Socioeconomic Patterns for Global Mangrove Cover Changes with Multivariate Analyses

Ruihan Lin

Institute of Urban Environment

Shen Yu (✉ syu@iue.ac.cn)

Institute of Urban Environment <https://orcid.org/0000-0002-7543-6082>

Bing Hong

Institute of Urban Environment

Research Article

Keywords: global mangrove cover change, socioeconomic drivers, aquaculture, urbanization

Posted Date: October 29th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-949258/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

Socioeconomic patterns beyond the land conversions of global mangrove cover changes were few discussed. This study integrated databases of global mangrove covers, i.e., a multi-database in 1980-2016 with a combination of FAO country-survey and the global mangrove watch, and a mangrove biome cover database in 2000-2012. Annual mangrove cover change (%) of each mangrove holding country or territory was incorporated with its socioeconomic indicators in the two periods to testify possible socioeconomic patterns beyond the mangrove deforestation. The socioeconomic indicators consisted of GDP per capita and urban population percentile, and aquacultural indicators (production per capita, sales value per capita, contribution to the national GDP, and product price). Results indicated that annual mangrove cover change was interactively driven by multi-factors of national economy measures, urbanization, and aquaculture, instead of aquacultural dominance or GDP per capita alone. The multi-factor driven patterns of annual mangrove changes differed geographically among the continents. Temporal change of aquacultural product price was significantly and positively correlated to annual mangrove cover change (increase), especially in Asia and Oceania for both the periods, suggesting positive feedbacks of mangrove conservation and restoration in the two continents although the price was used to a motivator of mangrove deforestation, such as currently in Africa. These findings preliminarily bridge the knowledge gap between land conversion losses and socioeconomics of global mangrove cover changes.

Introduction

An action decade on ecosystem restoration has been called by the United Nations for the Agenda 2030 Sustainable Development Goals (United Nations 2019). The call of “UN Decade on Ecosystem Restoration” facilitates and supports restoration of degraded ecosystems globally. An existing goal is to restore 350 million hectares of degraded ecosystems under the Bonn Challenge (<http://www.bonnchallenge.org>). Mangrove ecosystems are one of the world's most valuable but rapidly declining and degrading coastal ecosystems (Cardier et al. 2020). In addition to their value as a natural ecosystem, mangroves offer important ecosystem services in disaster mitigation against coastal flood risk and blue carbon sequestration against climate change (Alongi 2008; Mcleod et al. 2011; Twilley et al. 2018; Dasgupta et al. 2019; Menéndez et al. 2020). To halt and even reverse degradation and loss of mangrove ecosystems by 2030 were highly desired through the action agenda of the UN Decade on Ecosystem Restoration (International Union for Conservation of Nature 2020).

Global mangrove covers have been continuously monitored via national survey by the Food and Agricultural Organization (FAO), United Nations (Food and Agriculture Organization 2003, 2007, 2020) and through remote sensing by researchers (Spalding et al. 1997, 2010; Giri et al. 2011; Hamilton and Casey 2016; Bunting et al. 2018). Although there were arguments on accuracy of the coverage database via different approaches, overall loss rates of global mangrove cover were definitely greater in the late decades of the 20th Century than those in the beginning decades of the 21st Century (Friess et al. 2019). Deforestation by anthropogenic activities has resulted in substantial losses of global mangrove cover regardless of time period. Most deforested mangrove cover has been converted to aquaculture and agriculture (plantations), and then to urban land uses (Richards and Friess 2016; Friess et al. 2019). Approximately 62% of global mangrove covers were deforested and converted to aquaculture and agriculture in the period 2000-2016 (Goldberg et al. 2020) while over 50% of the deforested mangroves in Southeast Asia became aquaculture and rice plantation in the past (Bryan-Brown et al. 2020). In 2000-2012, mangrove deforestation in Southeast Asia had a declined loss to aquaculture down to approximately 30% but nearly 88% loss to rice plantation in Myanmar, 40% loss to oil palm plantation in Malaysia and Thailand, and 63% loss to urban land use in Vietnam (Richard and Friess 2016; Bryan-Brown et al. 2020). Crude oil and gas production in coast also caused mangrove deforestation for drilling and infrastructure, and even worse during oil spill events while fuelwood and charcoal productions contributed to the early losses (Duke 2016; Friess et al. 2019). Comprehensive losses of socioeconomic benefits have been assessed for mangrove deforestations (Walters et al. 2008). Knowledge of mangrove cover losses was highly concentrated in land use conversions (Richards and Friess 2016; Friess et al. 2019). What was beyond the land use conversions was scarcely argued. Economic driving forces of the deforestation were conducted by a cross-country analysis of 89 countries in the late 20th century with a conclusion as “the higher the level of GDP per capita, the more mangrove area remains” (Barbier and Cox 2003). Given the pattern of global mangrove cover change was significantly shifted, its socioeconomic drivers or pattern might be altered accordingly. Other factors, such as the number of protected areas, length of coastline, and political stability, also determined mangrove cover area remained in a country (Barbier and Cox 2003). A recent multi-scale estimation on mangrove cover loss of 77 countries using a DPSIR model confirmed that the protected areas slowed the loss rates between 1996-2016 while the regulatory quality determined the mangrove covers outside of the protected areas (Turschwell et al. 2020) using the global mangrove watch database (GMW, Bunting et al. 2018). Population density was another important driver for mangrove cover loss in countries with low regulatory quality (Turschwell et al. 2020).

Aquaculture has been continuously filling the increasing supply-demand gap of fisheries. As projected by the World Bank, aquacultural production would equal to capture fisheries by 2030 up to 93 million tons and be dominated afterwards (The World Bank 2013). The increasing aquaculture was the major cause of mangrove deforestation, especially in Southeast Asia in the past and even recently accounting for approximately 30% of the loss (Barbier and Cox 2003; Richards and Friess 2016; Bryan-Brown et al. 2020; Goldberg et al. 2020). However, motivational dynamics of aquacultural development on mangrove deforestation have not been discussed yet although GDP per capita, population density, and regulatory governances were important to the remaining mangrove cover in a country (Barbier and Cox 2003; Turschwell et al. 2020). The declining human-driven losses were observed (Goldberg et al. 2020), especially the aquacultural impacts but still contributed 30% of the global losses (Richards and Friess 2016). This study attempted to utilize these temporal changes to explore motivational dynamics of mangrove cover changes in response to socioeconomic development in the mangrove-holding countries and territories using multivariate analyses. Annual mangrove cover change (%) of each mangrove holding country or territory was assumed relatively reliable as the dependent variate for socioeconomic indicators rather than an absolute value of annual cover area, which was estimated via various approaches. Ha et al. (2012) found shrimp farmers would plant and protect mangroves if the benefits of mangrove production were more than those of the shrimp farming in the Mekong Delta, Vietnam. Therefore, it might further hypothesize that aquacultural product price with increasing demands might directly motivate farmers to deforest mangroves, rather than GDP per capita which might determine aquacultural product price. But the motivational dynamics might be geographically dependent or depend on aquacultural contribution to the national GDP. Findings of this study were expected to add new geographic understandings on economic dynamics of mangrove cover changes and would be supportive for strategizing mangrove conservation and governance in the future.

Materials And Methods

Data collections and calculations

Global mangrove covers were collected from national survey-based FAO estimates in 1980-2005 (117 countries, Food and Agriculture Organization 2003, 2007) and in 1990-2020 (113 countries, Food and Agriculture Organization 2020), and vector datasets of satellite image interpretation in 2000 (the NASA database with 105 countries, Giri et al. 2011, <https://earthobservatory.nasa.gov/images/47427/mapping-mangroves-by-satellite>), 2000-2012 (the database of continuous mangrove forest cover for the 21st century (CGMFC-21) with 103 countries, Hamilton and Casey 2016, <http://bit.ly/1IMJ9zj>), and 1996-2016 (the Global Mangrove Watch (GMW) database with 105 countries, Bunting et al. 2018, <https://data.unep-wcmc.org/datasets/45>). An ArcGIS® 10 platform was used to extract number and area of each mangrove patch from the vector datasets of satellite image interpretation and then to calculate the national mangrove cover areas. Temporal changes of global mangrove covers were shown in Fig. 1 with linear regressions for each database. The annual mangrove cover change was calculated in a period with available cover area values and assigned to the end year. For instance, the mangrove cover areas were presented by FAO (Food and Agriculture Organization 2007) for 1980, 1990, 2000, and 2005; and the annual mangrove cover changes were calculated by differences of 1980-1990, 1990-2000, and 2000-2005 divided by the cover area in 1980, 1990, and 2000 and interval years (10 years here), respectively, and expressed in percentage; then the calculated annual mangrove cover changes were assigned to the year of 1990, 2000, and 2005, respectively. The year 1980 was namely a reference year. Therefore, annual mangrove cover change (%) is a vector indicator, i.e., positive values indicating increased mangrove cover area in the year and vice versa. According to the mangrove patch definition approaches, two datasets of annual mangrove cover changes (%) were generated: the one integrated mangrove cover of the FAO dataset by 2007 (1990, 2000, and 2005 with a reference year 1980, Food and Agriculture Organization 2007) and the GMW dataset (2007, 2008, 2009, 2010, 2015, and 2016 with a reference year 1996, Bunting et al. 2018) and another one was derived from the CGMFC-21 dataset of mangrove biome cover for continuous 2001-2012 with a reference year 2000 (Hamilton and Casey 2016). The mangrove covers of the FAO dataset by 2020 (1990, 2000, 2010, and 2020, Food and Agriculture Organization 2020) were not included due to no data available at country (and territory) level. Integrating the FAO 2007 dataset with the GMW dataset was attempted to cover early period 1980-2005 with a general definition of mangrove cover while the CGMFC-21 dataset only for mangrove biome cover. Other databases, such as the 30-m resolution GEOTIFF by Goldberg et al. (2020), were not included because of no integrated vector data available at country (and territory) level and the period 2000-2016 overlapped with the GMW database (Bunting et al. 2018).

Patches from the GMW database (Bunting et al. 2018) in 1996 and 2016 were further analyzed. All the patches were geographically pair-compared between 1996 and 2016 to identify full or partial loss patches and expanding or rehabilitation patches in 2016 to understand mangrove cover change patterns at a patch level.

According to literature, the socioeconomical indicators consisted of GDP per capita (current USD) for overall socioeconomical development and urban population percentile for urbanization process in each mangrove holding country or territory, which were obtained from a database of the World Bank (<https://data.worldbank.org>). Two aquaculture indicators, aquacultural production per capita (kg) and sales value per capita (current USD), were extracted via FishStatJ (v4.00.17, <http://www.fao.org/fishery/statistics/software/fishstatj/en>). Price of aquacultural products (current USD per ton) was calculated by sales value per capita dividing production per capita. Meanwhile, a contribution of aquaculture to the national GDP was calculated by the sales value per capita dividing GDP per capita and expressed in percentage. Then, the 6 indicators built the socioeconomic dataset for mangrove holding countries and territories.

Annual mangrove cover change of the multi-databases matched the socioeconomic dataset in 83 countries and territories with 702 observations of 9 years (1990, 2000, 2005, 2007, 2008, 2009, 2010, 2015, and 2016), namely the multi-databases dataset or referred as the period 1990-2016 thereafter. Similarly, the annual mangrove cover change of the CGMFC database synchronized the socioeconomic-aquacultural dataset in 78 countries and territories with 902 observations in continuous 12 years from 2001 to 2012, namely the CGMFC dataset or referred as the period 2001-2012 thereafter. The two datasets were used for exploring periodic patterns of socioeconomic-aquacultural drivers on annual mangrove cover changes (%).

Statistics

Global mangrove cover changes over time were analyzed using a linear regression (Proc REG) for the combined databases in 1980-2005 (Food and Agriculture Organization 2003, 2007), the single database in 1990-2020 (Food and Agriculture Organization 2020), and the combined vector databases of NASA snapshot in 2000 (Giri et al. 2011) and GMW in 1996-2016 (Buntings et al. 2018), respectively, as shown in Fig. 1. Interactive relationships of annual mangrove cover change with the socioeconomic indicators were conducted by Spearman correlation analysis for both the multi-databases and CGMFC datasets, as presented in Table 1. Further, socioeconomic drivers for aquacultural product price and annual mangrove cover change were identified in both the datasets using an analysis of variance (ANOVA)-repeated measures (Proc Mixed) with year as the model repeated effect and continent as the group repeated effect (Table 2). Global patterns of mangrove cover changes in response to the socioeconomic-aquacultural development were depicted using a multidimensional preference analysis (MDPA, Proc PrinQual) for the multi-databases dataset (83 countries and territories) and the CGMFC dataset (78 countries and territories), respectively (Fig. 2). Further, continental patterns were analyzed using the MDPA (Proc PrinQual) for Africa, Asia, Oceania, North and Central Americas, and South Americas, respectively, for both the multi-databases and CGMFC datasets (Fig. 3 and 4). The above-mentioned statistical analyses were done at SAS® OnDemand for Academics (<https://welcome.oda.sas.com>).

Table 1

Annual mangrove cover changes (%) in the globe and continents of the multi-databases (FAO and GMW in 1990-2016 with 83 countries and territories) and the territories) in relation to the socioeconomic-aquacultural indicators explored by Spearman correlation

Annual mangrove cover change (%; a vector indicator)	Africa			Asia			Oceania			North and Central America			South	
		N	Coefficient	p	N	Coefficient	p	N	Coefficient	p	N	Coefficient	p	N
Socioeconomic-aquacultural indicator														
GDP per capita (current USD)	1990-2016	194	0.276	<0.001	191	0.234	0.001	72	0.353	0.002	185	0.179	0.015	60
	2001-2012	268	0.125	0.040	241	0.309	<0.001	69	-0.344	0.004	240	0.386	<0.001	84
Urban population percentile (%)	1990-2016	194	0.059	0.416	191	0.180	0.013	72	0.231	0.051	185	-0.039	0.596	60
	2001-2012	268	-0.029	0.637	241	0.384	<0.001	69	-0.379	0.001	240	0.125	0.054	84
Aquacultural production per capita (kg)	1990-2016	194	0.102	0.157	191	-0.051	0.481	72	-0.088	0.460	185	-0.030	0.683	60
	2001-2012	268	-0.119	0.052	241	-0.591	<0.001	69	-0.668	<0.001	240	-0.359	<0.001	84
Aquacultural sales value per capita (current USD)	1990-2016	194	0.171	0.017	191	0.013	0.859	72	0.211	0.075	185	-0.047	0.527	60
	2001-2012	268	-0.081	0.187	241	-0.501	<0.001	69	-0.320	0.007	240	-0.420	<0.001	84
Contribution of aquacultural sales values to national GDP (%)	1990-2016	194	0.057	0.431	191	-0.154	0.034	72	0.013	0.913	185	-0.111	0.131	60
	2001-2012	268	-0.081	0.189	241	-0.579	<0.001	69	-0.131	0.284	240	-0.481	<0.001	84
Aquacultural product price (current USD per ton)	1990-2016	194	0.185	0.010	191	0.143	0.049	72	0.270	0.022	185	0.043	0.564	60
	2001-2012	268	-0.266	<0.001	241	0.499	<0.001	69	0.286	0.017	240	-0.055	0.393	84

Table 2

Socioeconomic-aquacultural drivers for annual mangrove cover change and aquacultural product price explored by the multi-databases (FAO and GMW) and CGMFC datasets using an ANOVA-Repeated Measures (Proc Mixed)

ANOVA-Repeated Measures (Proc Mixed) with Year as the model repeated effect and Continent as the group repeated effect.	The multi-databases dataset of FAO and GMW in 1990-2016 (83 countries and territories)					The CGMFC dataset in 2001-2012 (78 countries and territories)				
	DF	Annual mangrove cover change		Aquacultural product price (current USD per ton)		DF	Annual mangrove cover change		Aquacultural product price (current USD per ton)	
F	p	F	p	F	p	F	p			
Model (Chi-square)	4	343.29	<0.0001	733.11	<0.0001	4	30.74	<0.0001	208.58	<0.0001
GDP per capita (current USD)	695	2.99	0.0844	5.63	0.0180	895	9.15	0.0026	58.61	<0.0001
Urban population percentile (%)	695	0.37	0.5450	5.72	0.0170	895	0.25	0.6159	14.80	0.0001
Aquacultural production per capita (kg)	695	0.80	0.3705	62.59	<0.0001	895	5.73	0.0168	97.20	<0.0001
Aquacultural sales value per capita (current USD)	695	0.54	0.4619	24.84	<0.0001	895	0.42	0.5151	43.80	<0.0001
Aquacultural contribution to the national GDP (%)	695	0.00	0.9873	0.06	0.8011	895	0.13	0.7189	2.14	0.1436
Annual mangrove cover change (%)	695			0.28	0.5996	895			20.86	<0.0001
Aquacultural product price (current USD per ton)	695	0.34	0.5578			895	4.64	0.0315		

Results And Discussions

Socioeconomic drivers on annual mangrove cover changes

Annual mangrove cover change is a vector indicator for each country or territory, i.e., if negatively correlating with socioeconomic indicators means mangrove cover loss with the socioeconomic indicator increase and vice versa. As an important socioeconomic indicator, GDP per capita showed significant and positive correlations with annual mangrove cover change regardless of continents and the globe. The multi-databases dataset with 83 countries and territories in 1990-2016 ($p < 0.01$) had a greater significance level of the corrections than the CGMFC dataset with 78 countries and territories in 2001-2012 ($p < 0.05$), except that the Oceania ($p < 0.001$) and South America (not significant) had negative correlations in 2001-2012 (Table 1). The positive corrections were in agreement with the findings of Barbier and Cox (2003) but the negative ones suggest that the mangrove cover was deforesting with GDP per capita increases in the countries and territories of the Oceania and South America in 2001-2012 ($p < 0.01$, Table 1). The 6 included Oceanian countries and territories (Solomon Islands, Vanuatu, Fiji, Palau, New Zealand, and Australia in an increasing order) had a wider range of GDP per capita from 1,913 to 68,012 current USD than the 7 involved countries and territories in the South America (Guyana, Ecuador, Peru, Colombia, Suriname, Brazil, and Venezuela in an increasing order) with a range of 3,788 - 12,985 current USD by 2012, calculated from the World Bank data (<https://data.worldbank.org>).

Conversions to urban land uses were considerable in some countries (Branoff 2007; Richards and Friess 2016). It was true that the Oceania and South America had significant and negative correlations between annual mangrove cover change and urban population percentile, a common indicator of urbanization, in 2001-2012 ($p < 0.05$, Table 1). However, most mangrove covers are located in rural coasts except some coastal cities in the world. Therefore, it might be true in some regions that the more people moved into urban areas, the less mangrove covers were impacted and lost. In Asia, it was confirmed that urban population percentile was significantly and positively correlated to annual mangrove cover change for both periodic datasets, i.e., 1990-2016 ($p < 0.05$) and 2001-2012 ($p < 0.001$) (Table 1) although Vietnam had a large loss to urban lands in 2000-2012 (Richards and Friess 2016). Goldberg et al. (2020) pointed out that the urban land conversion did not impact mangrove covers as great as aquaculture and agricultural plantations.

Aquaculture had resulted in tremendous deforestation of the global mangrove covers in the past, especially in certain regions (Bryan-Brown et al. 2020; Goldberg et al. 2020). The aquacultural indicators, production per capita and sales value per capita, were significantly and negatively correlated with annual mangrove cover change for the globe and the continents (except Africa) in 2001-2012 while the aquacultural contribution to the national GDP had significant and negative correlations only in Asia, North and Central America, and the globe ($p < 0.01$, Table 1). The multi-databases dataset in 1990-2016 had negative correlations between the aquacultural contribution to the national GDP and annual mangrove cover change only in Asia ($p < 0.05$, Table 1). Among the 7 countries with the aquacultural contribution to the national GDP above 1% by 2016, Asia had 6 countries, including Vietnam (4.45%), Myanmar (2.97%), Bangladesh (2.54%), Cambodia (1.59%), China (1.28%), and Indonesia (1.18%) and only Ecuador (2.34%) from the South America. By 2012, only Indonesia was excluded from the abovementioned list with two additions of Belize (1.35%) and Honduras (1.27%) from the Central America. No African mangrove-holding countries had the aquacultural contribution above 1% of the national GDP across the period 1980-2016 except Seychelles with 1.4% only by 2003. The top Asian countries and Ecuador had increased aquacultural contributions to the national GDP from 2012 to 2016. On the other hand, aquacultural product price was positively and significantly correlated with annual mangrove cover change in Asia and Oceania for both periodic datasets and Africa and the globe only in 1990-2016, but negatively in Africa in 2001-2012 ($p < 0.05$, Table 1). The negative correlations suggest that aquaculture development drove mangrove deforestation in the period 2001-2012 and Asia was the hotspot, in agreement to the land conversion studies (Bryan-Brown et al. 2020; Goldberg et al. 2020). However, the aquacultural product price was not simply a motivative factor for farmers to deforest mangroves as hypothesized but also a consequence of mangrove cover protections, i.e., the less mangrove cover lost the higher price was in 2001-2012, except in Africa with low contributions to national GDP per capita (Table 1). It might be partially coincided to the findings of declining aquaculture impacts on mangrove covers in Southeast Asia in 2000-2012 (Richards and Friess 2016).

Overall patterns of socioeconomic-aquacultural indicators and annual mangrove cover change were relatively similar among continents between the two datasets, i.e., 1990-2016 and 2001-2012, visualized by a multidimensional preference analysis (Fig. 2). Only Africa was obviously separated from other continents mainly by the aquacultural indicators, including production per capita, sales value per capita, and contribution to the national GDP. However, annual mangrove cover change and aquacultural product price were highly overlapped with close relations to GDP per capita and urban population percentile in 1990-2016 but evidently separated in 2001-2012 (Fig. 2). GDP per capita and urban population percentile were consistently overlapped for both periods (Fig. 2). These patterns were highly coincident with the results of correlation analysis (Table 1) and suggested that annual mangrove cover change was mainly determined by the aquaculture but influenced by the national economy (GDP per capita) and urbanization (urban population percentile). It is evident that the influences of the national economy and urbanization were stronger on annual mangrove cover change in 1990-2016 than those in 2001-2012. It further confirmed the declining aquacultural impacts (Richards and Friess 2016). Among the continents, annual mangrove cover change was mainly determined by aquaculture in Asia and North and Central America while the others were driven by the national economy and urbanization, especially GDP per capita, in 2001-2012 (Fig. 4). However, in the period 1990-2016 the continental patterns were interactively impacted by the three drivers, i.e., the national economy, urbanization, and aquaculture (Fig. 3). On the other hand, aquacultural product price was consistently determined by GDP per capita and urban population percentile for all the continents in the two periodic datasets except the South America in 1990-2016 (Fig. 3 and 4), in coincidence with the correlations (Table 1).

Integrating findings from the correlation analyses and multidimensional preference analyses, annual mangrove cover change was interactively driven by the national economy, urbanization, and aquaculture, among which the aquacultural impacts were declining and the influences of national economy and urbanization were increasing. It was in agreement with findings in southeast Asia (Richards and Friess 2016). Meanwhile, aquacultural product price might be feedbacked by mangrove conservation, especially in Asia and Oceania within both datasets, as well as a motivative factor for mangrove deforestation in Africa within the CGMFC dataset as hypothesized. Removing temporal effects using an ANOVA-Repeated Measures (Proc Mixed), annual mangrove cover change was not significantly influenced by any selected socioeconomic-aquacultural indicators in 1990-2016 (the multi-databases dataset) and only by GDP per capita, and aquacultural production per capita and product price in 2001-2012 (the CGMFC dataset) although both models were statistically significant (p

< 0.05, Table 2). On the contrary, the aquacultural product price was consistently and significantly determined by GDP per capita, urban population percentile, and per capita aquacultural production and sales value in both periodical datasets excluding the temporal effects ($p < 0.05$, Table 2). In 2001-2012, the aquacultural product price was also significantly associated with annual mangrove cover change ($p < 0.001$, Table 2). It further confirms that the socioeconomic patterns of annual mangrove cover change periodically responded to the national socioeconomic development and regulatory governance (Barbier and Cox 2003; Slobodian et al. 2018; Turschwell et al. 2020). The aquaculture farmer's livelihood had to be insured during tradeoffs of mangrove restoration and conservation (Ha et al. 2012).

Impacts of global mangrove cover changes over the periods

Given socioeconomic development with varying periodic patterns in mangrove-holding countries and territories, it led to periodic changes of global mangrove covers.

Global mangrove covers had been dramatically declined at 1776 km² a year in 1980-2005 but at 379 km² a year in 1990-2020 upon the national survey by FAO (Food and Agriculture Organization 2003, 2007, 2020) (Fig. 1). However, the significant shift of annual declining rate might be contributed by the estimation technology. The FAO remarkably lowered the global cover estimate in 1990 and afterwards by 2020 in comparison with the previous estimates (Food and Agriculture Organization 2003, 2007, 2020) probably due to the remote sensing technology available to the most world, which were relatively comparable to the cover estimates and annual cover change (175 km² a year) in 1996-2016 via satellite image interpretation consisting of the NASA snapshot in 2000 (Giri et al. 2002) and GMW databases in 1996-2016 (Bunting et al. 2018) (Fig. 1). It had concluded that the fast decline of global mangrove covers in the late 20th century was slowed in the early 21st century (Friess et al. 2019), but overestimates might be possible for the national survey prior to the remote sensing application, with the global coverage around 198,000 km² in 1980 (Groombridge 1992; Fisher and Spalding 1993; Food and Agricultural Organization 2003). The earliest interpretation of integrated aerial and satellite images for global mangrove distribution mapping was the World Mangrove Atlas (Spalding et al. 1997) with an estimate of 181,077 km² in a wide timing span since 1980s, followed by the World Atlas of Mangroves at 152,361 km² mainly within 1999-2003 (Spalding et al. 2010) (Fig. 1). The cover estimates with mangrove biome and canopy (MFW) in the CGMFC dataset by Hamilton and Casey (2016) were quite different from the estimates of national surveys (Food and Agricultural Organization 2003, 2007, 2020) and satellite image interpretations (NASA and GMW) due to different approaches. The global mangrove biome cover of the CGMFC dataset (Hamilton and Casey 2016) was used individually in this study to compare with the FAO and GMW multi-databases for identifying socioeconomic drivers of annual mangrove cover changes globally. Given the remarkable shifts of mangrove cover estimates by various approaches over time, annual mangrove cover change might alleviate the systematic differences of the estimation approaches to explore socioeconomic patterns of mangrove cover changes instead of those direct estimates as the assumption. Meanwhile, the two different databases did present periodic socioeconomic patterns of annual mangrove changes (Table 1 and 2, and Fig. 2, 3, and 4).

At patch-level of the GMW dataset, approximately 17.1% of mangrove patches (over 118 km²) were fully lost while over 65% of mangrove patches were under shrinkage with an area loss of 8,384 km² (5.6% of mangrove cover area in 1996) during the 20 years in the world (Table 3). Importantly, the patch size significantly increased from 18.6 ha to 23.3 ha of the national average and from 14.2 ha to 17.1 ha of the national median (Table 3). It suggests that the small patches dominated mangrove cover losses, especially the full patch loss. Small patches of mangroves are important to its value as an ecosystem for blue carbon stock but also to surrounding habitats as nodes for interconnectedness (Barbier 2017; Curnick et al. 2019). In most developing regions, family-run aquacultural ponds were dominated, such as in India (Sarkar et al. 2015) where 83% ponds had a size less than 0.3 ha, relatively similar to the fully-lost mangrove patches, 0.105 ha of average and 0.069 ha of median according to the GMW databases (Table 3). On the other hand, the abandoned aquacultural ponds were highly recommended as an effective measure to restore mangrove ecosystems recently (Stevenson et al. 1999; van Bijsterveldt et al. 2020). However, it was very limited up to 2016, approximately 3,749 patches and 2.79 km² in area with a median patch size at 0.076 ha, similar to the fully-lost patches as above-mentioned (Table 3). Alternatively, the natural proliferation and expansion was remarkable in 1996-2016, approximately 3,498 km² in 80,248 patches globally (Table 3), maybe substantially contributed by the reserves or protected areas (Turschwell et al. 2020). Therefore, both deforestation and restoration/conservation activities or patterns might influence socioeconomic patterns of mangrove cover changes. More details required substantial studies in the future.

Table 3
Changes of mangrove covers in patch and area in the period 1996-2016^a

Changes of mangrove covers in patch and area in the period 1996-2016											
Item		Year	Existing patch	Full patch loss	Partial patch loss	Expanding patch	Rehabilitation patch	Increase of patch	Difference between existing and losses		
Number of countries and territories			105	89	97	87	9				
Patch number		1996	701,016								
		2016	584,632	120,128	456,449	80,248	3,749	3,749			
		Loss	116,384	120,128						-3,744	
		%		17.1%	65.1%	11.4%					
Area (km ²)		1996	149,481.52								
		2016	144,283.49	118.17	8,384.48	3,498.13	2.79	3,500.93			
		Loss	5,198.03	118.17	8,384.48						-3,304.63
		%		0.08%	5.61%	2.34%					
Patch size (ha)	Country Mean	1996	18.6								
		2016	23.3	0.105	3.17	24.8	0.108				
	Country Median	1996	14.2								
		2016	17.1	0.069	1.33	1.86	0.076				
*Data were extracted from the Global Mangrove Watch (Bunting et al., 2018).											

Conclusions

Via integrating two datasets of global mangrove covers (FAO+GMW in 1980-2016 and CGMFC-biome cover in 2000-2012) with six socioeconomic indicators in mangrove holding countries and territories, drivers on annual mangrove cover change were discussed at both global and continental levels for the two periods. Some common findings of the previous studies were confirmed, such as GDP per capita was positively associated with the mangrove cover remains (Barbier and Cox 2003) and human-driven mangrove loss was declining (Richards and Friess 2016; Goldberg et al. 2020) in some continents. Reverse findings were also observed. For instance, mangrove holding countries and territories in the Oceania and South America had annual mangrove cover change negatively correlated to GDP per capita in 2001-2012, maybe due to low aquacultural contributions to the national GDP. On the other hand, Asian countries and territories had more people moving to the urban areas lowered the impacts on mangrove covers (Table 1). Overall, socioeconomic patterns of annual mangrove cover change were interactively and geographically contributed by various drivers, including the national economy, urbanization, and aquaculture tested in this study (Fig. 2, 3, and 4) and others, such as regulatory governance, political stability and so on (Barbier and Cox 2003; Turschwell et al. 2020). In general, determined by socioeconomic development regardless of the periods (Table 2), aquacultural product price was also influenced by mangrove conservation and restoration not only as a motivational driver of mangrove deforestation (Table 1 and 2). These findings of this study only presented socioeconomic patterns beyond land conversion of mangrove cover in the majority of mangrove-holding countries and territories in the world. Further studies might be required in the future to include more drivers, such as harvesting and overutilization, pollution, natural erosion, extreme weather events, and conservation and restoration policies, etc.

Declarations

Funding: This study was financially supported by Ministry of Science and Technology of China (No. 2017YFC0506100) and National Natural Science Foundation of China (No. 41661144033, 41571483).

Conflicts of interest/competing interests: Not applicable.

Availability of data and material: Datasets would be provided as supplementary when the manuscript is accepted for publication.

Code availability: Not applicable.

Authors' contributions: RL collected, analyzed and interpreted the vector data of mangrove cover from various databases and the socioeconomic data from the World Bank, and drafted the manuscript. SY analyzed data statistically and re-wrote the manuscript. BH helped statistics and comments on manuscript.

Additional declarations: Not applicable.

References

1. Adame MF, Connolly RM, Turschwell MP, Lovelock CE, Fatayinbo T, Lagomasino D, Goldberg LA, Holdorf J, Friess DA, Sasmito SD, Sanderman J, Sievers M, Buelow C, Kauffman JB, Bryan-Brown D, Brown CJ (2021) Future carbon emissions from global mangrove forest loss. *Global Change Biology* 27:2856-

2866. <https://doi.org/10.1111/gcb.15571>
2. Alongi DM (2008) Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science* 76:1-13. <https://doi.org/10.1016/j.ecss.2007.08.024>
3. Barbier EB (2017) Seascape Economics: Valuing ecosystem services across the seascape. In: Pittman SJ (ed) *Seascape Ecology*. Wiley-Blackwell, New York, pp465-482
4. Barbier EB, Cox M (2003) Does economic development lead to mangrove loss? A cross-country analysis. *Contemporary Economic Policy* 21:418-432. <https://doi.org/10.1093/cep/byg022>
5. Branoff BL (2007) Quantifying the influence of urban land use on mangrove biology and ecology: A meta-analysis. *Global Ecology and Biogeography* 26:1339-1356. <https://doi.org/10.1111/geb.12638>
6. Bryan-Brown DN, Connolly RM, Richards DR, Adame F, Friess DA, Brown CJ (2020) Global trends in mangrove forest fragmentation. *Scientific Reports* 10:7117. <https://doi.org/10.1038/s41598-020-63880-1>
7. Bunting P, Rosenqvist A, Lucas RM, Rebelo LM, Hilaridees L, Thomas N, Hardy A, Itoh T, Shimada M, Finlayson CM (2018) The global mangrove watch - A new 2020 global baseline of mangrove extent. *Remote Sensing* 10:1669. <https://doi.org/10.3390/rs10101669>
8. Cadier C, Bayraktarov E, Piccolo R, Adame MF (2020) Indicators of coastal wetlands restoration success: A systematic review. *Frontiers in Marine Science* 7:600220. <https://doi.org/10.3389/fmars.2020.600220>
9. Curnick DJ, Pettorelli N, Amir AA, Balke T, Barbier EB, Crooks S, Dahdouh-Guebas F, Duncan C, Endsor C, Friess DA, Quarto A, Zimmer M, Lee SY (2019) The value of small mangrove patches. *Science* 363:239. <https://doi.org/10.1126/science.aaw0809>
10. Dasgupta S, Islam MS, Huq M, Khan ZH, Hasib MR (2019) Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. *PLoS ONE* 14:e0214079. <https://doi.org/10.1371/journal.pone.0214079>
11. Duke NC (2016) Oil spill impacts on mangroves: recommendations for operational planning and action based on global review. *Marine Pollution Bulletin* 109:700-715. <https://doi.org/10.1016/j.marpolbul.2016.06.082>
12. Fisher P, Spalding MD (1993) Protected areas with mangrove habitat. UNEP-World Conservation Monitoring Centre, Cambridge, UK.
13. Food and Agricultural Organization (2003) Status and trends in mangrove area extent worldwide. By Wilkie ML and Fortuna S. *Forest Resources Assessment Working Paper No. 63*. Rome, Italy. <http://www.fao.org/3/j1533e/J1533E02.htm>
14. Food and Agricultural Organization (2007) The world's mangroves 1980–2005. *Forest Paper No. 153*. Rome, Italy. <http://www.fao.org/3/a1427e/a1427e00.pdf>
15. Food and Agricultural Organization (2020) Global Forest Resources Assessment 2020: Main report. Rome, Italy. pp. 38-39. <http://www.fao.org/3/ca9825en/CA9825EN.pdf>
16. Friess DA, Rogers K, Lovelock CE, Krauss KW, Hamilton SE, Lee SY, Lucas R, Primavera J, Rajkaran A, Shi SH (2019) The state of the world's mangrove forests: Past, present, and future. *Annual Review of Environment and Resources* 44:89-115. <https://doi.org/10.1146/annurev-environ-101718-033302>
17. Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke N (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* 20:154-159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>
18. Goldberg L, Lagomasino D, Thomas N, Fatoyinbo T (2020) Global declines in human-driven mangrove loss. *Global Change Biology* 26:5844-5855. <https://doi.org/10.1111/gcb.15275>
19. Groombridge B (1992). *Global biodiversity: status of the earth's living resources*. UNEP/WWF/The National History Museum/IUCN/Worldwide Fund for Nature/World Resources Institute. Chapman & Hall, London, UK.
20. Ha TTT, van Dijk H, Bush SR (2012) Mangrove conservation or shrimp farmer's livelihood? The devolution of forest management and benefit sharing in the Mekong Delta, Vietnam. *Ocean & Coastal Management* 69:185-193. <https://doi.org/10.1016/j.ocecoaman.2012.07.034>
21. Hamilton SE, Casey D (2016) Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecology and Biogeography* 25:729-738. <https://doi.org/10.1111/geb.12449>
22. International Union for Conservation of Nature (2020) Restore our future: Bonn Challenge 2020 Report. www.bonnchallenge.org/resources/bonn-challenge-2020-report.
23. Mcleod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment* 9:552-560. <https://doi.org/10.1890/110004>
24. Menéndez P, Losada IJ, Torres-Ortega S, Narayan S, Beck MW (2020) The global flood protection benefits of mangroves. *Scientific Reports* 10:4404. <https://doi.org/10.1038/s41598-020-61136-6>
25. Richards DR, Friess DA (2016) Rates and drivers of mangrove deforestation in Southeast Asia, 2000-2012. *PNAS* 113:344-349. <https://doi.org/10.1073/pnas.1510272113>
26. Sarkar S, Kumar A, Kumar D, Sethi LN, Hazarika MM, Das G (2015) Optimal size of fish pond for socio-economical development of Cachar [Assam]. *International Journal of Agricultural, Environment and Biotechnology* 5:405-411. <https://doi.org/10.5958/2230-732X.2015.00048.0>
27. Slobodian LN, Rodriguez CM, Nguyen LTP, Rakotoson LN (2018) Legal frameworks for mangrove governance, conservation and use: Assessment summary. IUCN, Geneva, Switzerland, and WWF Germany, Berlin, Germany.
28. Spalding M, Kainuma M, Collins L (2010) *World Atlas of Mangroves*. Earthscan, London, UK.
29. Spalding MD, Blasco E, Field CD (1997) *World Mangrove Atlas*. The International Society for Mangrove Ecosystems, Okinawa, Japan.

30. Stevenson NJ, Lewis RR, Burbridge PR (1999) Disused Shrimp Ponds and Mangrove Rehabilitation. In: Streever W (ed) An International Perspective on Wetland Rehabilitation. Springer: Dordrecht. pp277-297.
31. The World Bank (2013) Executive Summary, Fish to 2030: Prospects for fisheries and aquaculture. Report No. 83177-GLB. Washington, DC, USA.
32. Turschwell MP, Tulloch VJD, Sievers M, Pearson RM, Andradi-Brown DA, Ahmadi GN, Connolly RM, Bryan-Brown D, Lopez-Marcano S, Adame MF, Brown CJ (2020) Multi-scale estimation of the effects of pressures and drivers on mangrove forest loss globally. Biological Conservation 247:108637. <https://doi.org/10.1016/j.biocon.2020.108637>
33. Twilley RR, Rovai AS, Riul P (2018) Coastal morphology explains global blue carbon distributions. Frontiers in Ecology and the Environment 16:503-508. <https://doi.org/10.1002/fee.1937>
34. United Nations (2019) United Nations Decade on Ecosystem Restoration (2021-2030). General Assembly A/RES/73/284.
35. van Bijsterveldt CEJ, van Wesenbeeck BK, van der Wal D, Afiati N, Pribadi R, Brown B, Bouma TJ (2020) How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds. Estuarine, Coastal and Shelf Science 235:106576. <https://doi.org/10.1016/j.ecss.2019.106576>
36. Walters BB, Ronnback P, Kavas JM, Crona B, Hussain SA, Badola R, Primavera JH, Barbier E, Dahdouh-Guebas F (2008) Ethnobiology, socio-economics and management of mangrove forests: A review. Aquatic Botany 89:220-236. <https://doi.org/10.1016/j.aquabot.2008.02.009>

Figures

Figure 1

Multiple databases of global mangrove cover in 1980 - 2020 and linear regressions. Food and Agricultural Organization (FAO) of the United Nations had three databases in 2003, 2007, and 2020 via country surveys. Three vector databases of satellite image interpretation were included as NASA snapshot in 2000 (Giri et al. 2002), global mangrove watch (GMW) in 1996, 2007, 2008, 2009, 2010, 2015, 2016 (Bunting et al. 2018), and biome and mangrove forest of the world (MFW) in 2000-2012 (Hamilton and Casey 2016). Global mangrove cover areas of two atlases were dash-lined in red for their possible timing spans (Spalding et al., 1997, 2010)

Figure 2

Socioeconomic patterns of annual mangrove cover change for five continents in 1990-2016 (Left, consisting of 83 countries and territories with the multi-databases dataset of FAO and GMW) and in 2001-2012 (Right, consisting of 78 countries and territories with the CGMFC dataset, mangrove biome cover by Hamilton and Casey, 2016) using a multidimensional preference analysis.

Figure 3

Socioeconomic patterns of annual mangrove cover change for countries in the five continents in 1990-2016 with the multi-databases dataset of FAO and GMW using the multidimensional preference analysis.

Figure 4

Socioeconomic patterns of annual mangrove cover change for countries and territories in the five continents in 2001-2012 with the CGMFC dataset using the multidimensional preference analysis.