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# Social benefits and environmental performance of aquaculture need to improve worldwide



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As a crucial source of protein for humans, aquaculture provides societal benefits but also poses environmental costs making it pivotal to strike a balance between costs and benefits to ensure aquaculture sustainability. Here we developed a composite sustainability index integrating societal benefits and environmental costs of aquaculture. The results show that two-fifths of the 161 countries achieved a high sustainability score (score > 50) in 2018, indicating a considerable need for improvement in the sustainability of aquaculture worldwide. This was particularly true for Asian countries (average score  $45.01 \pm 11.44$ ), while European countries outperformed other regions ( $60.15 \pm 13.64$ ). Moreover, a Boosted Regression Tree model revealed that 59.3% of the variance in aquaculture sustainability was supported by eight indicators, including social factors, geographical effects, and aquaculture structures. By focusing on bivalve production and maintaining an optimized choice of fishes and shrimp taxa, the sustainability of global aquaculture could be enhanced.

Aquaculture is the fastest-growing global food production industry, providing a major source of protein and essential micro-nutrients to the global human population<sup>1–5</sup>. It brings great societal benefits to people and plays an important role in achieving the United Nations Sustainable Development Goals 1 (No poverty) and 2 (Zero hunger)<sup>4,6,7</sup>. The live-weight biomass produced by global aquaculture has more than tripled in the last twenty years, increasing from 34 Mt ( $10^9$  kg) in 1997 to 112 Mt in 2017<sup>8</sup>. Nowadays, at least 624 species or taxa are used in aquaculture, with fishes, crustaceans, and mollusks accounting for almost all the global production of animal products from aquaculture<sup>8</sup>. Nevertheless, the expansion of aquaculture is also responsible from environmental costs impairing the services aquaculture provide to human societies<sup>9–11</sup>, by emitting pollutants and using resources from the environment<sup>12–14</sup>.

The issue of greenhouse gas emissions is one of the main challenges for aquaculture sustainability as previous studies showed a positive link between production and greenhouse gas emissions<sup>15,16</sup>. Excessive gas emissions not only lead to global warming, but also spawn a series of environmental problems, including acidification, glacier melting, and sea

level rise<sup>17–19</sup>. Besides, nitrogen and phosphorus emissions have also been assessed<sup>20,21</sup>. Those studies showed that feed and fertilizers used the aquaculture process causes eutrophication of water bodies, which has become an important challenge for the sustainability of the aquaculture industry<sup>22,23</sup>. For instance, Gephart et al.<sup>10</sup> found that across all aquatic foods, bivalves and seaweeds generate the lowest global environmental impacts in gas and nutrient emissions and land use changes. In addition, resource utilization is also an important parameter to consider in the assessment of aquaculture sustainability, through land, energy, and freshwater use<sup>9,24–27</sup>. Apart from the foregoing impacts, aquaculture also provides societal benefits in the form of human food and economic development, making it necessary to consider the pros and cons in the aquaculture sustainability assessments.

Nevertheless, the balance between global costs and benefits of aquaculture remains unmeasured. To tackle this issue, we here propose a simple framework to assess the sustainability of aquaculture. This framework encompasses the environmental costs and societal benefits of animal aquaculture across 161 countries representing most of the world aquaculture production in 2018. Societal benefits were measured using food and

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aquaculture economy metrics (Fig. 1). Environmental pollution (greenhouse gas emissions, nitrogen and phosphorus emissions), and resource utilization (land use, freshwater use, and energy use) were the two main types of environmental costs considered (Fig. 1). We then calculated scores of environmental pollution (EPS), resource utilization (RUS), and societal benefits (SBS) of aquaculture for each country based on the indicators available in the literature<sup>10,12</sup>. Those three scores were then combined to produce a composite sustainability score (CSS) for each country (Fig. 1), shedding light on the current sustainability status of global aquaculture and identifying strategies for maximizing societal benefits while minimizing environmental impairments. In order to investigate the influence of the environmental conditions and type of cultured species on the sustainability level, we conducted Boosted Regression Tree models – an advanced non-linear regression technique<sup>28</sup> – to assess the influence of aquaculture structure, geographical, and socio-economic factors on the sustainability of aquaculture over the globe.

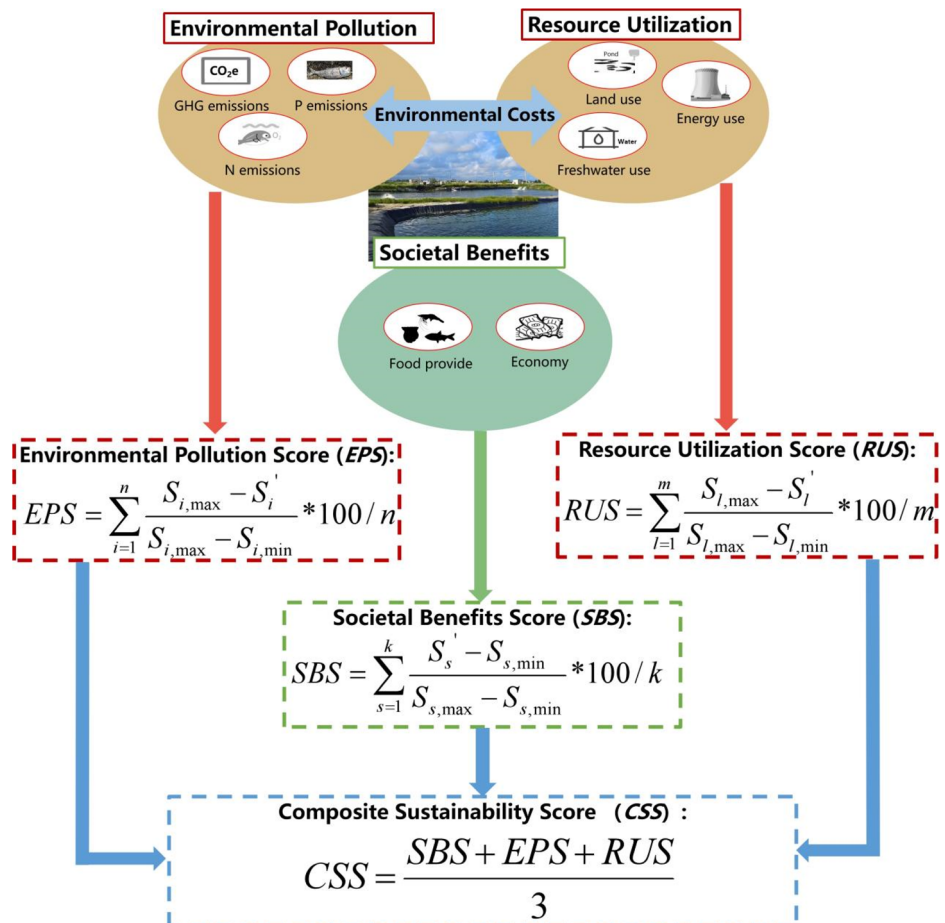
## Results

The sustainability of aquaculture measured by the composite sustainability score (CSS) was on average  $51.58 \pm 15.32$  over the globe, but strong discrepancies were observed between countries with CSS scores ranging from 18 to 118 (Fig. 2 and Supplementary Fig. S2). Three-fifths of the world countries (98 countries) showed a low sustainability with CSS scores lower than 50, whereas two-fifths of the world countries reached a CSS score higher than 50 (63 countries). Uruguay, South Africa, and New Zealand had the highest sustainable level with a CSS score of 118, 103, and 98, respectively. In contrast, Oman, Philippines and Brunei Darussalam had the lowest sustainable level with a CSS score of 18, 30 and 31, respectively. The CSS also showed geographic difference among the six continents with low CSS scores (CSS < 50) mainly concentrated in tropical

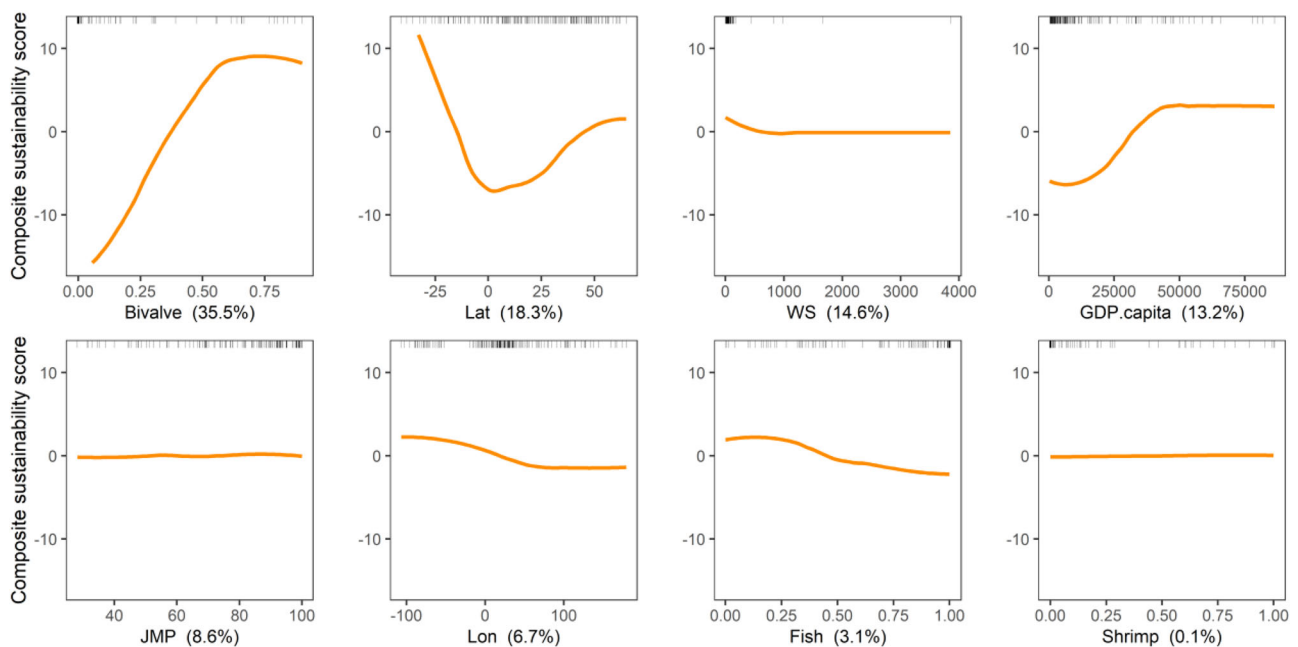
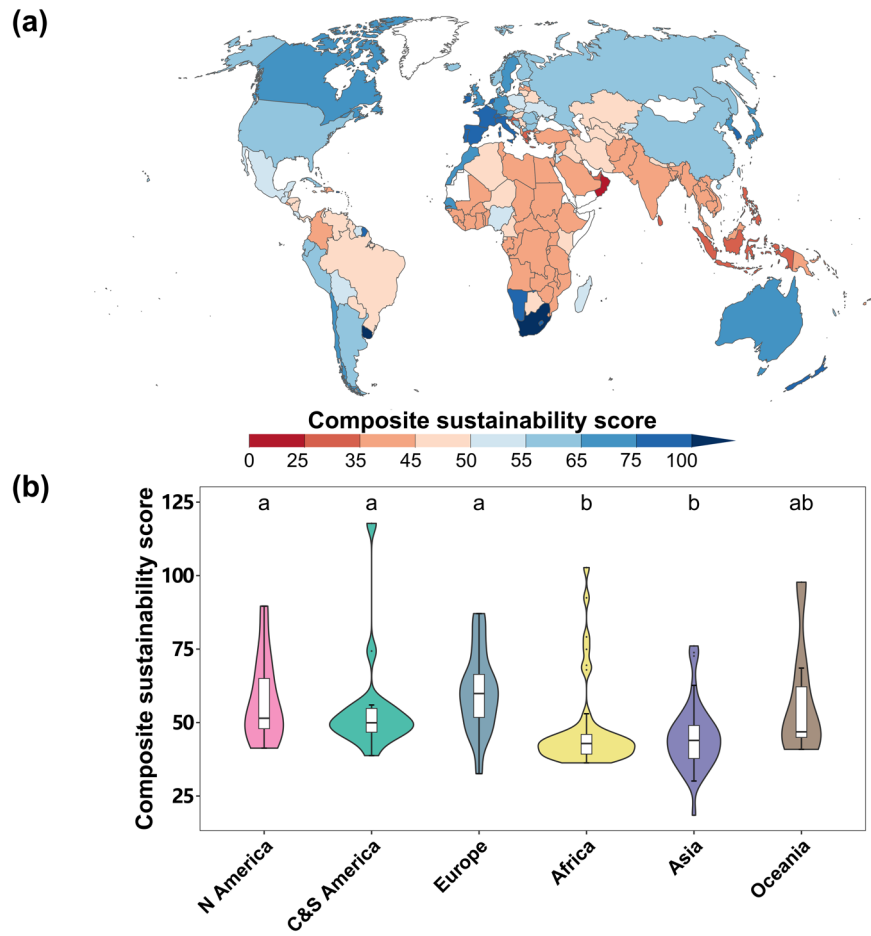
countries, whereas the Northern half of the globe performed better (Fig. 2a). Asia and Africa had lower CSS (average CSS  $45.01 \pm 11.44$  for Asia and  $47.34 \pm 14.61$  for Africa, Fig. 2b) than other continents, with CSS scores significantly differing from those of North America, Central & South America and Europe (pairwise Wilcoxon rank-sum test,  $p < 0.05$ ). Conversely, Europe demonstrated the highest performance (mean CSS  $60.15 \pm 13.64$ ) among the six continents, with 76% of European countries having a CSS above 50 (Supplementary Fig. S3). The North American CSS values were above 50 for the three largest countries (USA, Canada, and Mexico), but are much more variable in the West Indies (Fig. 2a) such as Haiti (CSS = 41) or Bahamas (CSS = 90). In contrast, Central & South American countries showed more discrepancies in CSS with countries from the western part of South America performing better than Central American and eastern South American countries (Fig. 2a). Scores ranged from 39 in Colombia to 118 in Uruguay, with 44% of the countries (8 countries) having a score above 50.

Based on the cross-validation procedure, the Boosted Regression Tree model predicted 59.3% of the total deviance in CSS. Notably, the bivalve production percentage contributed to 35.5% of CSS deviance, with a positive relationship between CSS and bivalve production (Fig. 3). Instead, shrimp production has almost no influence on aquaculture sustainability (Fig. 3 and Supplementary Fig. S4). Latitude, water stress (measuring the water scarcity in each country), and GDP per capita also contributed strongly to CSS with contributions of 18.3%, 14.6%, and 13.2%, respectively (Fig. 3 and Supplementary Fig. S4). CSS increased with GDP per capita for the developing countries (GDP per capita < 40,000 USD), and reach a plateau for the richest countries. Conversely, water stress, longitude, and fishes production percentage were negatively correlated to CSS (Fig. 3). Furthermore, the Boosted Regression Tree model revealed interactions among predictors. Latitude interacted with bivalve production percentage and longitude, while the

**Fig. 1 | Conceptual framework for the calculation of the composite sustainability score (CSS) for aquaculture.** CSS is calculated as the average value of the societal benefits score (SBS), environmental pollution score (EPS), and resource utilization score (RUS). Those three scores are calculated as the average of the normalized scores of all relevant indicators ( $S$ ). Higher score values indicating higher societal benefits (SBS) and minimal environmental pollution (EPS) and resource utilization (RUS). See Methods for details on scores computing.  $m$ ,  $n$ , and  $k$ , which represent the number of indicators in Resource Utilization, Environmental Pollution, and Societal Benefits, respectively. The data of greenhouse gas emissions, energy, and freshwater use for each country was extracted from Jiang et al.<sup>32</sup>; the parameters used to calculate nitrogen and phosphorus emissions, as well as land use, were sourced from Gephart et al.<sup>10</sup>, with these three parameters, we further calculated the total nitrogen and phosphorus emissions as well as land use for each country as well as the comprehensive sustainability index. See Methods for more details. The silhouettes of fish, shrimp and bivalve in societal benefits were downloaded from <http://phylopic.org>.



**Fig. 2 | Composite sustainability score (CSS) of the 161 countries in 2018. a** Composite sustainability performance of each country; **b** composite sustainability performance of each continent. Different letters above the violin plots show the significant differences between the values of the six continents (pairwise Wilcoxon rank-sum test,  $P < 0.05$ ); C & S America Central and South America, N American North America. The data of Hong Kong, Macao and Taiwan provinces of China are not included in Chinese aquaculture. For box plot in the violin plot, center line means median value; box limits means upper and lower quartiles.



**Fig. 3 | Results of boosted regression tree showing the partial dependency between composite sustainability score and the eight predictors.** The value in parentheses in each panel is the percentage of contribution of each predictor based on 100 times considered in the model. The rugs at the top of each panel show the

distribution of the countries along the predictor values. Bivalve bivalve production percentage, Lat latitude, WS water stress, GDP.capita Gross Domestic Product/capita, JMP rural population with access to safe drinking-water, Lon longitude, Fish fishes production percentage, Shrimp shrimp production percentage.

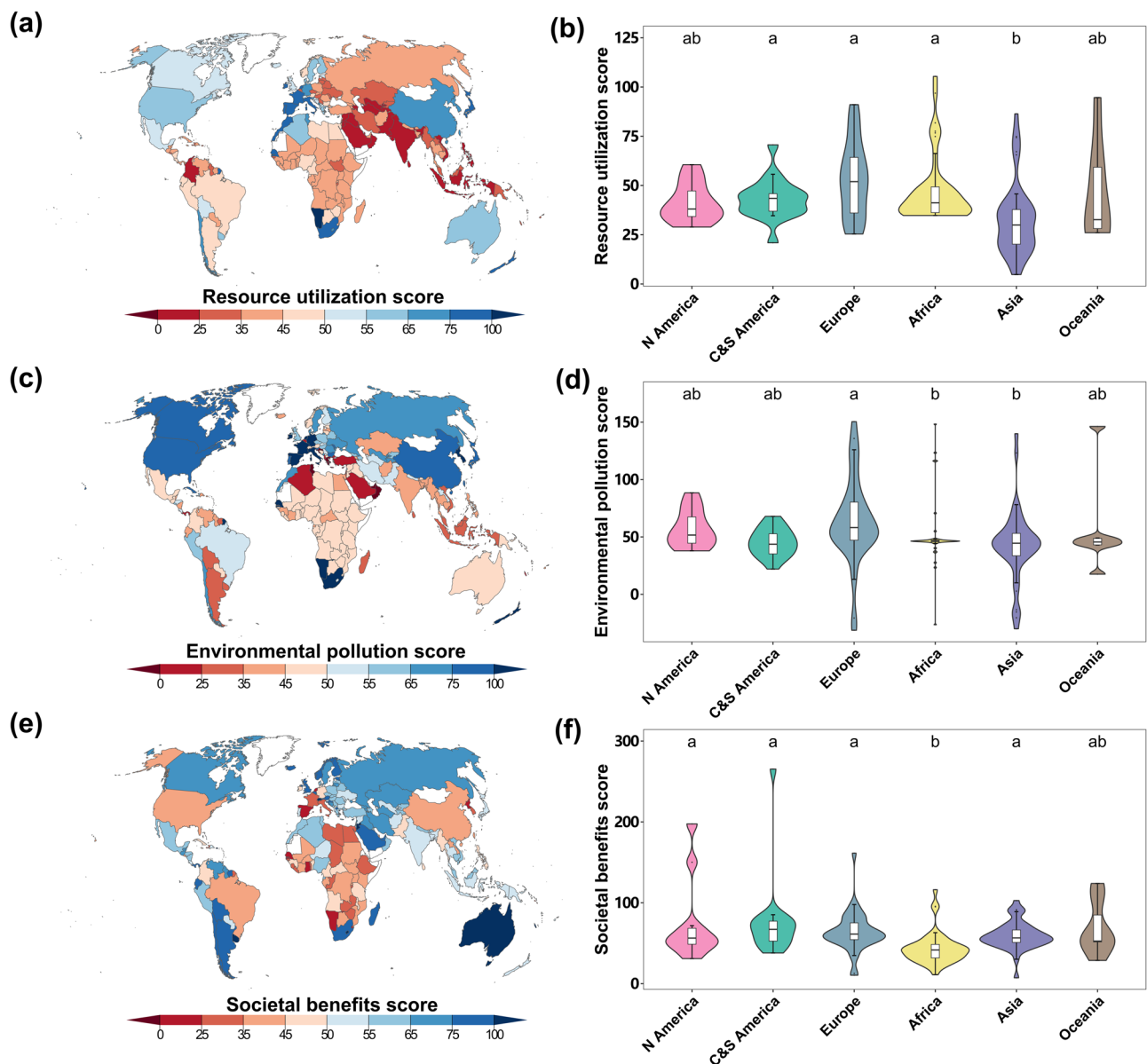
GDP/capita also showed significant interactions with bivalve production percentage and longitude (Supplementary Fig. S5).

Regarding the performance of the aquaculture of each country and continent in the RUS, EPS, and SBS components of the CSS, resource use for aquaculture was the most sustainable in Europe (mean RUS =  $52.78 \pm 19.19$ ; Fig. 4a, b and Supplementary Fig. S6) but countries from other regions of the globe such as China, USA, Chile, Namibia, Morocco or Australia also show high sustainability (Fig. 4a). The sustainability of resource use for European countries was due to limited land and freshwater uses for aquaculture, although energy demand for aquaculture remains important (Supplementary Fig. S7a–c). On the contrary, the land use sustainability of North American countries ( $38.67 \pm 23.00$ ) and the freshwater use sustainability of African countries ( $24.65 \pm 29.54$ ) were both relatively lower (Supplementary Figs. S7a, c, S8a, c, and S9a, c). Contrasting with the other continents, RUS of Asia remained significantly lower from that of

Central & South America, Europe and Africa (Fig. 4b, pairwise Wilcoxon rank-sum test,  $p < 0.05$ ) (mean RUS =  $32.64 \pm 18.43$ ), despite a strong discrepancy among countries (e.g., RUS for China = 67, Oman = 5).

Considering environmental pollution, European countries were the most sustainable, while African and Asian countries reached significantly lower scores (Fig. 4c, d, pairwise Wilcoxon rank-sum test,  $p < 0.05$ ) due to high emissions of greenhouse gas and nitrogen (Supplementary Figs. S7d, e, S8d, e, and S9d, e). The best environmental performances were achieved in west European countries (e.g., Netherlands, France, Spain) and in Southern Africa (South Africa, Namibia), whereas environmental pollution associated to aquaculture peaked in a few southern European (Croatia) and Asian countries (Cyprus) as well as in the countries from the Arabic peninsula (Fig. 4c).

Societal benefits exhibited marked variations within continents (Fig. 4e) but African countries had the lowest societal benefits scores. Those



**Fig. 4 | Composite score of three index (societal benefits score (SBS), environmental pollution score (EPS) and resources utilization score (RUS)) for countries and continents.** Composite scores of resources utilization (RUS, a, b), environmental pollution (EPS, c, d) and societal benefits (SBS, e, f) for each country in 2018. Low values (red scales on the maps) indicate high resource utilization, high pollution, and low societal benefits, whereas high values (blue scales) indicate low resource utilization, low pollution, and high societal benefits (a, c, e). Violin plots

(b, d, f) show the distribution of the values of the three scores for each continent. Letters above the violin plots show significant differences between the values of the six continents (pairwise Wilcoxon rank-sum test,  $p < 0.05$ ). C & S America Central and South America, N American North America. The data of Hong Kong, Macao, and Taiwan provinces of China are not included in Chinese aquaculture. For box plot in the violin plot, center line means median value; box limits means upper and lower quartiles.

scores were significantly lower than those of all continents but Oceania (Fig. 4f, pairwise Wilcoxon rank-sum test,  $P < 0.05$ ). The low sustainability of societal benefits in Africa was due to a combination of low scores for edible food (average food provide score =  $48.60 \pm 17.52$ , Supplementary Fig. S7g) with less than 0.58 tons edible weight/live weight production for each country (Supplementary Fig. S8g); and low economic incomes from aquaculture with less than 10000 USD/ton live weight for most countries (Supplementary Figs. S7h and S8h). Across the globe, eight countries achieved societal benefits scores higher than 100, among which Uruguay and Bahamas had the highest performance with scores of 265 and 198, respectively (Fig. 4e). In contrast, low societal benefits scores were recorded in countries from distinct continents, such as North Korea (SBS = 7), Netherlands (SBS = 10) or Gambia (SBS = 11) (Fig. 4e).

Overall, there was a negative correlation between societal benefits and costs (Spearman test,  $p = -0.23$ ). Additionally, societal benefits were significantly negatively correlated to environmental pollution (Spearman test,  $p = -0.30$ ). Furthermore, RUS and environmental pollution costs were positively correlated (Fig. 5a). Therefore, the countries providing the higher societal benefits, also have the higher environmental impacts. Although most countries show intermediate societal benefits and environmental costs, indicating an equilibrium between costs and benefits (Fig. 5b), several Asian countries from the Arabian Peninsula (e.g. Oman, Brunei Darussalam, United Arab Emirates, and Saudi Arabia), show high societal benefits but low environmental performance (Fig. 5b). Similarly, Greece and Tunisia show a low evenness RUS, EPS and SBS due to their high RUS score.

## Discussion

The global pattern of aquaculture sustainability shows marked variations across continents and countries. Sustainability increased with Gross Domestic Product (GDP) per capita (Fig. 3 and Supplementary Fig. S10), thus explaining higher CSS in developed countries from Europe and North America compared to Africa and Asia<sup>29</sup>, and thus a longitude gradient with higher CSS in lower longitude (Fig. 3). The higher environmental performance of developed countries (GDP/capita) was mainly due to reduced resource use and higher societal benefits associated with the aquaculture methods used in those countries (Fig. 3 and Supplementary Fig. S10b,d). Although Asian countries are leading the world production of aquaculture products<sup>4,30,31</sup>, the sustainability of Asian aquaculture remains limited, probably due to non-optimized farming techniques that are not as efficient as those employed in developed countries<sup>32</sup>. Indeed, most freshwater aquaculture in Asia is based on extensive pond aquaculture which is highly demanding in land use resources and not optimized for energy conversion<sup>33</sup>. Consequently, while Asian countries perform well in societal benefits, they also exhibit higher environmental costs (Fig. 5a).

The sustainability differences among countries were also dependent on the taxa cultured. The production of fishes and shrimps, which are commonly cultured species, requires substantial amounts of food, resulting in increased resource use and environmental pollution<sup>10,34</sup>. These factors contribute to higher negative impacts on the environment<sup>35,36</sup>. In contrast, bivalves play an important role in sustainability. They act as important carbon sinks and have the lowest negative impacts considering nitrogen and phosphorus emissions<sup>37–39</sup>. Moreover, bivalve culture requires less land use changes than other taxa because bivalves are often grown in the natural environment without needing land conversion (Supplementary Fig. S11)<sup>10,40,41</sup>. Higher production of bivalves thus correlates with higher composite sustainability scores (Fig. 3, Supplementary Fig. S10a).

Another striking pattern is the substantial decline of CSS in the tropical countries compared to temperate ones. This might be contributed to tilapia aquaculture. This warm-water freshwater fishes is grown in all tropical regions<sup>42</sup> and has a lower edible proportion and economic value compared to most other species, leading to its limited contribution to aquaculture sustainability<sup>10,43,44</sup>. Moreover, the cultivation of tilapia typically requires more food than most other species, resulting in higher negative impacts, such as increased nitrogen and greenhouse gas emissions than for most other cultured species<sup>10</sup>. Additionally, because the proportion of crop

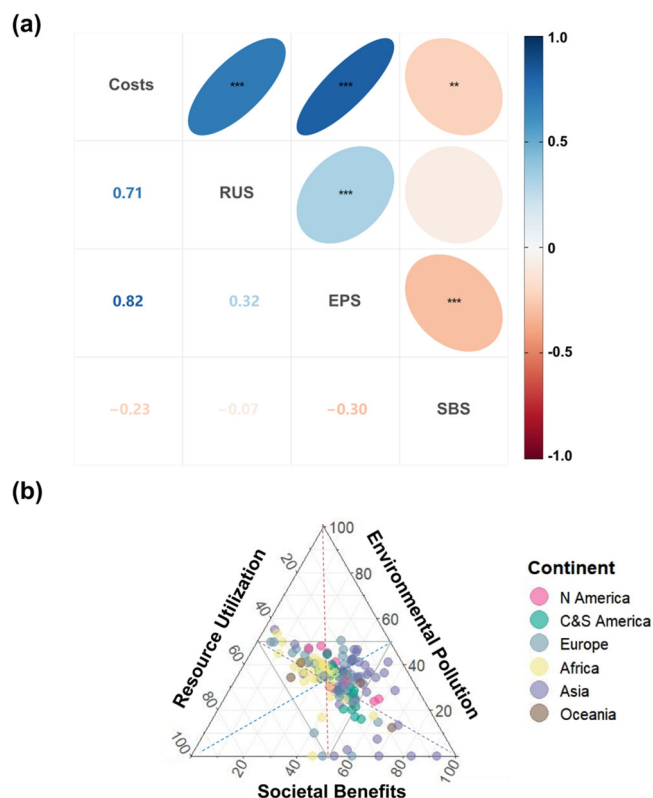
components in tilapia feed is relatively high, it often consumes more land than other species<sup>27,45</sup>. In contrast, species like salmon and trout thrive in cooler regions, and their yields peak in higher latitudes<sup>46,47</sup>. These salmonid species are more efficient in food transformation in edible proteins and possess a higher economic value than tilapia<sup>48</sup>. This combination of factors contributes to the overall sustainability in higher latitude aquaculture practices.

Combining bivalve aquaculture in natural environments to the development of advanced aquaculture methods for fishes and shrimps could represent a way to maintain the diversity of cultured products while controlling the aquaculture environmental costs. This is successfully achieved in South Africa and New Zealand, which we score among the most sustainable countries for aquaculture. In those countries bivalves represents a substantial part of aquaculture activity (Supplementary Table 2), while fishes culture is mainly represented by Salmonids (trouts and salmon)<sup>48</sup>, that are easily reared in controlled environments offering, therefore, higher benefits and lower environmental costs than most other fishes species<sup>10,49,50</sup>. Therefore, the combined Salmonid and bivalve farming plays a important role in achieving sustainable aquaculture practices. This successful selection of cultured species was also true for China, which remains among the most sustainable countries for aquaculture (ranked 33 out of the 161 countries) along with being among the most important global producers of aquatic resources with a production of 44.6 million tons of aquatic food (including fishes, shrimp and bivalves) in 2018, with fishes and shrimp accounting for about 69.79% of the production, while bivalves made up the rest<sup>14,51</sup>.

In contrast, countries that do not cultivate bivalves or cultivate them infrequently exhibit a less sustainable aquaculture performance (Fig. 3). For instance, Indonesia, one of the top aquaculture producers, with 5.39 million tons of aquatic products in 2018<sup>48</sup>, is among the least sustainable countries (CSS ranked 158 out of 161 considered countries). This was due to the aquaculture methods associated to fishes and shrimp culture that account for 99.08% of the total production. A similar situation is encountered in the Arabic peninsula with aquaculture mainly oriented toward marine fishes in Oman and Brunei. These marine fisheries generate high societal benefits in terms of economic activity, but those benefits are counterbalanced by high emissions of nitrogen and phosphorus to the natural environment<sup>52,53</sup>.

Based on our global assessment, the most important levers for improving the sustainability of global aquaculture would be to focus efforts on the countries with the lowest CSS scores, which are mostly developing countries such as Indonesia or India. Those countries are major aquaculture producers. They culture high economic value fishes and shrimps for exportation<sup>54,55</sup>, and contribute to feed the world with marine and freshwater products, but also have high environmental costs due to un-adapted aquaculture techniques that release many nutrients and greenhouse gases into the environment. International cooperation is therefore necessary to share knowledge and technology to reduce the negative effects of aquaculture production and improve sustainability in these countries. One area of improvement is feed, which is not only a major source of environmental pollution but also massively uses land and freshwater resources. For instance, wild fishes is often used as food for cultured fishes and shrimps, leading to increased greenhouse gas emissions and depletion of biodiversity in the marine environment<sup>56,57</sup>. Developing advanced feed compositions could therefore improve resource efficiency and reduce negative environmental impacts<sup>58–60</sup>. For instance, it has been suggested to feed fishes using microalgae or other animal proteins, thereby reducing the feed conversion ratio compared to the utilization of fishmeal proteins<sup>36,61,62</sup>. Additionally, continuous improvements in aquaculture technology (like using more clean energy, especially for inland countries where marine bivalves cannot be farmed) and modes (increase in the proportion of cultured bivalves, and selecting well mastered fishes cultured species) would play an important role in improving the sustainability of aquaculture.

This study merely provides a macro-level and rough estimate of the sustainability of global aquaculture. Some potentially important processes, such as genetic pollution, invasive species, sea floor impact, and evaporative water loss, were not considered in our assessment of aquaculture



**Fig. 5 | Relationships between three scores (societal benefits score (SBS), environmental pollution score (EPS) and resources utilization score (RUS)).**

**a** Correlation analysis between the three scores; **(b)** ternary diagram of the three scores for the 161 countries, X-axis represents resource utilization, Y-axis represents environmental pollution, and Z-axis represents social benefits. The color of each country indicates the continent to which it belongs. C&S America Central and South America, N America North America. The data of Hong Kong, Macao, and Taiwan provinces of China are not included in Chinese aquaculture. To account for outliers and keep the figure understandable, values were bounded to 0 and 100 when actual values were negative or exceed 100 in ternary diagram. Note that some drivers of environmental pollution such as genetic pollution, invasive species, and sea floor impact, are not included in the environmental pollution score, which may lead to a certain deviation from the actual pollution situation. (two-sided Spearman tests: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ ).

sustainability due to limitations in available data and/or highly context-dependent processes<sup>10</sup>, which may have led to underestimated negative impacts. For instance, biological invasions are a critical issue for aquaculture as they have notable impacts on the environment<sup>63,64</sup>, and cause considerable economic costs<sup>65</sup>. Aquaculture is recognized as a major provider of invasive species with approximately 693 freshwater fishes establishment events across the globe attributed to aquaculture<sup>64</sup>. Moreover, the spread in the natural environment of cultured populations from native species can cause genetic diversity damage to wild populations<sup>57</sup>. Therefore, it is crucial to evaluate the costs of invasions to incorporate them into future assessments of aquaculture sustainability. Feed is a main contributor to resource consumption and environmental pollution, but due to its diversity and complexity, it is difficult to fully incorporate into sustainability assessments. For example, the energy consumed during the capture and transportation of wild juvenile and miscellaneous fishes should be included in the energy use indicators<sup>66</sup>. In addition, besides formulated feed, wild fishes and other aquatic organisms are also used as feed directly in the cultivation of some species. The unconsumed portions of these feeds can also produce nitrogen and phosphorus emissions<sup>67</sup>. However, due to limited data availability and the fact that formulated feed accounts for most feed inputs, the impacts of these wild fishes species were not included for most indicators when setting the calculation boundaries for this study.

Nonetheless, our assessment framework serves as a solid foundation for future evaluations of aquaculture sustainability by integrating multi-dimensional influential factors. Furthermore, our study highlighted that the choice of cultured species, and their associated impacts on the environment and resources, plays a crucial role in determining the sustainability of aquaculture. By focusing on bivalve production and maintaining an optimized choice of the cultured fishes and shrimp taxa, the sustainability of the world aquaculture could be enhanced.

## Materials and methods

### Societal benefits (SBS)

Food and economic incomes were the two indicators used to represent the societal benefits of aquaculture because the primary objective of aquaculture is to provide a source of food for human consumption, but it also sustains economic development for people. Food income was measured as the amount of edible weight produced per year for the cultivated species and the edible proportion for each species group come from Gephart et al.<sup>10</sup>, and the edible proportion for the miscellaneous freshwater fishes species group is derived from data on miscellaneous diadromous fishes, while the edible proportion for the species group of miscellaneous brackishwater aquaculture fishes is calculated as the average of edible proportion from miscellaneous diadromous fishes and miscellaneous marine fishes. To ensure accurate comparisons between taxa and countries, we used edible weight instead of live weight. Bivalves, for instance, have an edible weight that is only about 20% of their total weight, which could lead to inaccurate comparisons. The data for aquaculture production (fishes, shrimp, and bivalves) and economy income in USD in 2018 for each country were obtained from the FAO FishStat database (<http://www.fao.org/fishery/>), and the economic value per unit of production is extracted from the results of Jiang et al.<sup>32</sup>.

### Resource utilization (RUS)

**Land use.** The land use ( $LU$ ,  $m^2$ ) refers to the land area allocated to aquaculture and was calculated as follows:

$$LU = \sum_{i=1}^n LUI_i * P_i \quad (1)$$

Where  $LUI_i$  is the land use intensity of species group  $i$ ,  $P_i$  is the production (tons) for species group  $i$  and the data is from FAO, and  $n$  is the number of species group for each country. The values of  $LUI_i$  for each species group come from Gephart et al.<sup>10</sup>, and we use the median value for each species group based on the live weight and mass allocation method. The  $LUI_i$  for the miscellaneous freshwater fishes species group is derived from data on miscellaneous diadromous fishes, while the value for the species group of miscellaneous brackishwater aquaculture fishes is calculated as the average of  $LUI_i$  from miscellaneous diadromous fishes and miscellaneous marine fishes.

The values of  $LUI_i$  for each species group was extracted from Gephart et al.<sup>10</sup>, and we then calculated the land use of each country based on  $LUI_i$  and production.

**Freshwater use.** Freshwater use was calculated as the amount of water consumed during the production and usage of aquaculture, and we used the feed-related method to estimate the water footprint<sup>24,68</sup>. Freshwater use data ( $WF_{feed}$ ) for each country was sourced from Jiang et al.<sup>32</sup>. The water footprint can be divided into green (consumption of rainwater), blue (consumption of surface and groundwater) and gray water (degree of pollution)<sup>68</sup>. These three categories play crucial roles in ecosystems since green water and blue water together ensures water availability for aquatic ecosystems, while gray water represents human disturbances on those ecosystems. The total water use for each country ( $WF_{feed}$ ,  $m^3/ton$ ) is calculated as in Pahlow et al.<sup>24</sup>:

$$WF_{feed} = \sum_{i=1}^n WF_{feed,i} \quad (2)$$

Where  $WF_{feed,i}$  is the green, blue, and gray water footprint of species  $i$ ,  $WF_{feed,i}$  was calculated by formula (3):

$$WF_{feed,i} = \sum_{p=1}^m Feed_{i,p} * WF_{i,p} \quad (3)$$

$WF_{i,p}$  is the green, blue and gray water footprint of feed ingredient  $p$  for species  $i$ , and  $m$  is the number of feed ingredients<sup>24</sup>.

The amount of specific feed ingredients used per species ( $Feed_{i,p}$ , ton/year) is determined as follows:

$$Feed_{i,p} = f_{i,p} * P_{feed} \quad (4)$$

Where  $f_{i,p}$  is the fraction of feed ingredient  $p$  in the composition of the commercial feed applied to species  $i$ .

The amount of commercial feed ( $P_{feed}$ ) is calculated as follows:

$$P_{feed} = FCR_i * P_i \quad (5)$$

Where  $FCR_i$  is the feed conversion ratio (tons of feed/ton of species) for species  $i$ ,  $P_i$  is the production (tons) of  $i$ .

**Energy use.** An energy intensity (energy/production) model was established considering culture species, culture system intensity (e.g., extensive, semi-intensive and intensive), culture technology, and climatic conditions according to Zhang & Kim<sup>69</sup>. This model was used to estimate the energy use of current global aquaculture. Based on the results of Zhang & Kim<sup>69</sup>, Jiang et al.<sup>32</sup> established the equation for calculating total energy use for each country (ES, TJ):

$$ES = \sum_{i=1}^n EEI_i * P_i \quad (6)$$

Where  $EEI_i$  is the energy intensity (energy use/ton production) of a specific species  $i$ . The data of total energy use for each country was extracted from Jiang et al.<sup>32</sup>.

## Environmental pollution (EPS)

**Greenhouse gas emissions.** Greenhouse gas emissions from aquaculture are mainly nitrogen ( $N_2O$ ) and carbon gases ( $CH_4$ ,  $CO_2$ ) produced from feed materials, on-farm energy use, fertilizer use and cultured animal metabolism<sup>70</sup>. The emissions intensity for the majority of species groups, encompassing fishes, shrimps, bivalves, and various others, was adapted from MacLeod et al.<sup>70</sup>.

$$GHG = GHG_{feed} + GHG_{energy} + GHG_{CH_4} + GHG_{N_2O} \quad (7)$$

Jiang et al.<sup>32</sup> have calculated the total greenhouse gas emissions (tons  $CO_2e$ ) for each country based on the method of MacLeod et al.<sup>70</sup>, and we extracted the greenhouse gas emissions for each country from Jiang et al.<sup>32</sup>.

**Nitrogen and phosphorus emissions.** Nitrogen and phosphorus emissions were estimated using the results of Gephart et al.<sup>10</sup>. The estimation of nitrogen and phosphorus emissions is based on the pressure sources both on and off aquaculture farms for the cultured species, and the formulas as follows:

$$NE = \sum_{i=1}^n NI_i * P_i \quad (8)$$

$$PE = \sum_{i=1}^n PI_i * P_i \quad (9)$$

Where  $NE$  and  $PE$  represent total emissions of N and P for each country;  $NI_i$  and  $PI_i$  represent the N and P emissions intensity for species group  $i$ ;  $P_i$

represents the production of species group  $i$ . The parameter of emissions intensity (kg N or P/ ton live weight) for each species group was evaluated by Gephart et al.<sup>10</sup>, and we use the median value for each species group based on the live weight and mass allocation method. The emissions intensity for the miscellaneous freshwater fishes species group is derived from data on miscellaneous diadromous fishes, while the emissions intensity for the species group of miscellaneous brackishwater aquaculture fishes is calculated as the average of emissions intensities from miscellaneous diadromous fishes and miscellaneous marine fishes. We calculated the total N and P emissions amount for each country based on the emissions intensity of species group available in Gephart et al.<sup>10</sup>.

## Composite sustainability calculation

The weak correlation among the eight indicators mentioned above indicates that there is not much overlap between any two of them, and thus these indicators represent distinct facets of the sustainability of aquaculture (Supplementary Fig. S1). The eight indicators were used to compute the composite sustainability score assessing the sustainability of global aquaculture (Supplementary Table S1). We considered 161 countries belonging to six main landmasses and associated marine coastal areas, hereafter called continents: Africa, Central & South America, North America (including Guatemala, Honduras, and West Indies), Asia, Europe (including Russia), and Oceania (including Australia and New Zealand). These continents consist of 45, 18, 11, 43, 37, and 7 countries, respectively (Supplementary Table 2). The data of Hong Kong, Macao, and Taiwan provinces of China are not included in Chinese aquaculture. To ensure comparability between countries, the eight indicators were standardized across 161 countries, taking into account variations in the land area allocated to aquaculture, thereby generating a comparable measure of the environmental costs and societal benefits associated with aquaculture. The steps for standardizing the eight indicators, calculating and comparing the composite sustainability index among countries are outlined as follows:

(1) The standardization process is a numerical treatment procedure that enables the comparison of the intensities across different indicators. In this study, to ensure that the overall data is not influenced by outlier values and to prevent outlier values from diminishing the differences among other data points after normalization, we followed the following steps for the standardization process: Firstly, we utilized the interquartile range (IQR) to identify and filter out outlier values<sup>71</sup>. The IQR is the difference between the third quartile (the value where 75% of the data points fall) and the first quartile (the value where 25% of the data points fall). By adding 1.5 times the IQR to the third quartile and subtracting 1.5 times the IQR from the first quartile, we obtained two threshold values. Any values exceeding these thresholds were considered outliers and were excluded from the dataset (a detailed list of these outliers is provided in Supplementary Table 3). Secondly, after excluding the outliers, we recalculated the maximum and minimum values of the remaining data points. These new maximum and minimum values would serve as the basis for the subsequent standardization process<sup>32</sup>. Thirdly, using these new maximum and minimum values, we standardized all the data points, including the outlier values. The standardization method typically involves subtracting the minimum value from each data point and then dividing the result by the difference between the maximum and minimum values. This process ensures that the standardized values fall within the range of 0 to 1. To align with the requirements of the study, we further scaled this range to 0 to 100. It is important to note that outlier values were not deleted during the standardization process but were standardized accordingly based on the new maximum and minimum values. Consequently, these outlier values may appear as values below 0 or above 100 after standardization, accurately reflecting their extreme performance within the original indicator. Finally, as the majority of countries' standardized values still fell within the range of 0 to 100, we designated the median value of 50 as the threshold based on the distribution of the standardized values. This threshold serves as a reference for further analysis and comparison. The formula for normalizing the intensity of indicators for

societal benefits come from Jiang et al.<sup>32</sup>, and it can be expressed as follows:

$$S = \frac{S' - S_{\min}}{S_{\max} - S_{\min}} * 100 \quad (10)$$

Where  $S$  denotes the normalized score of societal benefits indicators,  $S_{\min}$  and  $S_{\max}$  are the minimum and maximum values of  $S'$  (data without normalization), respectively. The normalized values range from 0 to 100 (except the outliers), higher values indicating a higher sustainability for the considered indicator (food intensity and economy intensity) to the exception of environmental pollution and RUS that have negative effect on the environment. For environmental pollution and RUS indicators, higher value represents lower sustainability. Thus, to be consistent with the normalized benefits values, the formula of normalization for the indicators in for EPS and RUS were modified as follows:

$$S = \frac{S_{\max} - S'}{S_{\max} - S_{\min}} * 100 \quad (11)$$

Where  $S$  denotes the normalized score of indicators,  $S_{\min}$  and  $S_{\max}$  are the minimum and maximum values of  $S'$  (raw data), respectively. The higher the normalized score, the lower the impact on the environment and therefore represents a higher sustainability in this aspect. The normalized values limit between 0 and 100 (except the outliers) as well.

#### (2) Integration of indicators<sup>32</sup>.

The societal benefits score (SBS):

$$SBS = \frac{S_{\text{food}} + S_{\text{economy}}}{2} \quad (12)$$

The environmental pollution score (EPS):

$$EPS = \frac{S_C + S_N + S_P}{3} \quad (13)$$

The RUS score (RUS):

$$RUS = \frac{S_{\text{land}} + S_{\text{freshwater}} + S_{\text{energy}}}{3} \quad (14)$$

$S_{\text{food}}$ ,  $S_{\text{economy}}$ ,  $S_C$ ,  $S_N$ ,  $S_P$ ,  $S_{\text{land}}$ ,  $S_{\text{freshwater}}$  and  $S_{\text{energy}}$  are the sustainability score of the eight indicators respectively.

To get a composite sustainability score (CSS) for each country, we calculated the arithmetic mean of normalized score for each country, with equal weights assigned to SBS, EPS, and RUS scores. Higher CSS scores indicating higher sustainability.

$$CSS = \frac{SBS + EPS + RUS}{3} \quad (15)$$

The variations in sustainability across the three components of CSS were represented on a ternary plot to assess the evenness of components for all countries. The analysis of evenness helps to identify the issues and weaknesses within the aquaculture system, enabling targeted improvements to be made accordingly. The countries located closer to the center of the plot indicate higher levels of evenness, while those farther away indicate lower evenness.

#### Aquaculture-related variables

We have used the percentage of fishes, shrimp, and bivalve production and incorporated a comprehensive set of variables that are widely recognized for their relevance in assessing the sustainability of aquaculture<sup>72</sup>. These variables were used to link geographical context (Longitude and Latitude), aquaculture activities (Fishes production, shrimp production and bivalve production) and socio-economic aspects (Gross Domestic Product per

Capita, Water stress and Rural population with access to safe drinking water) to aquaculture sustainability, and these variables were utilized in the Boosted Regression Tree model analysis. The Mean Longitude (Lon) and Latitude (Lat) of each country was used as an overall measure of the geographical context; Fishes production (Fish), shrimp production (Shrimp) and bivalve production (Bivalve) are the percentage of aquaculture activities in each country focused on fishes, shrimp and bivalve production (the production of other species has not been taken into account), respectively. Gross Domestic Product per Capita (GDP/capita) assesses the economic well-being of the country; Water stress (WS) is a United Nations Sustainable Development Goal indicator, measuring the water scarcity in each country; Rural population with access to safe drinking water (JMP) assesses the accessibility and safety of drinking water resources for rural populations. GDP/capita, WS, and JMP data were sourced from AQUASTAT, the FAO's global information system on water and agriculture<sup>72</sup>.

#### Statistical analysis

To assess the difference of sustainability between countries of the six continents, we used Kruskal–Wallis rank-sum test after checking the normality and homogeneity of variance of the data. Post-hoc pairwise Wilcoxon rank-sum tests were used to examine the differences between continents. Spearman correlations were performed to examine the relationships between the composite scores (CSS, SBS, EPS, and RUS) and the species cultured, as well as the economic indicator of each country (GDP per capita). Additionally, the relationships between costs and benefits were assessed by Spearman correlations. Furthermore, Spearman correlation analysis was used to analyze the associations between the eight normalized indicator scores and the species cultured, as well as the economic level. Kruskal–Wallis rank-sum test and pairwise Wilcoxon rank-sum test were performed using “kruskal.test” and “pairwise.wilcox.test” functions from “stats” R package.

Boosted Regression Tree serve as an advanced integrated statistical model that integrates regression trees with boosting techniques, breaking the limitations of traditional models<sup>28</sup>. Through recursive binary splitting, Boosted Regression Tree establishes associations between responses and predictor variables, and leverages boosting to combine simple models and enhance predictive performance. The Boosted Regression Tree model is presented in the form of additive regression, with each simple tree fitted in a staged manner to provide precise and comprehensive analysis. The Boosted Regression Tree model flexibly adapts to various predictor variables, requiring no complex preprocessing and capable of handling missing data, ensuring stability and reliability of the model<sup>28,73</sup>. It excels at capturing non-linear relationships and interaction effects, revealing complex patterns underlying the data<sup>74</sup>. By combining multiple trees, Boosted Regression Tree model overcomes the limitations of poor predictive performance in single-tree models, demonstrating superior predictive capabilities<sup>28,74</sup>. Compared to standard regression analysis, Boosted Regression Tree model, despite its complexity, presents clear and understandable results, providing deep insights<sup>75</sup>. We used Boosted Regression Trees model to investigate the relationship between composite sustainability scores and various predictor variables. The Boosted Regression Tree model was chosen based on its ability to handle a Gaussian distribution of the response variable<sup>28</sup>. The Boosted Regression Tree model relies on four key parameters: Learning Rate ( $lr$ ): this parameter determines the contribution of each tree to the growing model. A smaller learning rate makes the model more robust but requires more trees for accurate predictions. Bag Fraction ( $bf$ ): bag fraction represents the proportion of samples used at each step of the model building process. Tree Complexity ( $tc$ ): tree complexity controls whether interactions between predictors are fitted. A  $tc$  of 1 corresponds to an additive model, while a higher value allows for interactions between predictors. Number of Trees ( $nt$ ): the number of trees represents the boosting iterations required for optimal prediction<sup>28</sup>. More trees generally lead to better model performance but also require more computation. To optimize the Boosted Regression Tree model, we followed a two-step process: Parameter Tuning: we used 10-fold cross-validation (CV) to screen for the optimal values of these four parameters. This step ensures that the model is well-calibrated

and generalizes effectively to new data. The performance of various parameter combinations was assessed, and we retained the model with the highest CV-D<sup>2</sup> (deviance explained) as the optimal one. Model Evaluation: to ensure robustness and mitigate any random effects, the model was run 100 times under different random seeds. The mean values of the relative influence of each predictor were calculated based on these runs<sup>76</sup>. Furthermore, we examined interactions between pairs of predictors to understand how they influence sustainability scores. This analysis was conducted using the ‘gbm.interactions’ function within the ‘dismo’ package<sup>28</sup>. All of these statistical analyses and data visualization processes were conducted using R software version 4.1.

## Data availability

All data need to evaluate the conclusions in the paper are presented in the paper and/or the Supplementary Materials. Supplementary Tables 2 and 3, additional data, scripts, and files related to this paper can be available in a public online repository on GitHub ([https://github.com/jun905/Data\\_Code](https://github.com/jun905/Data_Code)).

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## Author contributions

C.X., G.S., and J.X. conceptualized the research idea and designed the overall study. C.X., K.Z., and M.Z. collected the data. Data compilation, analysis, and data interpretation were conducted by C.X., G.S., S.B., K.Z., M.Z., and J.X. Methods were designed by C.X., G.S., S.B., and J.X. The original paper was drafted by C.X., G.S., and J.X. All authors contributed to revising the paper and preparing and approving it for publication.

## Competing interests

The authors declare no competing interests.

## Additional information

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