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Spatiotemporal change in the land use and ecosystem service value in the Aral Sea basin (1993–2018)

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Abstract: The Aral Sea started shrinking since the 1960s due to natural factors and human activities; however, the relationship between land cover change and ecosystem services (ES) in the Aral Sea basin has not been fully studied. To analyze and explore the spatiotemporal variation characteristics of ecosystem service values (ESVs) in this region, we used the European Space Agency CCI Global Land Cover product with a spatiotemporal resolution of 300 × 300 m and the annual scale. The land use data of 1993, 1998, 2003, 2008, 2013, and 2018 in the study area were extracted, the study area's ESV in the corresponding years was calculated, and the temporal and spatial evolution characteristics were analyzed. Additionally, the change rate and sensitivity were analyzed. The results revealed that the area of urban land, bare land, grassland, wetland, and cropland in the Aral Sea basin increased from 1993 to 2018; water body and forestland decreased. The integrated value of water bodies, cropland, and grassland ES accounted for more than 96% of the total ESV; the change rate of land use types differed. Urban land and water changed the fastest; cultivated land, woodland, grassland, and wetland changed the slowest. From 1993 to 2018, the total ESV of the Aral Sea basin decreased from 455.10 to 414.56 billion (Overall decrease = −8.91%). The ESV study shows that the water area decreased sharply from 1993 to 2018, resulting in a loss of USD 46.84 billion. Biodiversity, food production, and water regulation were the main ES, accounting for 78.5% of the total ESV. The ESV of the Aral Sea basin declined from 1993 to 2018, and significant differences were observed among its regions. Some regions should thus focus on this aspect. A close correlation was observed between the ESV and land use. Hence, effective land use policies can control the expansion of cropland; protect water bodies, ecological environments, grassland, and forestland; and promote a more sustainable ecosystem.

Keywords: Land use; Ecosystem services; Spatial and temporal characteristics; Aral Sea; Sustainable

1 INTRODUCTION

Ecosystem services (ES) refer to life support products and services obtained directly or indirectly through the structure, process, and function of an ecosystem (Costanza et al. 1997, de Groot et al. 2012). The quantification and analysis of ecosystem service value (ESV) have become a vital tool to improve the public's understanding of the importance of ESV and ES (Costanza et al. 2014, de Groot et al. 2012). Value assessment includes ecological environmental protection (Bateman et al. 2013, Egoh et al. 2007), ecological function regionalization (Lautenbach et al. 2011), improving natural resource management decisions (Wainger et al. 2010), environmental economic accounting (Chen et al. 2019), and ecological compensation decision-making (Li et al. 2017).

The benefit transfer method (BTM) is often used to evaluate the value of ES at the global or regional scale: The first step is to multiply the value equivalent by the area of a certain type of ecosystem to obtain the value of a certain type of ES, and the second step is to calculate the value of the whole region by summation (Costanza et al. 1997, Costanza et al. 2014, de Groot et al. 2012, Xie et al. 2003, Xie et al. 2015). Costanza et al. (1997) estimated the economic value of 17 ES for 16 biomes based on the literature and the basic value transfer method.

Xie et al. (2003, 2015a, 2015b) analyzed the theories and methods of ES function and eco-economic value evaluation, estimated the ESV of China and the Qinghai Tibet Plateau, and formulated the equivalent factor table of the ESV of China. As different social environments and economic factors affect the ESV and the usage of ES, the BTM has limitations (Wilson & Howarth 2002). However, for researchers and decision makers who are limited by time and budget, this method quickly provides policy reference information (Brouwer 2000, Johnston & Rosenberger 2010, Sutton & Costanza 2002).

The global ESV is evaluated again and divided into 10 main ecosystem types: ocean, coral reef, coastal system, coastal wetland, inland wetland, lake, tropical rain forest, temperate forest, forestland, and grassland. For analysis, 665 data points from more than 300 studies are employed, and the global ESV and value coefficient are updated.

Land use and land cover change (LULCC) is an important cause of ES change (Song & Deng 2017) and a crucial part of global change and sustainable development research (Lambin et al. 2003), and the impact of LULCC on ES has been proved (Lautenbach et al. 2011, Sala et al. 2000). Therefore, achieving the sustainable development of ES and managing global environmental change through monitoring, modeling, forecasting, and decision-making of LULCC has become a key global concern. Humankind's business activities on land have substantially changed the land cover on the surface, thus driving the change in the ability to provide ES (Assessment 2005, Nelson et al. 2006). The loss of ES will seriously affect human well-being, thereby directly threatening regional and global ecological security (Assessment 2005).

The Aral Sea is a typical inland lake located in Central Asia. Rapid population growth has led to increased irrigation and the development of water resources. Due to the establishment of large-scale irrigation systems, water is consistently loaned from the Amu Darya and Syr Darya Rivers to promote agricultural irrigation (Lioubimtseva 2015, Micklin 2016). Such long-term, intense irrigation activities in the Aral Sea basin have changed the underlying surface conditions and led to serious environmental degradation and ecological problems, such as, large-scale shrinkage, desertification, and soil salinization of the Aral Sea (Kulmatov et al. 2018). The Aral Sea was the fourth largest lake in the world in the 1960s and has nearly lost 90% of its water surface thus far (Roy et al. 2014). In addition to the drying up of the Aral Sea, abandoned and reclaimed farmland and grassland degradation have significantly altered surface features, vegetation, and soil characteristics, thereby affecting the regional ES. Thus far, no quantitative assessment of ESV has been conducted in the Aral Sea basin.

Therefore, the purpose of this study was twofold: (1) use land change to estimate and predict ESV changes in the Aral Sea basin from 1998 to 2038 and (2) assess the elasticity of ESV in response to LULCCs by adjusting the value coefficient by 50%. The study results are discussed and provide an important reference for decision makers who are formulating the policy for the ecological environment protection and sustainable development of the Aral Sea basin.

2 MATERIALS AND METHODS

2.1 Study Area

The Aral Sea basin (55°–75° E, 35°–50° N) is located in the arid region of Central Asia, covering the Amu Darya and Syr Darya Rivers, the two major water systems of Central Asia. Tajikistan, Turkmenistan, and Uzbekistan are located in the Aral Sea basin. Approximately 37.7% of the land area of Osh, Jalalabad, and Naryn Provinces in southwestern Kyrgyzstan and 12.7% of the land area of Qyzylorda and South Kazakhstan in southern Kazakhstan are located in the Syr Darya River basin (Xiangrong et al. 2017) (Fig. 1).

The Aral Sea basin comprises unique ecosystems, ranging from alpine forests and glacial lakes in the east to savannahs and deserts in the west. The basin contains two large transboundary rivers, Amu Darya and Syr Darya, and the total population within the basin is 60.4 million persons (D Ukhovny & Sokolov 2006), roughly

concentrated along the river valley (Xenarios et al. 2019).

The Aral Sea basin is located inland and has a dry, typical continental climate (Lioubimtseva 2015). Its terrain is generally high in the east and low in the west, mainly composed of the Turan Plain in the west and the mountainous areas in the southeast. The average annual rainfall is less than 300 mm and that around the Aral Sea and the desert area is less than 100 mm; the average temperature is approximately 9° C (Harris et al. 2014).

Fig. 1 Map of the Aral Sea basin area

2.2 Data Collection and Land Use Classification

Land cover data for the Aral Sea basin are based on the European Space Agency (ESA) Climate Change Initiative Land Cover (CCI-LC) product (<http://maps.elie.ucl.ac.be/CCI/viewer>). The spatial resolution of this product is 300 m, and the time series is from 1992 to 2018 (Li et al. 2017).

We compared multiple LULC data sets from the study area, including GLC2000, GlobCover, MCD12 Q1, GlobeLand30 land cover data, and the newly released ESA CCI-LC product (Hua et al. 2018, Liu et al. 2018, Yongke et al. 2017). Studies have shown that the CCI-LC has higher spatial resolution and better accuracy in the study area (Hartley et al. 2017, Lai et al. 2019, Yongke et al. 2017). The weighted area overall accuracy figure of the 2015 CCI-LC map was 71.1%, and the overall accuracy reached 74.4% after the independent verification of the CCI-LC product with ground reference data and alternative sensors. CCI-LC data had the highest overlap with other land cover data sets, with 76% of the grassland cover data (Lai et al. 2019). The product has also achieved high accuracy for cultivated land, woodland, towns, bare land, and water bodies in Central Asia. Scholars have used CCI-LC data to monitor the dynamic change in cultivated land, grassland, and other land cover in Central Asia (Jin et al. 2017).

CCI-LC data comprise 22 land cover types. The focus of this paper is to analyze the changes in the characteristics of the main land cover types in the Aral Sea basin and reclassify the land cover data of 24 periods into cultivated land, woodland, grassland, bare land, water body, and town (Table 1). The product was developed using the GlobCover unsupervised classification chain and combines various earth observation products based on

the ESA GlobCover product. Unlike many remote sensing products based on a single sensor approach, this data set is generated using multiple sensors.

To verify the data, Defourny et al. (2016) found that the high-accuracy land classifications are rainfed cropland (89%–92%), irrigated cropland (89%–83%), broad-leaved evergreen forest (94%–96%), urban areas (88%–86%), bare areas (88%–88%), water bodies (92%–96%), and permanent snow and ice (97%–96%). To match Costanza's biome, the seven main LULC types are farmland, cropland, grassland, wetland, urban land, bare land, and water bodies (Table S1).

Table 1. Ecosystem service value (ESV) of the unit area of land use categories (USD·ha⁻¹·year⁻¹)

Service type	Sub-type	Cropland	Forestland	Grassland	Wetland	Urban	Bare areas	Water bodies
Provisioning	FP	2323	299	1192	614	0	0	106
	RM	219	181	54	539	0	0	0
Regulating	GR	0	0	9	0	0	0	0
	CR	411	152	40	3474	905	0	0
	WR	400	191	63	6014	16	0	9322
Supporting	SFR	639	107	46	4320	0	0	0
	WT	397	120	75	3015	0	0	918
	BD	1096	1097	2494	3502	0	0	0
Culture	RCT	82	990	193	4203	5740	0	2166
Total		5567	3137	4166	25681	6661	0	12512

GR – Gas Regulation; CL – Climate Regulation; WR – Water Regulation; SFR – Soil Formation and Retention; WT – Waste Treatment; BD – Biodiversity; FP – Food Production; RM – Raw Material; RCT – Recreation, Cultural and Tourism.

2.3 Estimation of ESV

In this study, based on the estimation of ESV by the BTM proposed by Costanza et al. (1997), Xie et al. (2008) derived data from the 17 ES listed by Costanza et al. (1997), which are divided into nine ES functions. In this study, the ES coefficients of cultivated land, forest, grassland, urban land, wetland, and bare land were selected to match the ESVs (Table S1) (Costanza et al. 2014), and the ESV of each land use type was estimated by using the equivalent value coefficients of ES and functions. The formula is given below:

$$ESV_k = \sum_f A_k * VC_{kf}$$

$$ESV_f = \sum_k A_k * VC_{kf}$$

$$ESV = \sum_f \sum_k A_k * VC_{kf}$$

where ESV_k is the ESV of land use type “k,” A_k is the area (ha) of land use type “k,” and VC_{kf} is the value coefficient (USD·ha⁻¹·year⁻¹) of function f for the LULC type “k” (USD·ha⁻¹·year⁻¹). ESV_f is the value of the ecological service function in item f of ecological system, and ESV is the total value of ES.

We use the following formula to evaluate changes in ESV:

$$ESV_{cr} = \frac{ESV_{t2} - ESV_{t1}}{ESV_{t2}} \times 100\%$$

In the abovementioned formula, ESV_{cr} refers to the rate of change in ESV from the initial year to the final year. In the previous year, ESV_{i1} and ESV_{i2} represent the total ESV at the beginning and end of the study, respectively.

2.3 Sensitivity Analysis

Because of the uncertainty in the representativeness of the indicators used for each land cover type and the accuracy of the value coefficient published by Costanza et al. (Costanza et al. 1997, Costanza et al. 2014), we conducted a sensitivity analysis to determine the degree of dependence of the changes in ESV on the ESV index.

We applied the concept of *elasticity coefficient* commonly used in economics to calculate the coefficient of sensitivity (CS) and the value coefficient (VC). The sensitivity index refers to the change in ESV due to a 1% change in the value coefficient of the ES function. To measure the sensitivity of ESV to value index VC, we adjustments the VC of various land use types by 50%(Kreuter et al. 2001).

If $CS > 1$, ESV is flexible to VC, which shows that it is not accurate and reliable. If $CS < 1$, the ESV lacks flexibility, which indicates that the result is reliable and accurate. The higher the CS value, the more critical the accuracy of the index(Gascoigne et al. 2011) . The sensitivity index was calculated:

$$CS = \frac{(ESV_j - ESV_i) / ESV_i}{(VC_{jk} - VC_{ik}) / VC_{ik}}$$

where VC_{ik} and VC_{jk} are the value coefficient of the ES function before and after the adjustment of the K-type ecosystem; ESV_i and ESV_k , respectively, represent the initial ESV and the ecosystem value adjusted by the ES value index.

3 RESULTS

3.1 Dynamics of LULCCs in the Aral Sea Basin (1993–2018)

From 1993 to 1998, the seven main land cover types in the Aral Sea basin, from the highest to the lowest area, were cropland, forestland, grassland, wetland, urban land, bare land, and water bodies. The spatial distribution results of LCC are shown in Table 2 and Fig. 2. The main types of land cover in the Aral Sea basin were grassland and bare land, and the scale of urban land increased over time.

During the study period, cropland, grassland, wetland, urban land, and bare land increased, and forestland and water bodies decreased. From 1993 to 1998, grassland and bare land have been the main land cover types in the Aral Sea basin. Fig. 2 shows the spatial distribution pattern of LULC in the Aral Sea basin from 1993 to 2018, and Table 2 shows the change range in the same period.

The proportion of the highest level of land cover in terms of the value of the highest level of land cover was between 36.53% and 36.95% from 1993 to 2018. Bare land was the second largest land cover type, accounting for 35.08%–37.04% from 1993 to 2018, followed by cropland from 22.06% to 22.07%, and forestland from 1.64% to 1.59%. Water bodies accounted from 4.53% to 1.74%, urban land from 0.09% to 0.55%, and wetland from 0.06% to 0.07% (Fig. 2). From 1993 to 2003, the following increased: urban coverage rate (129.67%), bare land coverage rate (4.56%), wetland (1.27%), and cropland (0.89%); in the same period, the following decreased: proportion of bare land (−40.83%), forestland (−1.92%), and percentage of net assets in the forest area (−0.10%). From 1993 to 2013, the following increased: urban coverage rate (379.05%), bare land coverage rate (6.07%), wetland (0.92%), cropland (0.55%), and farmland (0.93%); in the same period, water bodies and forestland continued to decrease at a rate of −62.14% and −7.57%, respectively.

From 2008 to 2018, the rates of change were as per the following: urban (63.74%), forestland (2.60%), grassland (0.47%), bare land (0.55%), water bodies (−22.18%), cropland (−0.61%), and wetland (−0.57%). Urban and bare land areas increased gradually, and the water bodies decreased slower than them. From 1993 to 2018,

urban land use changed the most among all land use types in the Aral Sea basin and showed an increasing trend. Rapid urbanization also increased the proportion of urban construction land from 12.27×10^4 ha in 1993 to 45.20×10^4 ha in 2008. In 2018, it was 74.01×10^4 ha, with an average annual growth rate of 20.13% (Table 2). The coverage rate of bare land increased from 35.08% to 37.04% from 1993 to 2018, with an increase of 262.43×10^4 ha and an annual growth rate of 0.22%.

During the study period, the water bodies decreased significantly, shrinking at a rate of 2.46% per year: from 607.58×10^4 ha in 1993 to 299.65×10^4 ha in 2008 and further to 233.18×10^4 ha in 2018. Thus, the water bodies decreased 374.4×10^4 ha from 1993 to 2018. Wetlands accounted for 0.07% of the total area studied, and the wetland area increased from 8.67×10^4 ha in 1993 to 8.73×10^4 ha in 2018.

Fig. 2 Spatial distribution of land use and land cover in the Aral Sea basin: (a) 1993, (b) 1998, (c) 2003, (d) 2008, (e) 2013, and (f) 2018

Table 2. Area changes in land use and land cover in the Aral Sea basin from 1993 to 2018

LULC	Cropland	Forestland	Grassland	Wetland	Urban	Bare areas	Water bodies	Total
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	1993	2961.21	220.32	4903.25	8.67	12.27	4708.25	607.58	13421.54
	1998	2,974.41	215.84	4,889.85	8.76	13.86	4,821.95	496.88	13,421.54
	2003	2987.70	216.08	4898.40	8.78	28.18	4922.90	359.51	13421.54
Area(*10 ⁴ ha)	2008	2,980.68	207.80	4,935.99	8.78	45.20	4,943.44	299.65	13,421.54
	2013	2,977.52	203.64	4,948.92	8.75	58.78	4,993.87	230.06	13,421.54
	2018	2,962.43	213.21	4,959.31	8.73	74.01	4,970.68	233.18	13,421.54
Changes(%)	1993-1998	0.45%	-2.03%	-0.27%	1.04%	12.96%	2.41%	-18.22%	
	1998-2003	0.45%	0.11%	0.17%	0.23%	103.32%	2.09%	-27.65%	
	2003-2008	-0.23%	-3.83%	0.77%	0.00%	60.40%	0.42%	-16.65%	
	2008-2013	-0.11%	-2.00%	0.26%	-0.34%	30.04%	1.02%	-23.22%	
	2013-2018	-0.51%	4.70%	0.21%	-0.23%	25.91%	-0.46%	1.36%	
	1993-2003	0.89%	-1.92%	-0.10%	1.27%	129.67%	4.56%	-40.83%	
	2003-2013	-0.34%	-5.76%	1.03%	-0.34%	108.59%	1.44%	-36.01%	
	1993-2018	0.04%	-3.23%	1.14%	0.69%	503.18%	5.57%	-61.62%	

200

201 **3.2 Changes in the Total ESV**

202 According to the statistical data, the total amount of ESV in the Aral Sea basin in 1993 was approximately
203 USD 455.1 billion (Table 3). The contribution rate of grassland was the highest (44.88%), followed by farmland
204 and water (36.22% and 16.7%, respectively) (Fig. 3).

205 Due to LULCC, the value of regional ES decreased by USD 28.82 billion from 1993 to 2003, mainly due to
206 the decrease in ESV caused by the decrease in the area of water bodies.

207 From 2003 to 2013, the regional ESV further decreased by USD 13 billion. Overall, the ESV in the Aral Sea
208 basin decreased by USD 40.54 billion between 1993 and 2018. Notably, from 1993 to 2018, the proportion of
209 water in the Aral Sea basin decreased rapidly, resulting in a direct loss of USD 46.84 billion (Table 3)

210

211 **Table 3. Ecosystem service value of the Aral Sea basin from 1993 to 2018**

	LULC	Cropland	Forestland	Grassland	Wetland	Urban	Bare areas	Water bodies	Total
	1993	164.85	6.91	204.27	2.23	0.82	0.00	76.02	455.10
	1998	165.62	6.77	203.71	2.25	0.92	0.00	62.17	441.44
ESV(billion	2003	166.33	6.78	204.07	2.25	1.88	0.00	44.98	426.28
US\$)	2008	165.93	6.52	205.63	2.25	3.01	0.00	37.49	420.84
	2013	165.76	6.39	206.17	2.25	3.92	0.00	28.78	413.27
	2018	164.92	6.69	206.60	2.24	4.93	0.00	29.18	414.56
Changes(%)	1993-1998	0.47%	-2.03%	-0.27%	0.90%	12.20%	0.00	-18.22%	-3.00%
	1998-2003	0.43%	0.15%	0.18%	0.00%	104.35%	0.00	-27.65%	-3.43%
	2003-2008	-0.24%	-3.83%	0.76%	0.00%	60.11%	0.00	-16.65%	-1.28%
	2008-2013	-0.10%	-1.99%	0.26%	0.00%	30.23%	0.00	-23.23%	-1.80%
	2013-2018	-0.51%	4.69%	0.21%	-0.44%	25.77%	0.00	1.39%	0.31%
	1993-2003	0.90%	-1.88%	-0.10%	0.90%	129.27%	0.00	-40.83%	-6.33%
	2003-2013	-0.34%	-5.75%	1.03%	0.00%	108.51%	0.00	-36.02%	-3.05%
	1993-2018	0.04%	-3.18%	1.14%	0.45%	501.22%	0.00	-61.62%	-8.91%

212

Fig. 3 (a) Percentage of land use area and (b) the percentage of ecosystem service value of different land use types

The ESV of administrative units of the Aral Sea basin in 1993 was further analyzed (Fig. 4). The highest ESV is in Qyzylorda (78.43 billion), followed by Karakalpakstan (47.40 billion) and South Kazakhstan (41.79 billion). The ESV of Qyzylorda was mainly grassland (43.06%) and water bodies (39.08%). The ESV of South Kazakhstan was mainly grassland (55.79%) and cropland (41.57%). The ESV of Karakalpakstan was mainly water bodies (63.74%) and cropland (24.51%).

We also calculated the rate of change in ESV in administrative units (1993–2003, 2003–2013, 2008–2018, and 1993–2018) (Fig. 4). From 1993 to 2018, Karakalpakstan's ESV declined (–52.76%), with a total loss of USD 25.06 billion (Fig. 4a). The ESV of Qyzylorda and Aqtobe also decreased significantly, mainly due to the reduction of the area of water bodies.

The ESV of Jalal-Abad, Osh, Jizzakh, Talas, and South Kazakhstan increased, mainly due to the increase in cropland area. From 1998 to 2008, Karakalpakstan's ESV declined (–33.83%), with a total loss of USD 14.12 billion (Fig. 4a). From 2008 to 2018, the ESV of Karakalpakstan and Aqtobe declined further (Fig. 4b). Karakalpakstan's ESV declined (–18.9%), with a loss of USD 5.219 billion, followed by Aqtobe's ESV (–20.7%), with a loss of USD 660 million. The ESV of Ferghana, Sirdaryo, Namangan, Navoi, and Leninabad increased (Figs. 4c and d).

Fig. 4 Ecosystem service value change rate (%) from 1993 to 2003 (a), 2003 to 2013 (b), 2008 to 2018 (c), and 1993 to 2018 (d).

Table 4. Estimated values for ecosystem functions in the Aral Sea basin from 1993 to 2018

Service type	Sub-type	Ecosystem service value (billion US\$)					
		1993	1998	2003	2008	2013	2018
Provisioning	FP	128.59	128.61	128.87	129.07	129.07	128.87
	RM	9.58	9.59	9.63	9.62	9.61	9.6
Regulating	GR	0.44	0.44	0.44	0.44	0.45	0.45
	CR	14.88	14.94	15.13	15.25	15.36	15.46
	WR	72.52	62.24	49.5	43.9	37.4	37.66
Supporting	SFR	21.79	21.87	21.96	21.92	21.9	21.82
	WT	21.54	20.56	19.36	18.8	18.15	18.14
	BD	157.46	157.23	157.59	158.36	158.6	158.8
Culture	RCT	28.3	25.94	23.82	23.48	22.73	23.78
Total		455.1	441.41	426.28	420.84	413.27	414.56

GR – Gas Regulation; CR – Climate Regulation; WR – Water Regulation; SFR – Soil Formation and Retention; WT – Waste Treatment; BD – Biodiversity; FP – Food Production; RM – Raw Material; RCT – Recreation, Cultural and Tourism.

3.3 Changes in Values of ES Functions

Table 4 shows the changes in individual ecosystem function (ESV_f). Food production, water regulation, and biodiversity were the most important ES functions in the Aral Sea basin, accounting for 28.6%, 15.93%, and 34.60% of the total ESV in 1993 and 30.67%, 10.43%, and 37.63% of the total ESV in 2008, respectively. In 2018, these factors accounted for 31.09%, 9.08%, and 38.31% of the total ESV. From 1993 to 2018, most ESV_f decreased, except for food production, raw material, gas regulation, climate regulation, soil formation and retention, and biodiversity, which increased by 0.22%, 0.21%, 2.27%, 3.90%, 0.14%, and 0.85% respectively. Notably, the ESV_f of water regulation declined much faster than that of other ES (−48.07%), followed by recreation and culture and tourism (−15.97%) and waste treatment (−15.78%).

Table 5. Percentage change in estimated total ESV and coefficient of sensitivity

Change of value	1993		1998		2003		2008		2013		2018	
coefficient	%	CS	%	CS	%	CS	%	CS	%	CS	%	CS
Cropland VC $\pm$ 50%	18.11	0.36	18.75	0.37	19.51	0.39	19.71	0.39	20.05	0.40	19.89	0.4
Forestland VC $\pm$ 50%	0.76	0.02	0.77	0.02	0.80	0.02	0.77	0.02	0.77	0.02	0.81	0.02
Grassland VC $\pm$ 50%	22.44	0.45	23.07	0.46	23.94	0.48	24.43	0.49	24.94	0.50	24.92	0.5
Wetland VC $\pm$ 50%	0.24	0.00	0.25	0.01	0.26	0.01	0.27	0.01	0.27	0.01	0.27	0.01
Urban VC $\pm$ 50%	0.09	0.00	0.1	0	0.22	0.00	0.36	0.01	0.47	0.01	0.59	0.01
Bare land VC $\pm$ 50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waterbodies VC $\pm$ 50%	8.35	0.17	7.04	0.14	5.28	0.11	4.45	0.09	3.48	0.07	3.52	0.07

3.4 Ecosystem Sensitivity Analysis

According to the CS, the sensitivity of the ESV to the value coefficient was analyzed by transferring 50% of the VC of various ES up and down. The results are shown in Table 5. The sensitivity index of ESV to VC of the same ecosystem type changed little in different periods. During the same period, the ESV sensitivity index of different ecosystem types to the VC was significantly different. From 1993 to 2018, grassland had the highest CS (0.50), mainly due to its high VC and large area (Table 5). The service VC of cropland increased from 0.36 in 1993 to 0.39 in 2003 and further to 0.4 by 2018. Compared with grassland and cultivated land, the CS (0.02) of forestland was relatively stable. The CS of water bodies decreased from 0.17 in 1993 to 0.11 in 2003 and further to 0.07 in 2018. The sensitivity indexes of each period are far less than 1, indicating that the ESV of each year in the Aral Sea basin is inelastic to the functional VC. The VC used in this study is suitable for the actual situation of the Aral Sea basin, and the study results are credible.

4 DISCUSSION

4.1 Impact of LULCCs on ES in the Aral Sea

The change in ES is the concentrated embodiment of the interaction of the natural ecological environment and human activities on the earth's surface. LULC is the impetus of substantial changes in the earth's surface structure and substantially affects the regional climate, hydrology, water resources, soil, biodiversity, and biogeochemical cycle (Sterling et al. 2013, Tian et al. 2012). Human activities influence the structure and function of the entire ecosystem through different land use strategies, change the structure and process of the ecosystem, and affect the regional ecosystem's ability to provide products and services (Assessment 2005, Feng et al. 2017).

Land use change is an important factor leading to the change in ES, and the ecosystem is affected by the change in land use structure, composition, pattern, and intensity (Locher-Krause et al. 2017). In the past 50 years, significant changes have been observed in LULC in the Aral Sea basin, particularly due to the irrational use of water resources caused by the intensification of agricultural activities, the shrinking area of the Aral Sea, the rapid growth of the population and the development of the planting industry, the construction of many irrigation systems and reservoirs in the basin, and the rapid increase and consumption of river irrigation water.

Therefore, the amount of salty water entering the Amu Darya and Syr Darya Rivers has decreased significantly, and the water surface area has sharply decreased from 68000 km² in the 1960s to approximately 7000 km² at present, most of which has dried up and disappeared (Dukhovny & Schutter 2011, Sokolov 2020).

The large-scale farmland transformation and large-scale irrigation projects have led to the exploitation of saline water resources, especially in the middle and lower reaches. The negative effects included a sharp decrease in the water inflow into the Aral Sea, a shrinking water surface, deterioration in water quality, aggravation of salinization and desertification, destruction of the original ecological chain and some biological species, and disruption of original ecological balance of the Aral Sea basin. The problems related to resources and the environment in the Aral Sea basin have become increasingly prominent (Karimov et al. 2020, Kulmatov et al. 2021, Mueller et al. 2014), thus affecting regional ES (Nahuelhual et al. 2020).

According to the statistics of the World Bank, the average annual population growth rate of the Aral Sea basin from 1990 to 2015 was 12.6 ‰. With the total population of the basin at the end of 2015 as the base, it is estimated that the total population of the basin will reach 82.84 million and 106.4 million in 2030 and 2050, respectively (Xiangrong et al. 2017). As the population grows and the demand for food increases, there will be a pressure to increase the irrigated area. The economic and social development of the countries in the basin will increase the demand for water. This trend will cause the overexploitation of water resources to fulfill the population's demand for water, food, and energy (Xiangrong et al. 2017).

From 1993 to 2018, bare land (5.57%) and urban land (503.18%) expanded significantly, and water bodies (−61.62%) and forestland (−3.23%) shrank (Table 2). Accordingly, from 1993 to 2018, the value of grassland ES increased by USD 2.33 billion, and the value of urban ES increased by USD 4.11 billion (Table 3). From 1993 to 2018, the water bodies area decreased sharply, resulting in a loss of USD 46.84 billion (Table 3). Urban expansion leads to a decline in the value of ES provided by affected land. Over time, changes in the value of ES depend on the interaction of changes in various land cover types (Kreuter et al. 2001). Coastal and marine ecosystems provide some of the most important services for human beings, but they are endangered because of overexploitation and loss (Barbier 2012). However, many unique marine habitats have vital cultural functions (Barbier 2017). We demonstrated that the water regulation (USD −34.857 billion); waste treatment (USD −3.397 billion); and recreation and culture and tourism (USD −4.522 billion) services in the Aral Sea basin decreased from 1993 to 2018. Food production (USD 278 million), raw material (USD 22 million), gas regulation (USD 09 million), climate regulation (USD 581 million), the service functions of water regulation (USD −34.857 billion), waste treatment (USD −3.397 billion), and recreation and culture and tourism (USD −4.522 billion) decreased. The service functions of soil formation and retention (USD 32 million) and biodiversity (USD 1.338 billion) increased (Table 4). From 1993 to 2018, we observed the following. First, Aral Sea basin Water Regulation (USD −34.857 billion), waste treatment (USD −3.397 billion), and recreation and culture and tourism (USD −4.522 billion) reduced service functions, and second, food production (USD 278 million), raw material (USD 22 million), gas regulation (USD 0.9 million), climate regulation (USD 581 million), soil formation and services increased for retention (USD 32 million) and biodiversity (USD 1.338 billion) (Table 4).

The development and construction of urbanization, dams, and water conservancy projects also significantly change the watershed ecosystem (Sdiri et al. 2018). The main human activities that use water in the basin are

related to agriculture, industry, and cities. Agriculture is the largest water-consuming sector and has long been criticized for shrinking the Aral Sea (Zou et al. 2019). The expansion of construction land (128.83 km²/year) and agricultural land (66.68 km²/year) from 1992 to 2015 increased water consumption, thereby exacerbating the stress on the water resources in the Syr Darya River basin (Zou et al. 2019). The Aral Sea was threatened by the substantial increase in the irrigated farmland in its basin (Lioubimtseva 2014). The increase in cultivated land in the Aral Sea basin was mainly in the Karakum Canal, the largest irrigation project in the world. In the initial years of the 21st century, the Aral Sea will continue to shrink; thus, the Aral Sea crisis will continue probably due to the competition related to acquiring the irrigation water for agriculture among the regions in the basin (Li et al. 2021).

In recent years, the Aral Sea has continued to shrink further, and the cultivated land area has remained stable or increased slightly, indicating that no large-scale abandonment or expansion of cultivation scope has occurred. The expansion rate of urban land was slightly higher; thus, urbanization is progressing rapidly, thereby leading to increases in water consumption (Conrad et al. 2016, Lioubimtseva 2015, Su et al. 2021). Many studies on ESV assessment have shown that land use change reduces the ESV (Kreuter et al. 2001, Long et al. 2014, Song & Deng 2017, Zhao et al. 2004).

4.2 Limitations and Areas of Further Research

The calculations in the study were conducted by multiplying the value per unit area by the area of each ecosystem. However, this approach has several limitations, such as, over-reliance on the VC per unit area. Because of the differences in the composition of a service function selected by researchers in the estimation of physical quality, the unit price of ES is significantly different, highlighted by the spatial heterogeneity of ESV that needs to be considered (Gao-di et al. 2008). The ESV results are related to the accuracy of land use classification results. Therefore, to overcome these limitations and increase the accuracy of the assessment of ES in the Aral Sea basin, further research should use higher spatial resolution remote sensing data and more precise LULC classification. From the perspective of sustainable development in the Aral Sea, the future direction of land use management should consider the balance between agriculture, ecosystems, and environment and devise a reasonable water resource utilization plan in upstream and downstream areas. At present, no quantitative or qualitative evaluation of the interaction between the ES in the region has been conducted, and the various ES are not independent. The distribution difference of multiple ES has been compared to improve the understanding of the coordination and trade-offs of ES (Qin et al. 2015, Sun et al. 2017, Wang et al. 2017). Further research should quantify the impacts of human activities and climate change on ES in the region (Han et al. 2018, Prather et al. 2013, Wang et al. 2016) and explain the internal driving mechanism of ecological degradation succession in the Aral Sea basin.

5 CONCLUSIONS

Our study shows that from 1993 to 2018, the area of urban land, bare land, grassland, wetland, and cropland in the Aral Sea basin increased, and the area of water bodies and forestland decreased. The value of water ES decreased by approximately USD 46.84 billion owing to a decrease in water area (−61.62%). Importantly, with little change in the cropland, agricultural water use will continue to shrink the Aral Sea, thereby potentially leading to the loss of natural ES (e.g., water resource management and climate management). Many ES are fading, and decision-making policies are necessary to ensure the sustainability of ES, particularly the drivers that have adverse impacts on ecosystems. Therefore, this study contributes to avoiding further negative impacts because the results improve policy makers' understanding of the changes in ES caused by LULCCs and provide relevant scientific data and decision support for the ecosystem protection and integrated management of the Aral Sea basin and a scientific basis for the coordinated development of land use and ES.

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Declarations

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