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Transitions in Ancient Inland Freshwater Resource Management in Sri Lanka Affect Biota and Human Populations in and around Coastal Lagoons

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Summary

The increasing anthropogenic pressure on natural environments results in impacts that affect tropical forest areas and their biodiversity [1, 2]. Adverse impacts on terrestrial and oceanic environments often compound in the intertidal area, where mangrove forest ecosystems thrive. In tropical coastal areas of many developing countries where people depend on wood and other mangrove forest products and services, forest degradation leads to socioeconomic problems. At the same time, increasing freshwater needs in these areas are expected to cause additional problems [3–5]. On the basis of remote sensing and ground truthing complemented by colonial archival material from the Dutch East India Company (1602–1800), we report that changes to the historic system of inland freshwater management have increased dramatically in recent times. Hydrological changes, such as interbasin transfers, have resulted in a qualitative ecological and socioeconomic degradation in three coastal lagoons in southern Sri Lanka. Variations in river hydrology have caused changes in the areas suitable as mangrove habitat and, thus, have resulted in an altered distribution. However, increases in mangrove area can mask the degradation of the site in terms of floristic composition, significance of the species, and biodiversity (this effect is termed "cryptic ecological degradation"). It is important that such changes be carefully monitored to ensure biological and socioeconomic sustainability.

Results and Discussion

Sri Lanka has a long-standing tradition of water resource management. For several millennia, lake-sized water reservoirs sustained highly developed cultures, even in the dry environments of Anuradhapura, the Sinhalese capital from 437 B.C.E. to 1017 C.E., which developed into a metropolis of great importance [6]. This former capital is now a UNESCO World Heritage Site [7]. Out of an estimated 30,000 man-made reservoirs built in ancient times, over 10,000, with a total area exceeding 170,000 ha, are still scattered across the country, and many are restored and functional today [8].

In the 20th century, the freshwater needs of people have led several Sri Lankan governments to initiate major water management projects for socioeconomic development. Irrigation has been prioritized, but the technology and magnitude of contemporary hydrological projects are different from historical water-management policies. Storage reservoirs and diversion weirs have been used for irrigation since ancient times [9], but increasingly the diversion of river systems is used in freshwater management.

The Walawe Ganga river basin (Figure 1) has historically been used by man for irrigation purposes, as shown by an ancient water course near the Samanalawewa Dam. Archaeological remains of a first millennium C.E. iron-smelting industry [10] and an ancient Hambegamuwa Reservoir [11] have been found upstream, whereas downstream the legacy of ancient Sinhalese irrigation systems is represented by the Thenketiya diversion channel and the Magama or Urusitta Reservoir [9, 11]. With the foundation of the Irrigation Department at the beginning of the 20th century and the adoption of a Water Resources Development Plan in 1959, modern irrigation and hydropower development began. The Udawalawe Scheme was constructed between 1964 and 1981 and formed the 3,400 ha Udawalawe Reservoir, containing 268.76×10^6 m^3 water at full supply [4, 12], and associated canals. The purpose of the Udawalawe Scheme was to provide irrigation water for 32,000 ha of newly developed land, particularly paddy fields, and to generate hydroelectricity [13]. Consequently, additional freshwater was diverted into the river basins of the nearby Kuchchigal Ara, Urubokka Oya, and Kirama Oya rivers (Figure 1). The aim of this study is to quantitatively and qualitatively assess the biological impact of these transitions from ancient small-scale to modern large-scale freshwater resource management on the biota and human population in a set of three coastal lagoons. To investigate this, we used a unique interdisciplinary approach that tran-

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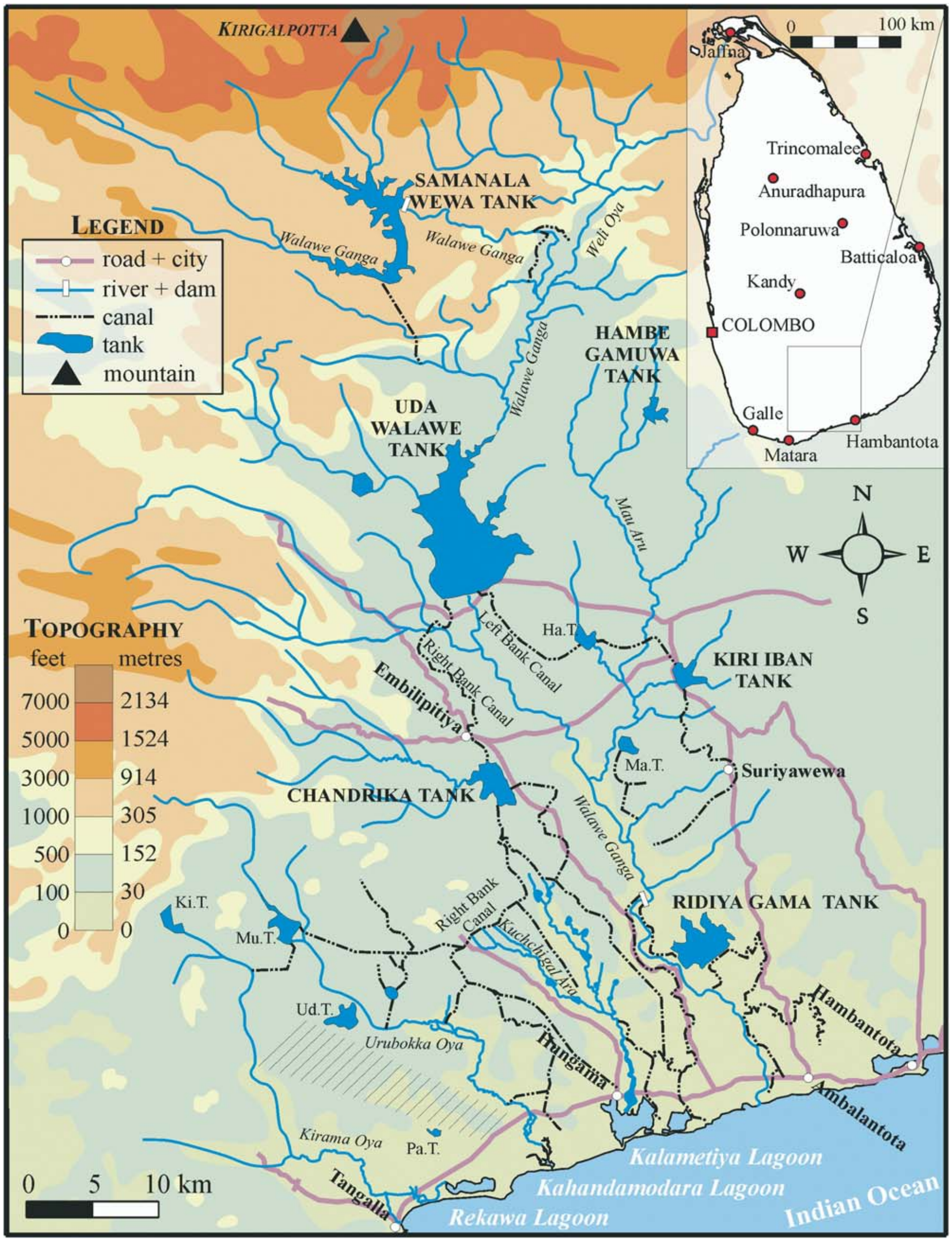

Figure 1. Geographical and Hydrographical Settings

River basins of Walawe Ganga, Kuchchigal Ara, Urubokka Oya, Kirama Oya, and their tributaries, with indication of the main irrigation channels originating from the Udawalawe Scheme. For map composition details, please refer to the Study Sites section of the Experimental Procedures in the text. Particularly in the lower topographic areas (0–152 m), a complex network of paddy and chena fields in between the rivers and the irrigation canals connects the different catchments (e.g., shaded area; see cover photograph of this issue of *Current Biology*). The following reservoir or tank (T) abbreviations were used: Ha, Habaralu; Ki, Kirama; Ma, Mahagama; Mu, Muruthawela; Pa, Pattiyapola; and Ud, Udukiriwala.

scends the sciences and combines disciplines from the basic and applied sciences (biological and vegetation sciences, geosciences) with disciplines from the social and human sciences (socioeconomic surveys, archive research). The main finding of the study is that increase of freshwater flow to these lagoons has led to a quantitative increase in mangrove forest areas, which is masking a disastrous qualitative shift from typical vulnerable mangrove species to eurytopic mangrove associates and minor mangrove vegetation elements. These changes will also have an impact on ethnobiological relationships.

Remote sensing, ground-truthing data, and information obtained from local informants show major transitions in spatial extent, structure, and species composition of mangrove vegetation, in faunal elements, and in subsistence livelihoods in three southern Sri Lanka lagoons: Rekawa, Kahandamodara or Tillawatawana,

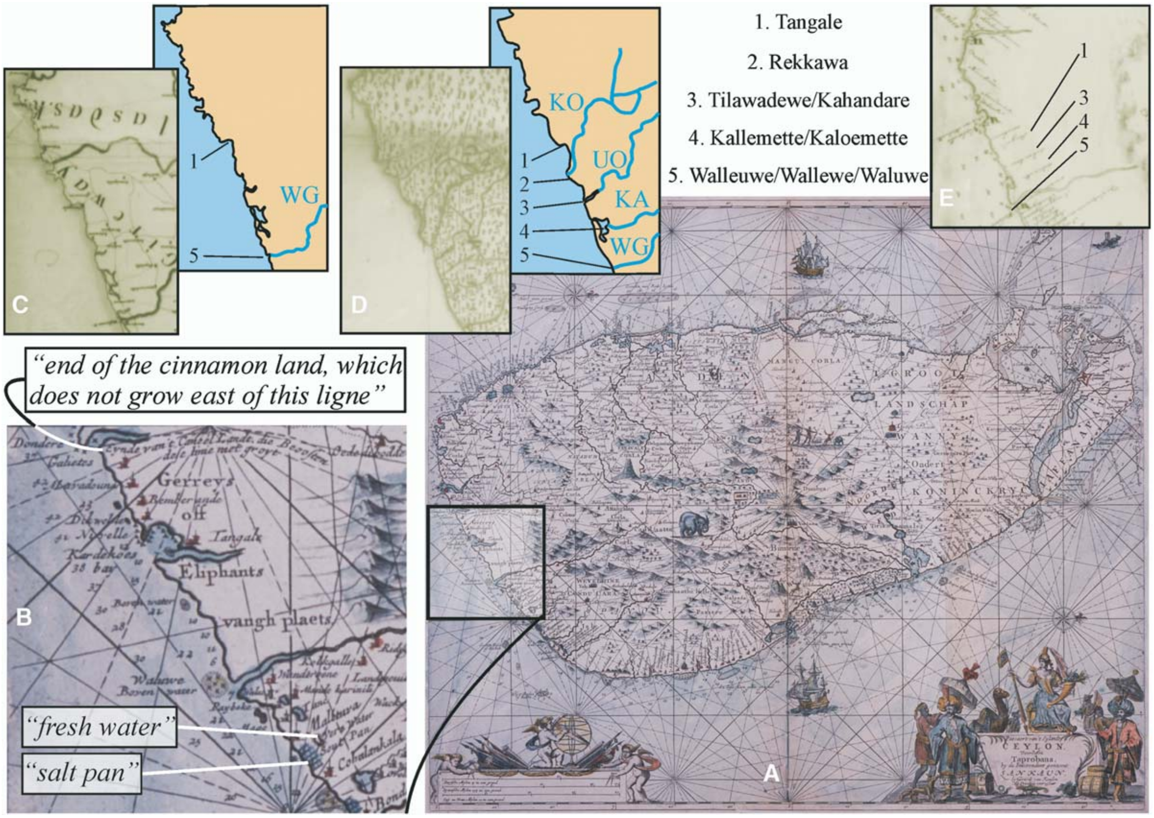

Figure 2. Cartographic Historic Archives (18th Century) from the Dutch East India Company

(A) Map of Sri Lanka of 1753 (by Gerard Van Keulen); a close-up of the southern section (B) shows the locations of the Walawe (*Waluwe*) River, Tangalla (*Tangale*), adjacent to Rekawa Lagoon, and the eastern limit of cinnamon plantations, as well as indications of fresh water and salt formation. Translations from Dutch are italicized.

(C and D) Close-up sections from 18th century maps show the location of the three lagoons under study: Rekawa, Kahandamodara, and Kalametiya. The rivers in our study area and the edge between land and ocean have been digitized from the historic maps to accentuate the positions of the lagoons and their hydrography.

(E) 18th century map particularly highlighting the names of the lagoons under study.

The legend shows the names of the lagoons as they appear on the historic maps (in logical figure order where differential). Recent naming and spelling is as follows: 1, Tangalla; 2, Rekawa; 3, Tillawatawana or Kahandamodara; 4, Kalametiya; and 5, Walawe. The map in (D) was drawn by Duperron (1789), whereas maps (C) and (E) are anonymous. The orientation of all maps is with the north to the right, regardless of text orientation.

and Kalametiya Lagoon (see the Study Sites section in the Experimental Procedures). These transitions are the result of upstream hydrological changes in the Walawe Ganga, and they exceed those modeled [14] as possible effects of the Udawalawe Scheme. The three lagoons differ in hydrographical complexity, but all have originally received freshwater runoffs of between 220 and 400 × 10^6 m^3 y^{-1}. The cartographic and written archives of the Dutch East India Company reveal that Sri Lankan lagoons displayed a natural variability [15, 16]. They also show that fresh water, natural salt formation, and salt pans, indicators of salinity, were present at the time [16] (Figures 2A and 2B) and that the lagoons and rivers have been in their present place for over 300 years (Figures 2C–2E).

Comparison of maps from 1956 and 1994 clearly shows that over 38 years, the area of "mangrove," which includes major, minor, and associate species, according to the Forest Department [17], displayed between 24% and 550% net increase in mangrove area, depending on the lagoon (Figure 3; Table 1). Moreover, it is observed that the area of increased mangrove cover in each lagoon is dominated by a particular species or species assemblage. Previously dominant mangrove species may have been displaced or disproportioned, as evidenced by the calculation of areas of mangroves that had disappeared, increased, or remained unchanged (Table 1). Only the mangrove associate *Acrostichum aureum* L. in Kahandamodara (+59%), and only *Sonneratia caseolaris* (L.) Engler, which is adapted to freshwater conditions, increased in Kalametiya (+2989%). The increased areas in Rekawa lagoon are dominated by *Avicennia marina* (Forsk.) Vierh., *Avicennia officinalis* L., *Aegiceras corniculatum* (L.) Blanco, and *Excoecaria agallocha* L. (+196%), or by a mixture of *Avicennia marina*, *Excoecaria agallocha*, and *Lumnitzera racemosa* Willd. (+4% Mixed mangrove, Figure 3). Most of these species are adapted to high salinity conditions.

Mangrove formations are spatiotemporally dynamic

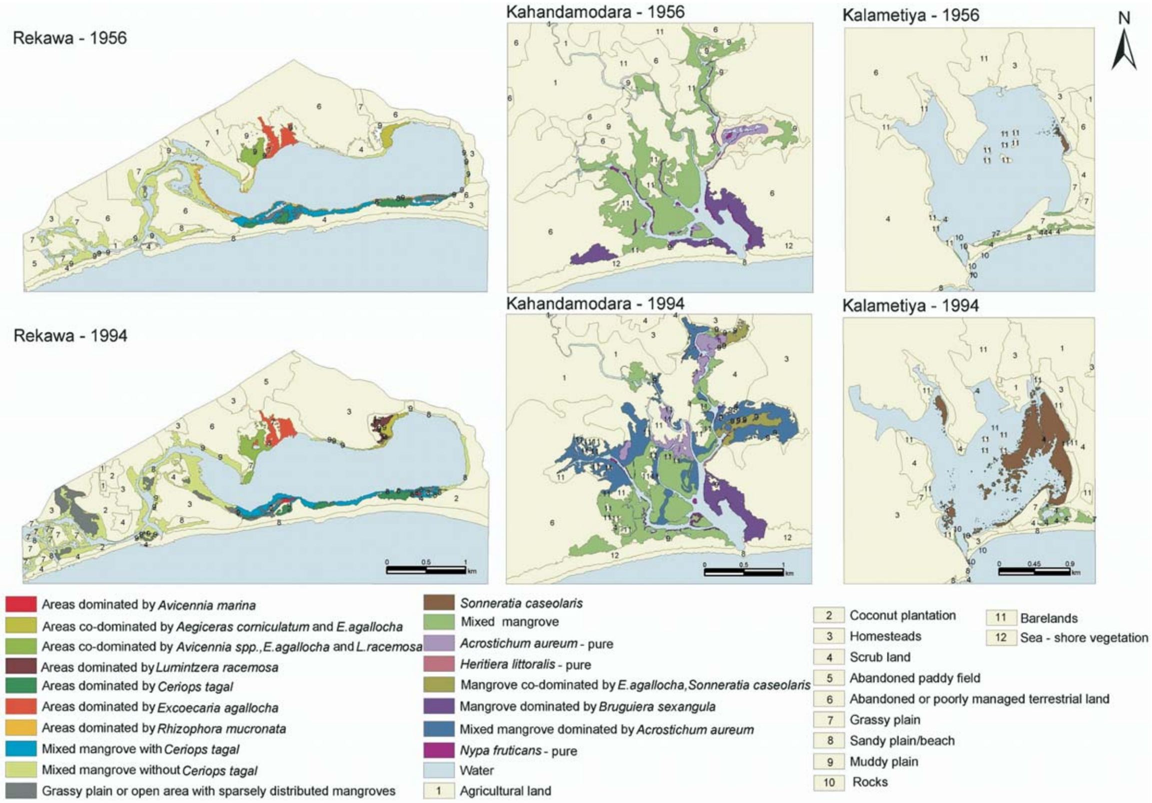

Figure 3. Sequential Remote-Sensing Maps

Distribution of different mangrove assemblages and non-mangrove land-use/land-cover classes in Rekawa Lagoon (left column), Kahandamodara Lagoon (middle column), and Kalametiya Lagoon (right column) in 1956 (top row) and 1994 (bottom row), as detected from aerial photography. See Table 1 for quantitative results.

systems, both qualitatively (species composition) and quantitatively (relative area) [15–21]. An entire riverbed displacement, as observed in the Indian Godavari Delta twice within a century [22], or the impacts of coastal infrastructural projects in Sri Lanka [21] may be part of the dynamism, but they seldom result in large quantitative or qualitative transitions in a short period. We maintain that the reported changes, for the present temporal and spatial scale, were not due to natural dynamics because it usually takes hundreds of years for significant canopy turnover to occur [18, 19].

Decreases in mangrove area because of human action are reported from all over the (sub)tropical world [23], but natural or man-induced increases in mangrove

Table 1. Quantitative and Qualitative Changes in Areas Covered by Different Mangrove Assemblages

Lagoon	Mangrove Species/ Assemblage	Area in 1956 (ha)	Area in 1994 (ha) and Areal Change with Respect to 1956 (%)	Details of Areal Change in ha between 1956 and 1994		
				Disappeared	Unchanged	Newly Grown
Rekawa	A.spp+E.aga+A.cor	12.9	38.2 (+196.1%)	2.9	10.0	28.2
	Mixed mangroves	90.3	94.3 (+4.4%)	18.3	72.0	22.3
	All mangroves	103.2	132.5 (+28.4%)	21.2	82.0	50.5
Kahandamodara	*Acrostichum aureum*	44.2	70.2 (+58.8%)	1.0	43.2	27.0
	Mixed mangroves	89.3	95.3 (+6.7%)	13.0	76.3	19.0
	All mangroves	133.5	165.5 (+24.0%)	14.0	119.5	46.0
Kalametiya	*Sonneratia caseolaris*	4.5	139.0 (+2988.9%)	0.0	4.5	134.5
	Mixed mangroves	19.5	17.0 (–12.8%)	13.0	6.5	10.5
	All mangroves	24.0	156.0 (+550.0%)	13.0	11.0	145.0

Areal coverage of the mangrove area of each lagoon in 1956 and 1994 and the net change of mangrove cover in hectares and in percentage of former area for each assemblage and for the totality of the mangrove forest, with additional details of disappeared, unchanged, and newly grown mangrove area (A.spp = *Avicennia marina* + *A. officinalis*; E.aga = *Excoecaria agallocha*; A.cor = *Aegiceras corniculatum*; mixed mangroves include all the species recorded from the relevant lagoon, as given in the text, and include the representatives from the Rhizophoraceae). See Figure 3 for a detailed map overview.

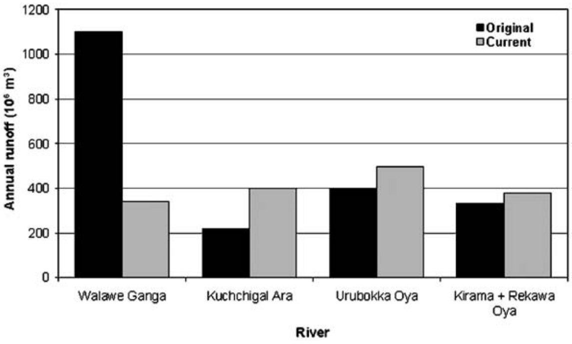

Figure 4. Runoff Changes Owing to the Waterwork Infrastructure

Comparison between the average annual runoff before and after the construction of the Udawalawe Scheme. For calculation details and statistics, please refer to the Hydrological Calculations section of the Experimental Procedures.

area are rarely reported. Mechanisms such as reduction of anthropogenic pressure on mangroves, which would naturally increase mangrove vegetation, or artificial mangrove-habitat expansion [24] that would allow an increase in the extent and frequency of tidal inundation were not observed in our study area. Abandonment of plantations of cinnamon (see Van Keulen's map in Figures 2A and 2B) or coconut [21], reported in specific coastal areas elsewhere in Sri Lanka, is also not applicable to our sites (Figure 3). Comparison of land uses in areas surrounding the mangrove in each lagoon indicates that the extent of agricultural lands and settlements has increased from 1956 to 1994. This undoubtedly leads to an increased impact and reliance on mangrove resources in view of common utilization patterns [25], although there are no data to corroborate this for these particular sites. Also, the report of increased fragmentation of the mangrove areas along the coast in Sri Lanka [26] indicates that there has been no reduction in anthropogenic pressure. There was also no evidence or report of replanting or other campaigns to artificially increase the mangrove area in any of the three lagoons in the past.

As evidenced by the Central Environmental Authority (CEA)/Euroconsult [13] and the Sri Lanka Survey Department's 1:50,000 topographic maps from 1985 (Figure 1), the freshwater inflow channels leading into each of the lagoons have increased with the operation of the Udawalawe Scheme in 1967. Prior to this, the lagoons received freshwater only from their natural river catchments during the winter rainy season. This was corroborated by our hydrological calculations, which indicate a decrease in runoff for the Walawe River as a result of the construction of the Udawalawe Scheme, while the runoff of the rivers feeding the three study lagoons increases (Figure 4; see also Figure S1 in the Supplemental Data available with this article online). In addition, the Udawalawe Scheme receives and diverts runoff from the wet-zone areas, where average annual precipitation ranges between 2000 and 5000 mm. However, the catchments of the rivers leading to our study lagoons are located almost entirely in the intermediate and dry zones, where the average annual precipitation is no more than 2000 mm [27]. Scientific water-quality studies were not carried out in the three lagoons before the construction of the Udawalawe Scheme. However, socioeconomic evidence shows that the lagoons were much more saline prior to the commencement of the scheme. People report distinctive changes to freshwater conditions by the decrease in the number of lagoon fisherman families and by the quantity, type, and quality of fish and shellfish caught. The presence of luxuriously growing freshwater plants and invasive pests such as *Salvinia molesta* D.S. Mitchell and *Eichhornia crassipes* (Martius) Solms-Laubach, species to which lethal levels of salinity are as low as 3 g/l^{-1} [28, 29], indicates a change to freshwater conditions. The new use of lagoon water for drinking, bathing, and washing [30] is also indicative of such a change. Similarly, an assessment of the opinions of users of the water in the upper Nilwala Ganga, about 30 km southwest of the Udawalawe Reservoir, reported adverse changes in water, soils, forests, grasslands, wildlife, and biodiversity [31]. Increased siltation in the lagoons as a result of irrigation water flushing paddy fields, along with a more regular distribution of freshwater on one hand and a less regular distribution of salt water on the other hand, also produces conditions favoring mangrove establishment.

However, the reported increases in mangrove extent are in no way indicative of a healthy status or dynamic equilibrium of the mangroves, nor of a properly protected and managed ecosystem. The increases at Rekawa, Kahandamodara, and Kalametiya Lagoons (+196%, +59%, and +550%) have favored species that are considered mangrove associates (e.g., the herbaceous mangrove fern *Acrostichum aureum*) that are either adapted to low salinity conditions or euryhaline (e.g., *Sonneratia caseolaris*, *Avicennia officinalis*, and *A. marina*) or that are tolerant to disturbance (e.g., *Excoecaria agallocha*) [32]. Members of the Rhizophoraceae did not expand significantly or were reduced in the lagoons (+4%, +7%, and –13%, respectively). The Rhizophoraceae are the most vulnerable from an ecological point of view [33–35], most valuable and affected from an ethnobotanical point of view [25, 36, 37], and most characteristic of mature natural mangroves from an aesthetic point of view [34, 35].

Ominously, the reported relative increases in "mangrove" area (e.g., *Acrostichum aureum*) indicate degradation of the strict mangrove species composition. The reported changes have an adverse effect on the faunal assemblages of fish and shellfish [30, 38, 39] and of crabs [40]. Also, people in subsistence-economy-based fishing communities have specific uses for true mangrove species [25, 37]. Increased river discharge may also have positive impacts on the production in estuaries [41]. However, it is not known to what extent positive impacts or novel uses in the area outbalance functions and services lost by degradation. The use of *Acrostichum aureum* as a vegetable or *Sonneratia caseolaris* fruit juice, jam, and ice cream (personal observation) can be considered novel uses, whereas *Acrostichum aureum* can inhibit the establishment of mangrove propagules [42]. Effects on offshore biotopes or faunal assemblages, owing to change in breeding, spawning, hatching, and nursery grounds in the affected mangrove areas [39], cannot be ascertained, but should not be excluded from consideration.

All the above floral, faunal, and human elements are closely linked or dependent on the mangrove for survival. The ecological, social, and economic consequences of major hydrological projects, even far upstream, need early consideration, particularly taking into account increasing local [3, 4] and global [5] freshwater demands. This Sri Lankan study exemplifies how changes in historic-freshwater resource management can increase in magnitude over a relatively short time period and can result in qualitative ecological and socioeconomic degradation that is masked by an easily detectable quantitative increase in vegetation (this effect is termed “cryptic ecological degradation”). However, many other waterworks around the world, some small scale, but many with much more ambition, will lead to similar or greater effects on downstream ecosystems [43]. This study therefore illustrates the global need for monitoring and early warning of degradation for coastal ecosystems such as mangroves, which also act as physical barriers against ocean influences. The use of very high-resolution remote sensing can provide much useful information on disappearence of or changes to typical species assemblages (species shifts, introgression by mangrove associates) at an early stage [44].

Experimental Procedures

Study Sites

Rekawa lagoon is shallow, with its western end connected to a deeper ocean canal that regulates both inflow and outflow. However, the lagoon does not have a continuously free ocean connection because its mouth frequently closes through sand-bar formation, a phenomenon observed since the 17th century for Sri Lankan lagoons and rivers ([15, 16]; Supplemental Data). For rivers, this may lead to a localized repositioning of the mouth just before they discharge into the sea. A branch of the Kirama Oya, the major freshwater inflow of Rekawa Lagoon, forms a rather complex network of channels before connecting to the mouth and the inflow-outflow canal. A mixed mangrove belt of a varying thickness fringes this network of channels, the inflow-outflow canal, and the lagoon.

The joining of Urubokka Oya, the major freshwater inflow, with three short channels makes up Kahandamodara Lagoon, the smallest of the three estuarine lagoons. It forms a small water body with a narrow mouth that opens to the ocean, but this connection is also not continuous. Mixed mangroves and mangrove associates predominantly cover small islands and banks of the canals.

Kalametiya Lagoon has the largest surface area, but more than 75% of the lagoon is shallow (<0.5 m) and covered with marsh vegetation. Only the lagoon mouth contains open water, to about 1.5 m in depth. The freshwater inflow to the lagoon is the Kuchchigal Ara, which receives freshwater influx from paddy fields upstream (see cover photograph of this issue). Mangroves of the Kalametiya Lagoon cover a considerable portion of the shallow area of the lagoon and part of the seaward bank.

There was no single detailed map available of the river basins of Walawe Ganga, Kuchchigal Ara, Urubokka Oya, Kirama Oya, and their tributaries with indication of the main irrigation channels originating from the Udawalawe Scheme. Therefore, we compiled a map from the Project Basic Plan of the River Valley Development Board of 1972, the Sri Lanka Survey Department’s 1:1,000,000 orohydrographic map of 1976 and 1:50,000 topographic maps of 1985, and a 1987 reconnaissance survey carried out by the Japanese International Corporation Agency (JICA, Tokyo, Japan) on the Walawe Irrigation Upgrading and Extension Project. No satellite images of submeter resolution were available for the study area to corroborate the above maps. Conflicts between the basic maps were minimal and were sorted out by following the most detailed topographic maps. The resulting map is given in Figure 1.

Remote Sensing and Ground Truth

Two sets of aerial photographs per lagoon (1956 at scale 1: 40,000 and 1994 at 1:20,000) were scanned at 600 dpi. The digital images obtained were georeferenced to the standard Sri Lanka Survey Department's 1:50,000 topographic maps of 1985 within the geographic information system (GIS) Arc-View 3.2 (ESRI, USA) with a set of ground control points measured with GPS (Global Positioning System). Lagoons, mangrove areas, and adjoining land uses were identified, and the corresponding polygons were drawn onscreen. Differences in image attributes such as texture, structure, and tonality for the mangrove crowns, as formerly used in identification keys for retrospective sequential aerial photography [21], were used to delineate mangrove assemblages. The coverage of 1956 and that of 1994 were superimposed in the GIS with GPS-measured ground control points to quantify changes in the different assemblages. Because the photographs were scanned at high resolution and were geocorrected to a common spatial reference, the same level of crown detail (at a given zoom level) was available for the two dates, and the scale difference of the original hard-copy documents did not, therefore, hamper the on-screen identification.

The mangrove assemblages delineated on the 1994 aerial photograph were verified with ground information acquired during field visits. A 5-m-wide georeferenced belt transect was established perpendicular from the shore of the lagoon to the landwater margin of the mangrove vegetation in each assemblage. Georeferencing was not only carried out with GPS, but also by individual trees that were clearly visible on the images and in the field. Each transect was subdivided into 5 m × 5 m quadrants in which the density of each constituent species (mangroves and mangrove associates) was recorded. Along the middle line of each belt transect, we also sampled adult trees at 10 m intervals through the Point Center Quarter Method or PCQM [45]. For individuals with a girth $G_{130} >$ 13 cm (term according to Brokaw and Thompson [46] but formerly referred to as the girth at breast height, i.e., 130 cm above the floor along the stem), sample-point-to-nearest-tree-distance, G_{130}, height, and crown diameter were recorded following Cintrón and Schaeffer Novelli [45]. Unusual tree architectures were approached as described by these authors [45]. Visualization of PCQM data through GIS-based overlay analysis was a possible way to link the field data to the remotely sensed imagery [21, 47]. Also, the plot density data and construction of intertidal profile diagrams were used to verify species dominance in each assemblage and to ground-truth the vegetation maps. In addition, all delineated vegetation assemblages and land-use classes were visited in the field. Values of relative density, relative dominance, and relative frequency of each constituent species were calculated and used to characterize and label the assemblages.

Socioeconomic Survey

People who were older than 55 years of age, had been living adjacent to the lagoons all their lives, and had been involved in lagoon-related activities were interviewed. As reported for Kalametiya [30], the numbers of people that correspond to these criteria were unfortunately limited (n = 5 or 6 for each of the lagoons). The respondents, aged between 55 and 84 years, provided the type of information we were seeking with respect to changes in water quality and use, mangrove flora and fauna, fisheries (catch quantity and quality, fishermen family demography), and connection between the lagoon and the ocean.

Hydrological Calculations

A comparison was made of the average annual runoff for each of the catchments leading to the lagoons before and after the construction of the Udawalawe Scheme. This comparison was based on total water balance (see Equations 1 and 2), the calculation of which is one of the most basic in hydrology and highly relevant in this type of study [48, 49]. For the Walawe River, original and current flow data were obtained from the International Water Management Institute (IWMI). For the rivers feeding the three study lagoons, flow data representing an original situation without water development works were obtained from a long-term hydrometeorological study [3]. For current flow, calculations are based on a calculated return flow of irrigation water from the Udawalawe Reservoir to the study catchments; the calculations take into account irrigation demands and surfaces [12] and reservoir and crop evaporation and evapotranspiration rates [12, 50] (Figure 4). Infiltration into groundwater is a negligible factor because no major groundwater aquifers have been found anywhere in the Walawe basin [13]. There was also no indication of a significantly larger precipitation after the hydrological works. On the contrary, national and local long-term hydrometeorological studies in the south of Sri Lanka report either no significant trends or a decrease in rainfall and runoff over the past four decades [27, 51, 52]. In the original situation, the total discharge for the Walawe catchment and the three lagoons equalled 2050 × 10^6 m^3. This is reduced in the current situation to 1616 × 10^6 m^3 because of an increased evapotranspiration of 460 × 10^6 m^3 from the irrigation schemes and the reservoirs fed by the Walawe River. The total water balance of the entire system is not significantly different before and after the hydrological works ($\chi^2 = 0.150$; degrees of freedom = 1; $p > 0.1$ not significant). The decrease in discharge in the Walawe River is compensated by an increased evapotranspiration but also by an increased discharge to the three lagoons as a result of the return flow from the irrigation schemes (Equation 1):

$$Q_W(t_0) - Q_W(t_1) \approx E_{UWS} + \sum_{i=1}^{3} RF_i \qquad (1)$$

where Q_w is the discharge of the Walawe Ganga in the original t_0 and current situation t_1, E_{UWS} is the evapotranspiration from the large water reservoirs and the Udawalawe irrigation Scheme (UWS), and RF_i is the UWS return flow that feeds the lagoon rivers Kuchchigal Ara ($i = 1$), the Urubokka Oya ($i = 2$), the Kirama, and Rekawa Oya ($i = 3$). RF_i is defined as:

$$RF_i = [ID_{UWS} - (IS \times ET_{paddy})] \times EPRF_i$$
$$\text{with} \sum_{i=1}^{3} EPRF_i = 1 \qquad (2)$$

with where ID_{UWS} is the irrigation demand of the UWS, IS is the irrigation surface, ET_{paddy} is the evapotranspiration from the paddy fields, the main crop, and $EPRF_i$ is the estimated proportion of return flow from the UWS to river i. High return flow from old irrigation schemes is a well-known problem and in many cases a major contributor to water-dependent valuable areas downstream of the irrigation schemes [49]. As is shown from the water balance evaluation of the Walawe River, the return flow from the irrigation schemes is the major cause of the increased fresh water inflow to the lagoons. The increases (Figure 4) are significant for the Kuchchigal Area and the Urubokka Oya ($50.616 < \chi^2 < 396.057$; d.f. = 1; $0.001 < p < 0.01$), but not for the Kirama/Rekawa Oya ($\chi^2 = 3.185$; d.f. = 1; $0.05 < p < 0.1$ n.s). This reflects the geographic position of the three lagoons and the number of artificial irrigation canals feeding their catchments (Figure 1), and it is also reflected in the degree of quantitative and qualitative changes (Table 1, Figure 3).

Supplemental Data

Some supplemental information and one supplemental figure are available at http://www.current-biology.com/cgi/content/full/15/6/579/DC1/.

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The tsunami disaster on December 26, 2004 affected our mangrove sites and many people we know; we feel that the antierosion function of mangroves has been paid too little attention. For years, we, together with many other scientists, have critically assessed and criticized the conversion of mangroves to tourist resorts or shrimp farms in light of the ecological, socioeconomic, and physical function of these forests. An early warning system to announce the arrival of tsunamis or other ocean surges (let us not forget that the much more frequent cyclones locally have the same effect) can save many lives, but an additional early warning system such as the one introduced in this paper to detect obvious or cryptic mangrove degradation may even save more in those areas where mangroves protect communities living behind and within the mangrove forest. We dedicate this paper to all those who were affected by the tsunami, particularly those who, were it not for inappropriate land management, could have been helped by mangroves.

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