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An ecosystem service value assessment of land-use change on Chongming Island, China

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Abstract

Chongming Island is the world's largest alluvial island. Its coastal wetland and tidal flats provide many important ecological services including buffers against tidal surges and staging areas for migratory birds. Due to its extraordinary resources, scenic qualities, and its proximity to the city of Shanghai 45 km away, the island is also an attractive tourist destination, and it supports important agricultural and fisheries economies. Yet, large-scale land reclamation projects that are severely affecting these ecosystems have been implemented. In this paper, we report an investigation of changes in land use and ecosystem services on Dongtan (East Beach of Chongming Island) between 1990 and 2000. We used three LANDSAT TM and/or ETM data sets to estimate changes in the size of five land-cover/land-use categories, and we also used previously published value coefficients to estimate changes in the value of ecosystem services delivered by each land category. Finally, we ranked the contribution of various ecosystem functions to the overall value of the ecosystem services. We determined that the total value of ecosystem services in Dongtan declined by 62% from \$ 316.77 to 120.40 million per year between 1990 and 2000 (totaling \$855.26–981.85 million over 10-years). This massive decrease is largely attributable to the 71% loss of wetlands/tidal flats. Our sensitivity analysis suggested that these estimates were relatively robust. We also found that the contribution of water regulation, water supply, waste treatment, and raw materials increased, while the contribution of nutrient cycling, food production, disturbance regulation, recreation, habitat/refugia, and biological control decreased during the 10-year time period. We conclude that future land-use policy formulation should give precedence to the conservation of these ecosystems over uncontrolled reclamation, and that further land reclamation should be based on rigorous environmental impact analyses.

Keywords: Chongming Island; Coastal wetlands; Ecosystem services; Land use; Reclamation; Remote sensing; Tidal flats

Introduction

Economic valuation of ecosystem services is becoming more widely used to understand the multiple benefits provided by ecosystems (Guo et al., 2001). Ecosystem services represent the benefits that living organisms derive from ecosystem functions that maintain the Earth's life support system. They include nutrient cycling, carbon sequestration, air and water filtration, and flood amelioration, to name a few (Costanza et al., 1997, 1998). Since 1990 numerous studies have been conducted to estimate the values of various ecosystem services. Some notable examples include assessment of the economic value of tropical forests (Peters et al., 1989; Tobias and Mendelsohn, 1991; Bacilli and Mendelsohn, 1992; Chopra, 1993), evaluation of methods for estimating the economic value of different biological resources (Pearce and Moran, 1994), economic incentives for biodiversity conservation (McNeely, 1993), economic valuation of protected areas (Cacha, 1994; Lacy and Lockwood, 1994; Munasinghe, 1994), and economic value of endangered species management

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(Hyde and Kanel, 1994; Kramer and Munasinghe, 1994; White et al., 1997). Perhaps most notably, Costanza et al. (1997) attempted to estimate the global biospheric value of 17 ecosystem services provided by 16 dominant global biomes.

Estuaries and coastal wetlands, both vegetated (mangroves, salt marshes, and sea grass beds) and unvegetated (mudflats and sand beaches), are critical transition zones between land, freshwater habitats, and the sea. These transition zones provide many essential ecosystem services, including shoreline protection, organic decomposition, nutrient cycling, water quality improvement, fisheries resources, habitat and food for migratory and resident animals, and regulation of fluxes of nutrients, water, particles, and organisms between land, rivers, and the ocean (Levin et al., 2001; Snelgrove et al., 1997, 2000).

In the case of tidal marshes, productivity can equal that of highly fertile agricultural lands, and plants growing in tidal marshes serve as natural water filters (Daiber, 1986). In addition, organically rich tidal mud flats, estuaries and their surrounding wetlands provide the spawning grounds and nurseries for many fisheries and they support shell-fishery industries in many coastal zones. Inter-tidal mud flats also provide feeding grounds for a variety of birds including migratory birds that use them as staging areas, and they act as storm buffers because they efficiently dissipate wave energy (French, 1997).

Despite the critical ecological functions that they provide, inter-tidal mud flats are often valued more for their development potential than the ecosystem services that they provide. This is especially so in the current era of rapid economic growth in China, which is being fueled by powerful social and economic forces that are promoting individual development and land reclamation (Yang, 1999; Yang et al., 2001). In Shanghai, which is just south of Chongming Island, rapid industrial and urban development has significantly reduced the availability of arable land for peri-urban agriculture and this trend is likely to continue (Chen et al., 1999). Sustaining peri-urban agricultural production in the Yangtze delta area to support Shanghai's urban expansion and economic development has, therefore, become a key issue facing the government.

In contrast to these social and economic pressures, many groups are advocating the conservation of inter-tidal mud flats in the vicinity of Shanghai (Xie and Yang, 1990; Ji et al., 2002). The momentum for such advocacy is being driven by the extensive reclamation of these mud-flats. This destroys a biologically rich natural resource that people have used sustainably for thousands of years and the productivity of which is likely to become more important over time (Tubbs, 1978; Lovejoy, 1982). As a result of the deleterious ecological impacts of the large-scale reclamation initiatives, conflicts have arisen between groups wanting to conserve the tidal flats and those promoting the reclamation and development of these areas. In addition, the net economic value of reclamation is questionable because of the astronomically high costs of reclaiming inter-tidal areas. As Daiber (1986) indicates, exploitation of mud flats is generally for the single purpose of economic gain with little concern for, or even recognition of, the ecological consequences. Partly in response to these concerns, the Organization for Shanghai Sustainable Development identified an urgent need for scientific research to address specific problems related to strategic development plans such as China's Agenda for the 21st Century in the Shanghai Action Plan (GSICI, 1996; GSCCI, 1988). In particular, there is a great need to understand better the ecology and productive capacity of tidal flats.

While changes in coastal wetland areas may significantly affect the ecosystem processes and services that they provide, evaluating the impacts of land-use changes on such ecosystems is not easy. As Kreuter et al. (2001) pointed out, monitoring changes at the regional scale is difficult because of the large volume of data and interpretation required, while accurately quantifying the ecosystem service impact of changes in a single land-cover category (such as coastal wetlands) is hindered by the lack of information about the contribution of modified landscapes to these services. In addition, comprehensive decision-making based on comparisons of the impact of land-use changes on ecosystems requires more explicit measures than simple indices for the value of affected ecosystem services. Because the actual services provided by ecosystems and the values of these services are site specific, it is preferable to determine the nature and value of ecosystem services at a small spatial scale.

In this study, we conducted field surveys and used mathematical simulations to estimate the annual economic value of ecosystem services provided by wetlands on Chongming Island, China. We used Geographic Information System (GIS) techniques to determine land-use change within the study area because the research benefits of GIS approaches have been demonstrated by many ecological studies, but such approaches have seldom been used for ecological economic valuations (Eade and Moran, 1996). The three primary objectives of the study were: (1) to determine the extent of local changes in wetlands during the 1990s; (2) to determine the effectiveness of using generalized ecosystem service value coefficients from Costanza et al. (1997) to estimate changes in the value of ecosystem services at the local level; and (3) to make some preliminary policy recommendations to ensure the sustainable use of these ecologically important wetlands.

Methods

Study area

The island of Chongming is located north of Shanghai city at the mouth of the Yangtze (Changjiang) River (Fig. 1). Covering 1200 km^2 and increasing in size by about 500 ha annually through the deposition of sand, silt, and mud by the Yangtze River, the island is the third largest in China and the largest alluvial island in the world. It supports a population of about 735,000 people.

Our study area is located in Dongtan (Eastern Beach of Chongming Island), which typically consists of marshy land. It is a migratory staging and wintering site for millions of birds, and provides spawning and feeding grounds for 63 species of fish, including the protected Chinese sturgeon (*Acipenser sinensis*). Due to its extraordinary resources, scenic qualities, and its proximity to the city of Shanghai 45 km away, the site is an attractive destination for ecotourism and environmental education (though the numbers of visitors are regulated), and it supports an important fisheries economy.

Data collection and preparation

The data used to estimate changes in the size of various ecosystems were extracted from two cloud-free LANDSAT Thematic Mapper (TM) images obtained in December 1990 and February 1997, and one cloud-free LANDSAT Enhanced Thematic Mapper (ETM) image obtained in June 2000. Although these satellite images were pre-geo-referenced, they could not be compared directly because the coordinate reference system and resolution used in each image was not consistent. To reduce potential position errors between the three data sets, we used a three-step image preparation procedure. First, we identified the X and Y coordinates of pairs of points that represent prominent features on both the 2000 ETM image and the 1:100,000 topographic map of Shanghai (Shanghai Municipal Institute of Surveying and Mapping). Second, we used the same topographic map as the geo-referenced standard together with the GEOREFERENCING and RESAMPLING modules of IDRISI® Release 2 software (Clark Labs, 2001) to resample the 2000 ETM data set into a Universal Transverse Mercator (UTM) coordinate system. Next, using the same procedure as in the second step and the geo-rectified 2000 data as the master dataset, we resampled and rectified the 1990 and 1997 TM RAW images. Average root mean square (RMS) error of less than 0.5 in step 2 and 3 is achieved for all the images and the pixel size was kept as $30 \times 30\,m^2$.

Land use classification

Our remotely sensed data were taken in different seasons: accordingly, there was a danger that the differences between time periods might have resulted from the difference in data collection rather than from actual changes taking place on the ground. We minimized this danger in three ways. First, we standardized the atmospheric conditions of the 3 years' imageries. Bi-variate scatter diagrams were used to find out the cut-off values that might have been contributed

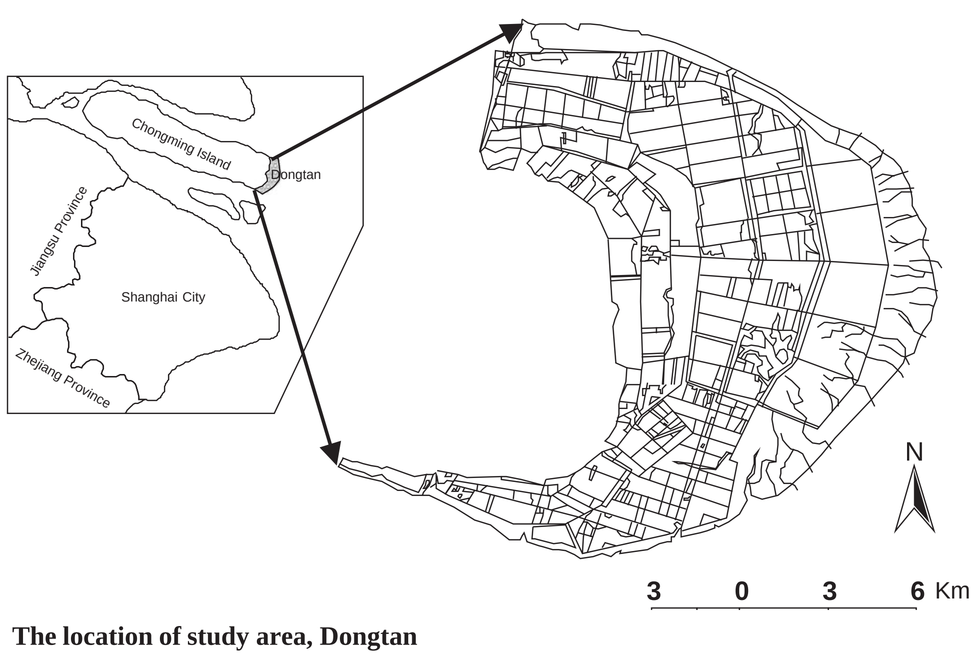

Fig. 1. The location of study area.

by the atmosphere. The cut-off values were then used to standardize the atmospheric conditions of the images. Second, we identified five land-cover/land-use (LCLU) categories that could be clearly distinguished with a three-band TM image composite (bands 2–4). Finally, we conducted intensive ground-truth studies during autumn 2001 and summer 2002. To obtain historical land-cover data, we interviewed farmers at nine locations to determine whether or not each of the five land categories existed in 1990, 1997 and 2000. The LANDSAT data were subsequently classified into these five land categories by using a combination of unsupervised and supervised classification techniques, the latter depending heavily on expert knowledge about land cover and land use in the study area as well as field data about the prevailing land cover. The field data used to ground truth the LANDSAT images were collected from 34 sites, including nine locations where we interviewed farmers, the geographic coordinates of which were determined using GARMIN-12 Global Position Systems (GPS) (Zhao et al., 2003).

Based on the characteristics of prevailing land cover and land use in Dongtan and the LANDSAT data classification procedure described above, the five generic land categories that we identified in the study area included: wetland/tidal flats, aquaculture pond, farmland, orchard/plant-nursery, and settlement. Wetlands/tidal flats consist of various types of marshes and swamps, while aquaculture ponds are managed open water bodies used for producing fisheries food products. Farmlands are managed for growing various green food items, and orchards/plant nurseries consist of managed green areas including a mixture of grass, trees and other plants. Finally, settlements consist of commercial and residential areas and their associated transportation surfaces.

Assignment of ecosystem service value

In order to obtain ecosystem services values for each of the five land-cover categories used to classify the LANDSAT datasets, each category was compared with the 16 biomes identified in Costanza et al.'s (1997) ecosystem services valuation model. The most representative biome for each category was used as the proxy for the category. Specifically, the lakes/rivers biome was used as a proxy for aquaculture ponds, cropland for farmland, forest for orchard/plant nurseries, urban for settlements, and estuaries for wetlands/tidal flats (Table 1). According to the Ramsar Convention (www.ramsar.org/key_ris_types.htm), wetlands are broadly divided into marine/coastal wetlands (including estuaries), inland wetlands, and human-made wetlands. Based on this categorization and in conformity with Costanza et al.'s biome delineation, we divided the wetlands of Shanghai and surrounding areas into three types: open ocean, coastal estuaries, and lakes/rivers. We used Costanza et al.'s Coastal estuary biome as a proxy for the wetlands/tidal flats occurring in our study area because only the estuarine form of wetlands occurs there.

Table 1
Costanza et al. (1997) biome equivalents for the five land-use categories, and the corresponding ecosystem values

Land cover land use categories	Equivalent biome	Ecosystem service coefficient ($/ha/y)
Aquaculture pond	Lakes/rivers	8498
Farmland	Cropland	92
Orchard/plant nursery	Forest	969
Settlement	Urban	0
Wetland/tidal flats	Estuaries	22,832

The total value of the ecosystem services represented by each land-cover category was obtained by multiplying the estimated size of each land category by the value coefficient of the biome used as the proxy for that category

$$ESV = \sum(A_k \times VC_k), \tag{1}$$

where ESV is the estimated ecosystem service value, A_k the area (ha) and VC_k the value coefficient ($/ha/yr) for land use category 'k' (Kreuter et al., 2001). The change in ecosystem service values was estimated by calculating the difference between the estimated values for each land- cover category in 1990, 1997 and 2000.

The biomes used as proxies for the land-cover categories were not perfect matches. Specifically, orchard/plant-nursery areas differ from Costanza et al.'s temperate/boreal forest biome. Because orchards consist of trees and shrubs of regular age and size, they do not have the same hierarchical structure as forests and lack the spectrum of ecosystem services provided by forests (e.g., climate regulation, soil formation and water treatment). However, orchards produce more food, and in China, plant nurseries may represent greater recreation and cultural values than forests because they produce ornamental plants used in public areas and private gardens. Similarly, aquaculture ponds are not well represented by Costanza et al.'s lakes/rivers biome because they do not supply freshwater, regulate water flow, or act as waste treatment filters, and they generally produce considerable more food per unit area than natural water bodies. Finally, we were concerned that the high value coefficient assigned to the wetland/tidal flats category could overwhelm the estimates of the total value of ecosystem services in our study area.

Due to these uncertainties, we conducted sensitivity analyses to determine the dependence of our estimates of changes in ecosystem service values on the applied coefficients. The ecosystem value coefficients for orchard/plant nursery, and aquaculture pond categories were

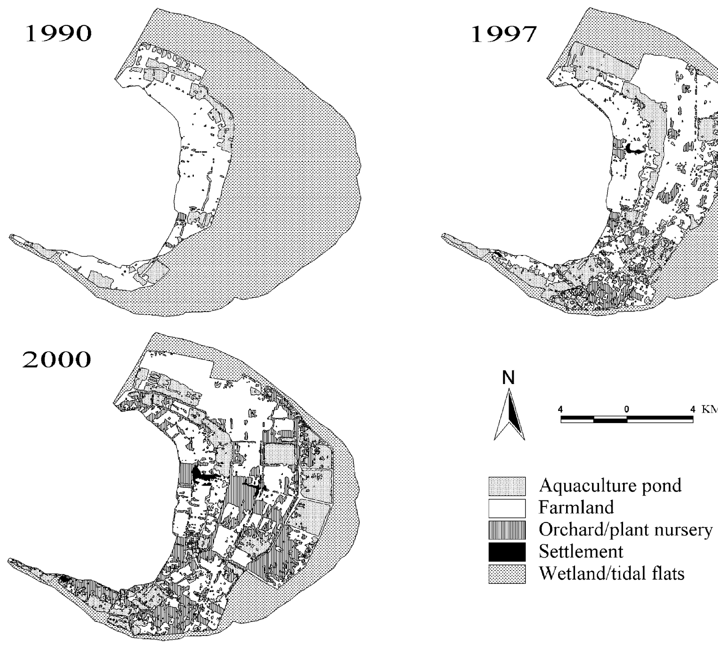

Fig. 2. Land-use change in Dongtan of Chongming Island in 1990, 1997 and 2000.

each adjusted by 50%. Even though farmland category here matches Costanza et al.'s (1997) definition, we also adjusted its value coefficient by 50% in the sensitivity analysis. Three biomes in Costanza et al.'s (1997) study could be related to our wetland/tidal flats category—coastal-estuaries, freshwater wetlands, and tidal marsh/mangroves. While we selected coastal-estuaries as the initial proxy for wetland/tidal flats, the other two biomes might be suitable alternatives. To test the robustness of our analysis, we substituted these two value coefficients for the coastal estuary coefficient. The impact of these adjustments on our estimates of the total value of ecosystem services and the associated Coefficients of Sensitivity (CS) are presented.

Results

Land use change detection

The changes in the area of each of the five generic land categories in our study are presented in Fig. 2. The most affected category was wetlands/tidal flats, which shrank in area from 13,432 ha in 1990 to 7915 ha in 1997, and 3856 ha in 2000. The second most affected category was orchard/plant nursery, which increased from 80 ha in 1990 to 954 ha in 1997 (almost 12-fold over 7 yr) and to 3863 ha in 2000 (more than 4 times over 3 yr). The area of other three categories also increased during this 10-year period. Aquaculture ponds increased in area from 1140 to 3291 ha, farmland increased from 3470 to 7008 ha, and settlements increased from 4 to 107 ha (Zhao et al., 2003).

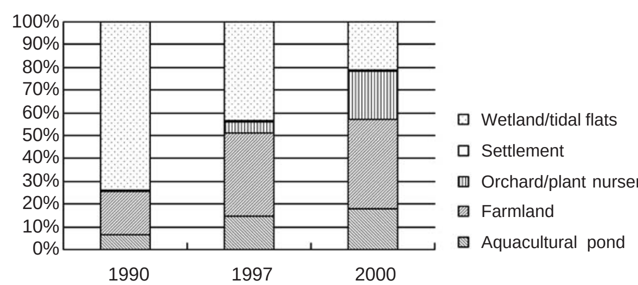

Fig. 3. Land use/land-cover change in Dongtan, Chongming Island from 1990 to 2000.

These shifts are further emphasized in Fig. 3, which shows the relative proportions of each land category in 1990, 1997, and 2000. In 1990, more than 74% of the study area was covered by wetland/tidal flats, over 19% by farmland, and more than 6% in aquaculture ponds. By 1997, the percentage coverage of these three land categories had changed to 44%, 15% and 36%, respectively, and by 2000, the percentage of wetland/tidal flats had decreased to only 21% as a result of reclamation, while the percentages of other two land-use classes had increased to 18% and 39%, respectively. The proportional contribution of orchard/plant nursery areas and settlements also increased during the 10-year time period of our study. These changes emphasize a drastic decrease in the ecologically important wetlands and a concomitant increase in production orientated land uses.

Table 2
Total ecosystem service value (ESV in US$ $\times 10^6$/yr) estimated for each land cover category in the study area using Costanza et al. coefficients, and the overall change and rate of change between 1990 and 2000

Land cover land use category	ESV (US$ $\times 10^6$/yr)			1990–1997			1997–2000			1990–2000		
	1990	1997	2000	$ $\times 10^6$	%	%/yr	$ $\times 10^6$	%	%/yr	$ $\times 10^6$	%	%/yr
Aquaculture pond	9.70	22.38	27.98	12.69	131	15.0	5.59	25	11.8	18.28	189	12.5
Farmland	0.32	0.61	0.65	0.29	90	11.3	0.04	6	3.1	0.33	102	8.1
Orchard/plant nursery	0.08	0.92	3.74	0.85	1100	51.3	2.82	305	101.2	3.67	4729	53.8
Settlement	0.00	0.00	0.00	0.00	—	—	0.00	—	—	0.00	—	—
Wetland/tidal flats	306.68	180.72	88.04	−125.96	−41	−8.4	−92.68	−51	−30.2	−218.64	−71	−13.0
Total	316.77	204.63	120.40	−112.14	—	—	−84.23	—	—	−196.37	—	—

Estimation of changes in ecosystem services

Using the estimated change in the size of each land-cover category together with the ecosystem service value coefficients reported by Costanza et al. (1997), we found that land-use changes in the 18,128 ha of our study area resulted in an average net decline of $196.37 million per year in ecosystem services between 1990 and 2000 (Table 2). Assuming a linear decline in ecosystem services, this represents a cumulative loss of $981.85 million in ecosystem services over the 10-yr period of the study. However, our analysis detected that the rate of decline in the value of ecosystem services from 1997 to 2000 was greater than that between 1990 and 1997 (Fig. 4). By adding the ecosystem service declines during these two periods (shaded area in Fig. 4), we obtained a cumulative ecosystem loss of $855.26 million. Settlement land was assigned no ecosystem service value (which may underestimate its actual ecological value derived from plants in residential and urban areas), but assigning a value would have had a negligible effect on our estimate, because settlements covered only a small portion of the study area. In summary, the estimated 10-year 9576 ha loss of wetland to other land uses and the associated loss in ecosystem services appeared to have resulted in a massive loss in the annual value of such services within our study area.

In addition to estimating land-use change effects on the total value of ecosystem services, we also estimated the impacts of such changes on individual ecosystem functions within the study area. The values of services provided by individual ecosystem functions were calculated using the following equation:

$$ESV_f = \sum (A_k \times VC_{fk}), \qquad (2)$$

where ESV_f is the estimated ecosystem service value of function f, A_k is the area (ha) and VC_{fk} the value coefficient of function f ($/ha/yr) for land-use category 'k' (Table 3).

The contributions of ecosystem functions to overall value of ecosystem services in each year of analysis were ranked based on their estimated ESV_f in 1990, 1997 and 2000, while the overall ranking of each function was based on the average value of each ESV_f across the three years of analysis. The shift in the contribution of each ecosystem function to the total value of the ecosystem services is presented in Table 3 by an upward arrow for increasing contribution, downward arrow for decrease in contribution, and a dash for no change.

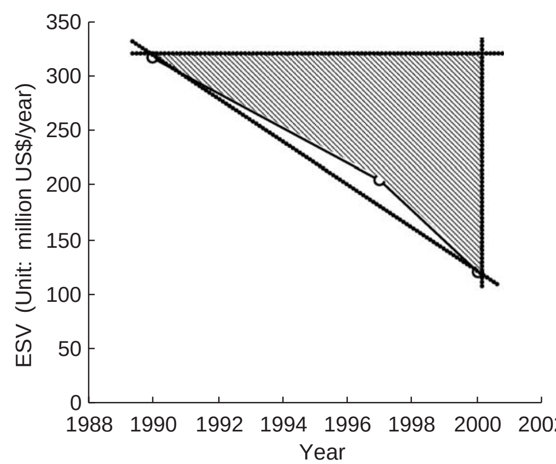

Fig. 4. Cumulative value by assuming a linear decline in ecosystem services from 1990 to 2000.

Although the contribution of nutrient cycling to total value of ecosystem services declines over the 10-year period it continues to be the dominant ecosystem function, contributing 69–89% of the total value. Water regulation, food production, water supply, disturbance regulation, recreation and waste treatment each contributed an average of more than 1% to the value of total ecosystem services, while the contribution of other ecosystem functions was minimal. Among the 10 top-ranked ecosystem functions, the contribution of water regulation, water supply, waste treatment, and raw materials increased substantially over the 10-yr period of our study, while the contribution of nutrient cycling, food production, disturbance regulation, recreation, habitat/refugia, and biological control decreased substantially during the same time period.

Table 3
Estimated annual value of ecosystem functions (ESV_f in US$ $\times 10^6$/yr)

Ecosystem function	1990			1997			2000			Overall rank	Tendency
	ESV_f	%	Rank	ESV_f	%	Rank	ESV_f	%	Rank		
Nutrient cycling	283.444	89.479	1	167.351	81.782	1	82.756	68.732	1	1	↓
Water regulation	6.213	1.961	4	14.344	7.010	2	17.933	14.894	2	2	↑
Food production	7.236	2.284	3	4.629	2.262	4	2.689	2.233	4	3	↓
Water supply	2.416	0.763	6	5.579	2.726	3	6.981	5.798	3	4	↑
Disturbance regulation	7.616	2.404	2	4.490	2.194	5	2.194	1.822	7	5	↓
Recreation	5.385	1.700	5	3.684	1.801	6	2.481	2.061	6	6	↓
Waste treatment	0.766	0.242	9	1.835	0.897	7	2.525	2.097	5	7	↑
Habitat/refugia	1.760	0.555	7	1.037	0.507	8	0.505	0.420	10	8	↓
Biological control	1.131	0.357	8	0.778	0.380	9	0.477	0.396	11	9	↓
Raw materials	0.347	0.109	11	0.330	0.161	10	0.629	0.523	8	10	↑
Climate regulation	0.011	0.004	13	0.135	0.066	12	0.545	0.452	9	11	↑
Cultural	0.390	0.123	10	0.231	0.113	11	0.120	0.099	13	12	↓
Pollination	0.049	0.015	12	0.092	0.045	13	0.098	0.081	14	13	↑
Erosion control	0.008	0.002	14	0.092	0.045	14	0.371	0.308	12	14	↑
Genetic resources	0.001	0.000	15	0.015	0.007	15	0.062	0.051	15	15	↑
Soil formation	0.001	0.000	16	0.010	0.005	16	0.039	0.032	16	16	↑
Gas regulation	0.000	0.000	17	0.000	0.000	17	0.000	0.000	17	17	—
Total	316.772	100	—	204.630	100	—	120.404	100	—	—	—

Table 4
Percentage change in estimated total ecosystem service value and coefficient of sensitivity (*CS*) resulting from adjustment of ecosystem valuation coefficients (*VC*)

Change in valuation coefficient	1990		1997		2000	
	%	*CS*	%	*CS*	%	*CS*
Aquaculture pond $VC \pm 50\%$	±1.53	0.031	±5.46	0.109	±11.61	0.232
Orchard/plant nursery $VC \pm 50\%$	±0.01	0.000	±0.23	0.005	±1.55	0.031
Aquaculture pond VC−50% + Orchard/plant nursery $VC \pm 50\%$	±1.54	0.031	±5.69	0.114	±13.17	0.263
Farmland $VC \pm 50\%$	±0.05	0.001	±0.15	0.003	±0.27	0.005
Wetland/tidal flats VC = Fresh−water wetlands VC	−34.12	0.968	−31.13	0.883	−25.77	0.731
Wetland/tidal flats VC = Tidal Marshes/mangroves VC	−54.45	0.968	−49.67	0.883	−41.12	0.731

Ecosystem service sensitivity analyses

In 1990, 74% of Dongtan on Chongming Island was covered by wetlands/tidal flats, but this land type decreased to little more than 21% in 2000. The value coefficient assigned to this land type is almost three times that of aquaculture pond, 24 times that of orchard/plant nurseries, and 248 times of that of farmland (Table 1). Consequently, it is not surprising that the decline in wetland/tidal flats land type has a dramatic effect on the estimated value of ecosystem services in the study area. To determine the robustness of our ecosystem service value estimates, we conducted a sensitivity analysis by adjusting the coefficients used to place a monetary value on the ecosystem services provided by each land type.

The effects of using alternative coefficients to estimate total ecosystem service values in the study area in 1990 and 2000 are shown in Table 4. Adjustment to the value coefficient for aquaculture pond, orchard/plant nursery, and farmland categories had very little effect on the estimates of total ecosystem service values (<2% change for a 50% change in value coefficient). The coefficient of sensitivity ranged from a low of 0 to 0.031 for the orchard/plant nursery and the farmland categories to a high of 0.031–0.263 when the coefficients for both the aquaculture pond and orchard/plant nursery categories were adjusted. The relatively low Coefficients of Sensitivity (CS—percentage change in total ecosystem service value per unit change in a land-cover value coefficient) values reflect the fact that the area and/or the value coefficients associated with these land-cover types are relatively small, and suggest that this ecosystem value estimate is reasonably robust. However, when the coefficient values for wetlands were adjusted downwards from the Costanza et al.'s coastal estuary coefficient (22,832 $/ha/yr) to that of fresh-water wetlands (14,785 $/ha/yr) and tidal marshes/mangroves (9990 $/ha/yr), the estimate total ecosystem service value dropped between 26% and 34%, and 41% and 54%, respectively. Nevertheless, the value of the loss of ecosystem services due to the decline in this land type is still very high. For example, when freshwater wetlands and tidal marshes/mangroves coefficients were used for wetlands, the 1990–2000 losses in total ecosystem service value were \$119.32 million and \$73.40 million, respectively. Due to the extensive cover of wetlands/tidal-flats in the study area, the corresponding CS for this land-cover category was high, ranging from 0.731 to 0.968. This large impact on our estimates reflects both the large area and dominating ecosystem service value of this land category in our study area. The result emphasizes the importance of this land type in the provision of ecosystems services, and underscores the substantial reduction in annual ecosystem services as a result of the extensive loss of coastal wetlands. However, the result of our sensitivity analysis also emphasizes the importance of obtaining accurate value coefficients for dominant land types in order to quantify accurately the ecological economic effect of LCLU shifts.

Discussion and conclusion

Our study showed that satellite data are useful and inexpensive for estimating changes in the value of ecosystem services at the local level. In many cases, remote sensing from satellites may be the only economically feasible way to gather regularly land-cover information with high spatial, spectral, and temporal resolution over large areas (Verstraete et al., 1996; Seidl and Moraes, 2000). The satellite-based data acquisition methods used in this study have at least two advantages over alternative data-collection methods. First, in natural wetland areas, like those found at Dongtan, extensive field-based survey methods can be difficult and expensive to implement due to restricted accessibility. In such areas, a limited amount of field sampling combined with satellite data can facilitate reasonably accurate large-scale analysis at relatively little cost. Second, most available LCLU data are based upon geopolitical boundaries and regional planning maps, neither of which relate well to the spatial arrangement changing land-use patterns.

Costanza et al.'s (1997) ecosystem-service values that we used in our analysis have been challenged on theoretical and empirical grounds. However, they represented the most comprehensive set of valuation coefficients available to us. Nevertheless, in order for the kind of ecosystem-service analysis that we conducted to become more meaningful for policy formulation affecting land use, it is imperative to obtain value coefficients for ecosystem services that more accurately reflect local conditions. One approach to implement this in a pragmatic way would be to identify benchmark ecosystem service values for dominant ecosystem types within a region and then to evaluate the ecosystem services provided at specific locations relative to the representative benchmark (Kreuter et al., 2001). Because ecosystem services are generally not traded directly, indirect valuation techniques (such as contingent valuation, hedonic values, and travel cost methods) will be needed to obtain location specific values for ecosystem services. Once such coefficients are determined, the values of ecosystem services can be calculated at larger regional scales though the use of remotely sensed data and GIS tools to classify land into representative ecosystems for which benchmark service values have been determined. In using such an approach, it is important to realize that absolutely accurate coefficients are often less critical for land-use change analyses than time-specific analyses of the value of ecosystem services because coefficients tend to affect estimates of directional change less than estimates of the magnitude of ecosystem values at a specific point in time.

The most important ecological feature in Dongtan is its coastal regime, which is defined by its wetlands and tidal flats where the sea impinges on the land. This zone has provided valuable coastal fisheries for thousands of years, and a rich base for fish farming and marine cultivation in the middle and lower reaches of the Yangtze River in recent decades. Now wetlands and tidal flats are being extensively drained and reclaimed along Dongtan due to the valuable land resources that the shallow coastal zone can provide. With limited agricultural land and in concordance with Chinese land-use policy, Shanghai is in constant search of additional farmland. While, small-scale reclamation of tidal flats has been ongoing for several hundred years (Zhao et al., 2003), more recent large-scale land reclamation for agriculture, fisheries, and other uses, has led to substantial land-use conflicts, especially in our study area where a series of large-scale tidal flat reclamation projects have been implemented.

Based on the estimated size of five land-cover categories and using Costanza et al.'s (1997) ecosystem services values for related biomes, we determined that the total annual ecosystem service values in Dongtan to have declined by 62% between 1990 and 2000. This massive decline in ecosystem services is largely attributable to the 71% loss of wetlands/tidal flats. Even if the value coefficients that we used in our analyses significantly overestimate the true value of lost ecosystem services provided by wetlands/tidal flats (e.g., nutrient cycling, food production, disturbance regulation, habitat/refugia, and biological control), the high rate of loss of such services will undoubtedly have serious negative ecological consequences in the long term. In addition, losses of ecological services such as dissipation of wave energy can lead to economically costly outcomes through the destruction of structures by high tidal surges. One way to mitigate such massive impacts would be to protect grassy areas, which are important for trapping silt and water-flow regulation, and they are key staging areas for migratory birds.

In addition to their ecological impact, the large-scale land reclamation activities also appear to contradict some of the stated objectives of the Shanghai government. One of its key objectives is to develop Chongming Island as the city's largest leisure and tourism area and its prime 'environmentally friendly' green food production flagship. To achieve this objective, it is necessary for the ecosystem services that provide cultural, recreation and food production values be enhanced. Ironically, our study indicated that the ecosystem services associated with these values declined between 1990 and 2000. This is contrary to the stated objectives of the Shanghai government and suggests that the current land-use policies need to be revised.

Recognizing the environmental importance of these wetlands/tidal flats, we argue that, in future land-use policy formulation, conservation of the wetlands and tidal flats and their resource rich ecosystems should take precedence over the single-minded, uncontrolled reclamation of these areas for economic purposes. While it may not be feasible to stop all reclamation activities in this area, it is imperative that future land-reclamation projects be controlled and based on rigorous environmental impact analyses. To achieve this, more detailed studies of the impacts of wetland/tidal flat reclamation projects on the ecosystem services provided in the Yangtze River estuary are necessary.

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