model, including controls for the historical extent of mangroves. Although mangroves evidently saved fewer lives than an early warning issued by the government, the retention of remaining mangroves in Orissa is economically justified even without considering the many benefits they provide to human society besides storm-protection services.

ecosystem services | India | forest | storm protection | natural disaster

The ability of mangroves to reduce damage caused by tsunamis and tropical storms is reportedly one of the most undervalued ecosystem services provided by such forests (1), but evidence supporting this claim is controversial. Studies conducted soon after the 2004 Indian Ocean tsunami reported that mangroves acted as bioshields, with villages located behind them suffering less damage than ones directly exposed to the coast (2, 3). In response to these findings and anecdotal evidence, organizations such as the United Nations Environment Program have emphasized rehabilitating ecosystems as a first line of tsunami defense (4). Subsequent publications criticized the initial studies, however, for being based on small samples and failing to control for confounding factors such as distance to coast (5–8). One recent review concluded that the value of coastal vegetation as a tsunami buffer is minor (9), and some critics have argued that promoting coastal green belts to guard against tsunamis diverts funding from early warning systems and evacuation programs and creates social injustices if rehabilitation projects evict coastal residents (6).

Some researchers who are skeptical about the ability of mangroves to protect against tsunamis have noted that mangroves might be more capable of protecting against tropical storm surges (6, 10). Storm surges differ from tsunamis in having shorter wavelengths and relatively more of their energy near the water surface (9). Theoretical models indicate that mangroves attenuate shorter waves more than longer waves (11), and field experiments confirm that relatively narrow strips of mangrove can substantially reduce the energy of wind-driven waves (12, 13). Although the ability of mangroves to provide protection against tropical storm surges has been debated since at least 1970 (14, 15), empirical studies that avoid the shortcomings of the tsunami studies are lacking.

Here we show that mangroves were associated with statistically significant reductions in human deaths during a super cyclone that struck the eastern coast of India in October 1999. Compared with the tsunami studies, we analyzed a much larger sample and controlled for a much wider range of factors that might have affected the observed number of deaths. We are aware of only one other study on the impact of mangroves on damage from this storm, and it analyzed just 3 villages (16).

The 1999 storm killed nearly 10,000 people, more than 70% of them drowned by its surge (17). The state of Orissa was hit hardest. We analyzed village-level data from Kendrapada District, which is a low-income, predominantly agricultural district in the state just north of the cyclone's landfall (Fig. 1). We focused on the 4 administrative units (*tahasils*) of the district that were inundated by the storm surge (17). This portion of the district is low-lying, with an average elevation of just a few meters (*District Planning Map for Cuttack*, *Jajpur*, *Kendrapada and Jagatsinghpur of Orissa*, Reg. No. 112-NA/DP-1000–1000, National Atlas and Thematic Mapping Organisation, Calcutta, 2000) and a maximum elevation of 5.61 m (18). In comparison, the height of the storm surge at the coast is estimated to have reached 5.9 m (19). Potential surge barriers included saltwater dikes in low-lying farmland, a few narrow (0.2–0.4 km) strips of casuarinas planted on coastal dunes, and mangroves. Trees in the genera *Avicennia*, *Ceriops*, *Excoecaria*, and *Heritiera* dominate Kendrapada's mangroves, with canopy heights rising from 2–3 m on the coast to 20 m inland (20, 21).

We analyzed the number of storm-related deaths in the 4 *tahasils*. Although 564 villages in the 4 *tahasils* were inundated by the storm surge, we limited our sample to the 409 villages that historically (as of 1944) had mangroves between them and the coast. We did this to ensure that any observed absence of mangroves as of 1999 was due to the loss of vegetation, not unsuitable habitat. Loss of mangroves represents the "treatment" in our study. Our null hypothesis was that, conditional on population and other relevant factors, villages with wider remaining mangroves between them and the coast had the same average number of deaths during the 1999 storm as villages with narrower or no mangroves. We tested this hypothesis by (*i*) compiling 1999 village-level socioeconomic data; (*ii*) using a GIS to measure the villages' spatial characteristics, such as 1999 mangrove width; (*iii*) using regression methods to estimate single-equation count-data models (poisson and negative binomial) that related the number of deaths to 1999 mangrove width, while controlling for potentially confounding variables (e.g., distance to coast and height of storm surge); and (*iv*) checking whether the regression coefficient on 1999 mangrove width was significantly different from zero. See *Data and Methods* for additional details.

Our study's focus on storm-surge damage, its village-level detail, and the range of controls we included distinguish it from a recent province-level study in Thailand, which reported that

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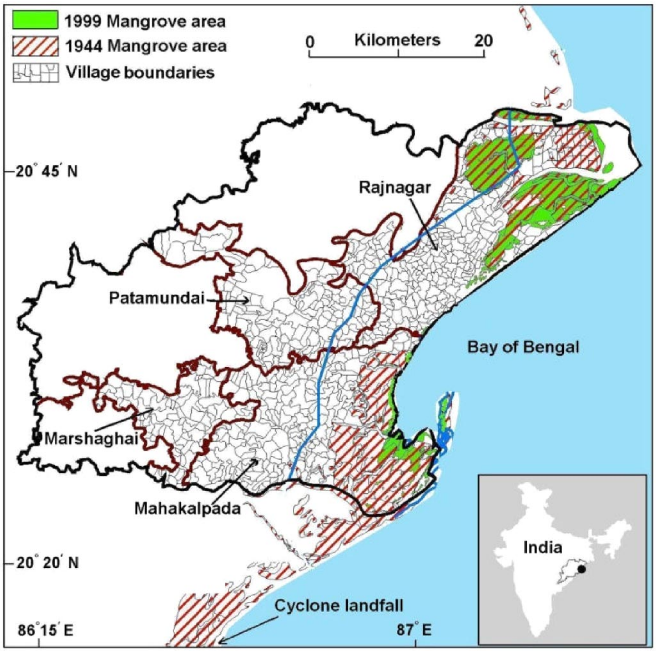

Fig. 1. Map of study site in Kendrapada District, Orissa state, India. Main map: black line represents district boundary; brown lines show boundaries of 4 *tahasils* inundated by storm surge; blue line is 10 km from the coast. Inset map: black line shows Orissa state boundary; dot represents the study site.

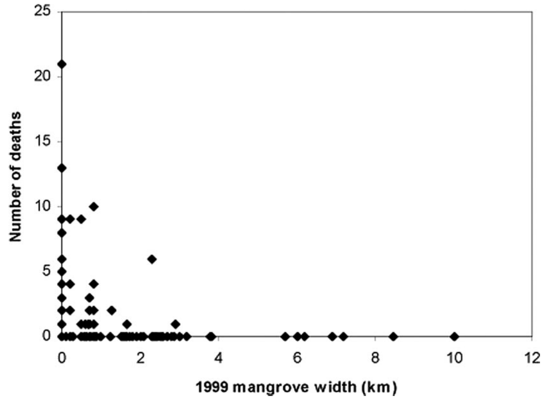

Fig. 2. Deaths per village during October 29, 1999, cyclone plotted against the October 11, 1999, width of mangroves between each village and the coast. Data are from 409 villages in the 4 *tahasils* of Kendrapada District, Orissa state, India, that were inundated by the storm surge.

mangroves reduced the incidence of coastal natural disasters (of all types, not just storm surges) during 1979–1996 (22).

Results

Mangrove Loss and Storm-Related Deaths. We measured mangrove width as the distance between the coast and the interior boundary of the forest along the shortest distance from each village to the coast. Average 1999 width across the 409 villages was 1.2 km, down from 5.1 km in 1944. Total mangrove area fell from 30,766 ha to 17,900 ha during the same period. Spontaneous agricultural expansion, mostly for rice, was the main cause, not government programs or commercial aquaculture (21). Remaining mangroves were in 2 major blocks. All were natural forests, with 93% being densely stocked according to the definition used by the Forest Survey of India (canopy cover >40%) (23).

The total number of deaths across the villages was 256, for an average of 0.63 (average village population = 1,002). The maximum was 21, and 307 villages had no deaths. The simple correlation of number of deaths with 1999 mangrove width was negative and significant ($r = -0.13$, $P < 0.01$; Fig. 2).

Regression Results: Full Sample. Our regression results rejected the hypothesis that 1999 mangrove width did not affect storm-related deaths (Table 1). (See Table S3 for full regression results.) The coefficient on 1999 mangrove width was negative and statistically significant ($P < 0.01$) when this variable was the only regressor other than population. It remained significant and changed little in magnitude as controls were progressively added for 1944 mangrove width; height of storm surge; topography; distances to the coast and other landscape features; socioeconomic characteristics; and government administration (the *tahasildar* is responsible for emergency response systems). The 1944 mangrove width is an important control because mangroves tend to occur in sheltered areas, which suggests that physical aspects of their habitat, not the vegetation itself, could be responsible for reducing damage (10, 24). The fact that the coefficient on 1999 mangrove width remained significant when we added this control implies that remaining vegetation did indeed play a protective role.

The cyclone made landfall on October 29. On October 26, the Orissa state government issued a warning to residents of villages within 10 km of the coast. Nearly 150,000 people from 4 districts, including Kendrapada, evacuated before the storm struck (17). To capture the impact of the warning, we allowed the regression constant and the coefficient on population to differ between the 154 villages within 10 km of the coast and the 255 villages beyond. The coefficient on 1999 mangrove width remained negative and significant, but the regression constant was much smaller for villages within 10 km than for those beyond (Table S4). This difference is consistent with the warning having a lifesaving impact, and its magnitude implies that the warning saved 5.84 lives per village within 10 km (Table S5). (The actual average death rate in these villages was 0.77.) To check this interpretation, we estimated the same model with the dependent variable (i.e., number of deaths) replaced by various measures of damage to houses, which being immobile should be less affected by the warning. Consistent with our interpretation, the 2 con-

Table 1. Estimates of regression coefficient on 1999 mangrove width: Full sample (409 villages)

Regressors in model, in addition to village population	Coefficient estimate: 1999 mangrove width
Only 1999 mangrove width	–0.631***
Add to above: 1944 mangrove width	–0.515***
Add to above: Height of storm surge at coast	–0.524***
Add to above: Topography (three 0–1 dummy variables: low elevation, casuarina buffer, seawater dike)	–0.519***
Add to above: Distances to: coast, minor rivers, major rivers, nearest road	–0.507***
Add to above: Socioeconomic characteristics: literacy rate, population share in scheduled castes, population shares in 5 occupations	–0.505***
Add to above: Government administration (0–1 dummy variable for each *tahasil*)	–0.485***

Estimates are from zero-inflated negative binomial models of number of deaths in villages in Kendrapada District, Orissa, India, during October 1999 cyclone. Variables were progressively added to those in preceding rows. ***$P < 0.01$ (two-tailed z tests). See Tables S1–S3 for variable descriptions and complete regression results.

Table 2. Estimates of coefficients on mangrove variables: Subsample of villages within 10 km of coast (154 villages)

Model and mangrove variable	Coefficient estimate
Model 1: Base model	
1999 mangrove width	−1.64***
Model 2: Add interaction with height of storm surge	
1999 mangrove width	−0.35
1999 mangrove width × height of storm surge at coast	−1.24
Model 3: Drop 1999 mangrove width	
1999 mangrove width × height of storm surge at coast	−1.54***
Model 4: Split interaction term according to height of storm surge	
1999 mangrove width × below-mean height of storm surge at coast	−1.85***
1999 mangrove width × above-mean height of storm surge at coast	−1.36***

Estimates are from Poisson models of number of deaths in villages in Kendrapada District, Orissa, India, during October 1999 cyclone. Other variables in the models were the same as in the model described in the last row of Table 1.

***$P < 0.01$ (two-tailed z tests); unmarked estimates, $P > 0.1$. See Table S7 for variable descriptions and complete regression results.

stants were not significantly different from each other in the house-damage models (Table S6).

Regression Results: Subsample of Villages Within 10 km of Coast. In view of the apparent difference between villages within and beyond 10 km of the coast, we reestimated the model separately for the 2 subsamples. The coefficient on 1999 mangrove width was significant ($P < 0.05$) only for the subsample within 10 km, and it was much larger than in the full sample (model 1 in Table 2). Mangroves evidently provided significant protection only within 10 km of the coast. If the impact of mangroves was indeed due to attenuation of the storm surge, then the coefficient on 1999 mangrove width should become insignificant when the interaction of that variable with storm surge is added to the model. This was the case (model 2). Although the interaction term was also insignificant, it was less so than the mangrove variable ($P < 0.138$ vs. $P < 0.701$), and it became significant ($P < 0.01$) when we dropped the latter from the model (model 3). Furthermore, if mangroves are less able to attenuate larger storm surges, then the coefficient on the interaction term should be smaller if the interaction is constructed using storm surge values above the mean rather than below. This too was the case (model 4).

As a final check, we added the distance of each village from the path of the cyclone eye to model 4 in Table 2. Average wind velocity is known to fall off with this distance. If deaths in our sampled villages were due mainly to high winds, then the storm surge variables should lose significance when we add this variable. Instead, the magnitudes and significance levels of the coefficients on the storm surge variables changed little when we added this variable, and the coefficient on the latter was insignificant (Table S8).

Predicted Impacts of Loss of Remaining Mangroves. Using model 4 in Table 2, we predicted that there would have been 1.72 additional deaths per village within 10 km of the coast if mangrove width had been reduced to zero (Table S9). This is a measure of the lifesaving impact of the mangroves that remained in 1999. It implies that the remaining mangroves saved 0.0148 lives per hectare. The average price of agricultural land near mangroves in 1999 was 172,970 rupees per hectare (personal communication, J. Dash, Indo-Asian News Service, Bhubaneswar, Orissa, June 10, 2007), which in turn implies that the average opportunity cost of saving a life by retaining mangroves was 11.7 million rupees per life saved. This is less than the value of reductions in mortality risks implied by wage differentials in India, which has been estimated as ranging from 13.7–14.2 million rupees (25) to 55.5–60.6 million rupees (26) per avoided death (we used the Indian consumer price index to convert the original estimates to the 1999 price level).

Discussion

Mangroves significantly reduced the number of deaths during the 1999 cyclone that struck the eastern coast of India. Statistical evidence of this lifesaving effect is robust, with the coefficient on 1999 mangrove width in our village-level regression analysis remaining highly significant after we controlled for a wide range of potentially confounding environmental and socioeconomic variables. By controlling for historical mangrove width, we revealed that the beneficial effect was mainly due to mangrove vegetation, not physical characteristics of mangrove habitat. Human impacts on the ecosystem (i.e., deforestation) thus affected the death toll. We emphasize that our findings refer only to deaths associated with tropical storms and might not apply to tsunamis, which we did not study.

Although an early warning issued by the government evidently saved more lives than mangroves did, our simple comparison of costs and benefits indicates that protecting remaining mangroves in Orissa is economically justified. And our comparison likely understates the case for protecting remaining mangroves, for 2 reasons. First, it ignores the value of the many other goods and services that mangroves provide (1). Second, it also ignores lives saved by mangroves during future storms: severe cyclonic floods occur in Orissa every 10 years, and moderate floods occur every 4 years (27). The case for mangrove protection would be even stronger if we accounted for these additional benefits.

Data and Methods

Data. We used October 11, 1999, images from the LISS-III Pan sensor of Indian satellite IRS-1D (23.58 m resolution) to map mangrove area just before the cyclone and a 1:250,000 U.S. Army map to determine the historical area (India and Pakistan AMS topographic maps, NF 45–14 Cuttack, Perry-Castañeda Library Map Collection, University of Texas at Austin; www.lib.utexas.edu/maps/ams/india/nf-45–14.jpg). The latter was based on 1929–1931 ground surveys, updated by 1944 aerial photographs. Extensive mangrove destruction did not start in Orissa until feudal land ownership was abolished in 1952 (28). We measured the height of the storm surge along the coast from a surge envelope curve constructed by the Indian Meteorological Department (19).

We used ArcView 3.2 to construct the spatial variables. We measured the distance of each village from the coast in 3 directions (southeast, east, northeast) and set the distance to coast equal to the minimum value. The minimum value was southeastern for most villages (63%) and eastern for nearly all of the rest (33%). We used the same direction in measuring 1944 and 1999 mangrove widths and height of the storm surge. The Kendrapada coast runs in a northeasterly direction (Fig. 1), and the cyclone came from the southeast, so for most villages the direction used was perpendicular to the coast and parallel to the cyclone path. The addition of dummy variables to control for the direction of the distance measurements did not change the regression results significantly, and the coefficients on these variables were not significantly different from zero (details available upon request).

The 3 topographical variables were 0–1 dummy variables, defined (in turn) as villages being located within the 1944 mangrove boundary (a proxy for low elevation), having a casuarina shelterbelt between them and the coast, or having a seawater dike within their boundaries. The government administration variables were also dummy variables, with one variable for each *tahasil* in the sample. We constructed socioeconomic variables for 1999 by interpolating values from the 1991 and 2001 population censuses. Occupation shares referred to 5 categories: cultivators, agricultural laborers, workers in home industries, marginal workers, and other workers. Means were not significantly different ($P < 0.05$) between villages with mangroves (i.e., 1999 mangrove width $\neq 0$) and ones without mangroves for any of the socioeconomic vari-

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ables. The ''control'' and ''treatment'' villages were thus not different on the basis of observable socioeconomic characteristics.

Regression Analysis. We used standard tests (χ^2 goodness-of-fit test for poisson, likelihood ratio tests for overdispersion and zero inflation, Vuong test) to determine the appropriate count-data estimator (poisson or negative binomial, with or without zero-inflation adjustment). The preferred estimators were zero-inflated negative binomial for the full sample and standard poisson for the subsample of villages within 10 km of the coast. The significance of the coefficient on 1999 mangrove width changed little when standard errors of the coefficients were clustered by *gram panchayat* (an administrative unit between *tahasil* and village), to account for nonindependence of errors between nearby villages, or constructed using the robust Huber-White sandwich formula, to account for unequal variances across villages (Table S10). Moran's *I* statistic indicated that regression errors were not spatially correlated (details available upon request), which is consistent with the similarity of the clustered and robust standard errors and with the lack of overdispersion in the sample of villages within 10 km of the coast (29).

Two villages had an unusually large (>10) number of deaths. Excluding these villages did not significantly change the coefficient on 1999 mangrove width in either the full sample or the subsample of villages within 10 km of the coast (details available upon request). The findings thus do not appear to be driven by outliers.

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