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Temporal patterns of adoption of mariculture innovation globally

Rebecca R. Gentry *, Elizabeth O. Ruff and Sarah E. Lester

Mariculture—farming seafood in the ocean—has been expanding in many countries and has the potential to be a critical component of a sustainable global food system. However, it has developed inconsistently across the globe, with minimal development in some regions, while in others intensive growth threatens sustainability. There is no overall understanding of trajectories of mariculture development around the world. We analyse mariculture development trends at the country level, drawing on diffusion of innovation theory. We show that most countries follow predictable patterns of development that are associated with key economic and governance indicators, such as regulatory quality. We also show that production of some taxa (for example, molluscs) is more strongly associated with stable production over time, as is growing a diversity of species. Taken together, our results suggest that enabling policies may unlock mariculture growth opportunities and that strategies that emphasize production of a diversity of species could contribute to a more stable mariculture industry. Further, by assessing each country's trajectory of mariculture development in relation to its production potential, we consider the limits and opportunities for future mariculture growth and its contribution to sustainable food systems.

Food production has notable and far-reaching effects, both positive and negative, on the health of people, society and the environment[1]. As food production expands to new locations with more intensified systems and undergoes changes in production methods and products, the impacts and benefits of production are also likely to shift. One of the most important recent changes in food production is the expansion and diversification of aquaculture—the farming of aquatic animals and plants. Aquaculture is currently the fastest growing food sector in the world and, as of 2014, produces more seafood than wild-capture fisheries[2]. As such, aquaculture is positioned to make a notable contribution to global food production and its growth trajectories may have a profound influence on sustainable food systems into the future.

Aquaculture's effects vary depending on the method, location and species farmed[3,4]. While the industry's development can provide food, jobs, community coherence and additional income opportunities, it can also negatively affect the environment and other commercial activities, exacerbate inequalities and create poverty traps through low-paying jobs[5–7]. While most aquaculture currently takes place on land raising freshwater and brackish species, the extensive space for production in the ocean, the limited land and freshwater resources available for increasing agricultural or freshwater aquacultural yields, and the potentially lower environmental impacts of farming in the oceans have collectively shifted expectations of future growth towards marine aquaculture (also called mariculture)[8–10]. However, expectations of where and how quickly mariculture will expand and the sustainable limits of its growth are fraught with uncertainty.

Despite the growing importance of mariculture for food production and sustainable economic development, the spatial and temporal patterns of this expansion have not been studied extensively. Limited research concentrates on specific drivers (such as regulation)[11] and/or narrow geographies (such as Indonesia)[12] but there is a lack of research that integrates across disciplines or geographies. Investigating the recent history and trajectories of mariculture production globally can inform predictions of future development; for example, identifying factors that may influence spatial and temporal patterns of mariculture and suggesting drivers of mariculture diffusion.

Large-scale mariculture is relatively new in much of the world. It requires shifts in livelihood strategies, expertise, infrastructure and governance. We assess its adoption and development through the lens of diffusion of innovation theory[13]. Specifically, we view mariculture as a system innovation, whereby new technology along with new social and institutional frameworks transform the seafood sector[14]. It has been argued that this type of system innovation, as opposed to incremental change, will be necessary to achieve ecological and social sustainability in aquaculture[14]. While a dearth of research focuses on the adoption and expansion of mariculture, the literature about the adoption and spread of innovation more generally is extensive[13,15–17]. Theoretically, the number of adopters of a new innovation follows an S-curve where adoption starts out among few due to hesitancy of individual actors to accept new practices, perceived risk and the time it takes for information to spread between potential adopters. As positive experiences, expertise and information spread, the innovation is taken up by many more adopters. Eventually, the innovation reaches its maximum saturation, there are limited opportunities for further uptake and adoption levels plateau. This pattern of slow initial rates of adoption, followed by faster rates of uptake and then a return to slower rates of adoption forms the typical S-curve[13,16,17]. This pattern of innovation diffusion has been observed across sectors and innovation types, including wind, agriculture[15,18] and even social work[17].

Furthermore, diffusion of innovation theory suggests that a variety of factors can affect the likelihood that a new innovation will be adopted and the rate at which it spreads. These include characteristics of the innovation itself, such as its complexity, demand for the innovation or its product and cost-efficiency, along with social factors, including an individual's or society's proclivity to innovate, the availability of information, training opportunities and the visibility of the new practice[17,19]. Additionally, enabling policies that diminish regulatory burden, supportive governance, favourable economic conditions, and conduits for scientific collaboration and information dissemination are key factors in successful innovation spread[20]. A small but emerging literature focused on aquaculture adoption, innovation and expansion supports many of these theories,

Department of Geography, Florida State University, Tallahassee, FL, USA. *e-mail: rrgentry@fsu.edu

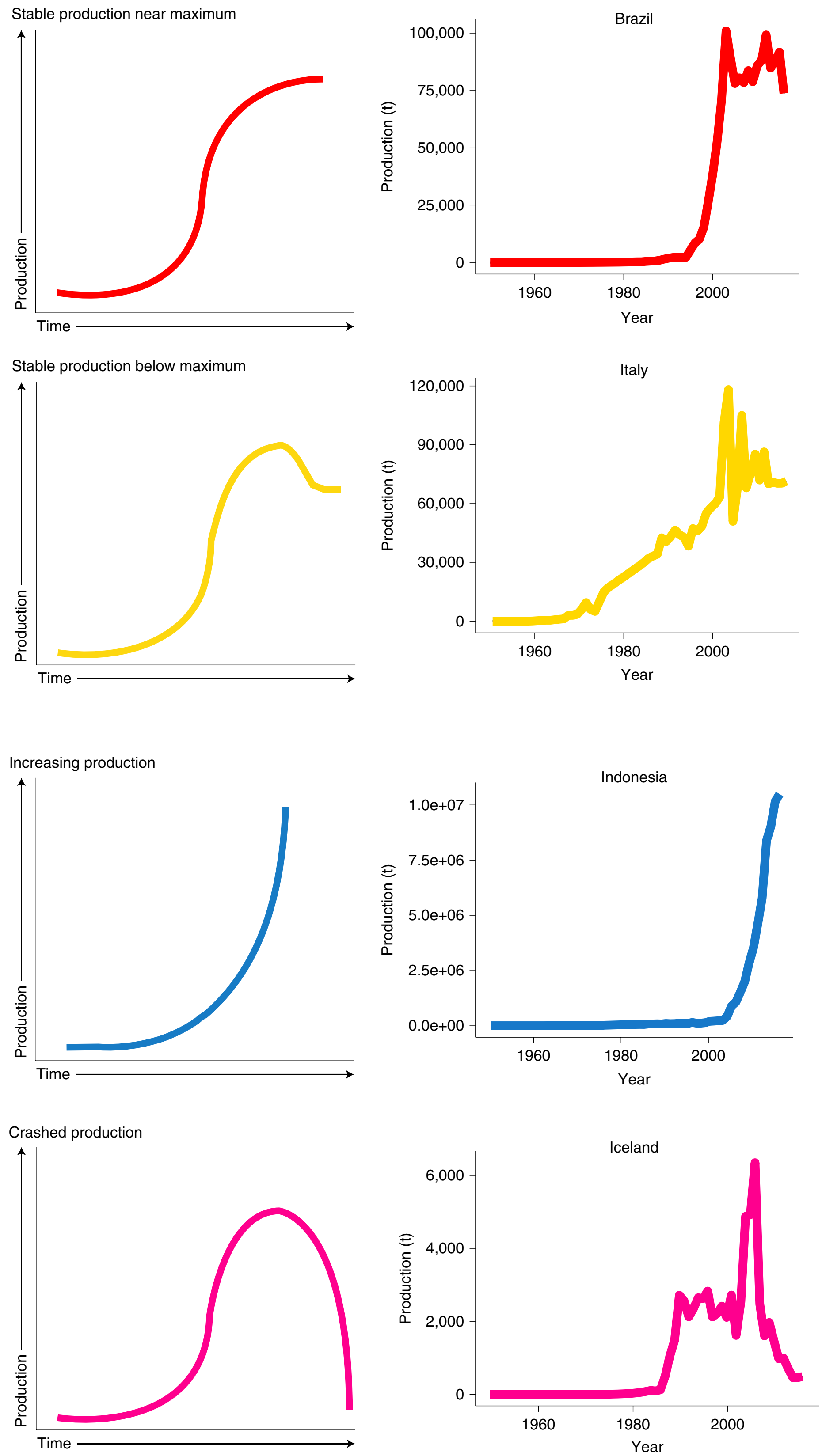

Fig. 1 | Examples of production curves for each curve category. The left column displays theoretical graphs of expected production patterns and the right column displays a production curve for an example country.

in particular suggesting that relative risks, potential profitability, opportunities to observe new practices, and supportive governance frameworks can facilitate innovation[21–24]. Understanding when, why and where mariculture is adopted and expanded is central to building a sustainable industry. Unconstrained growth can have negative social and environmental repercussions and the failure

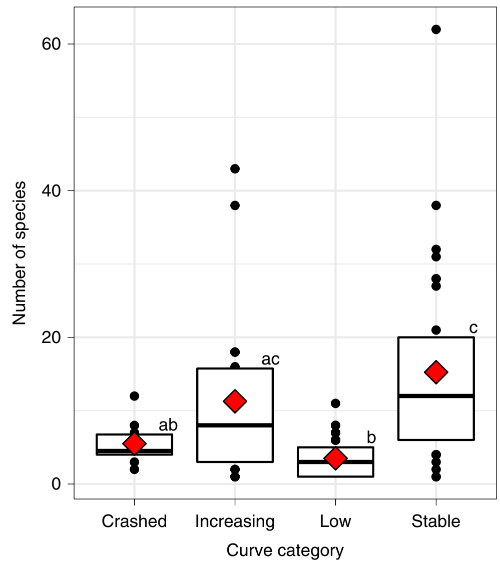

Fig. 2 | The number of species produced per country by curve category. The box indicates the 25th to 75th percentile for each category and the dots represent countries whose number of species fall outside the box. The horizontal line indicates the median number of species produced for each curve category and the red diamond indicates the mean number of species. Means sharing a letter are not significantly different at the level of $P < 0.05$.

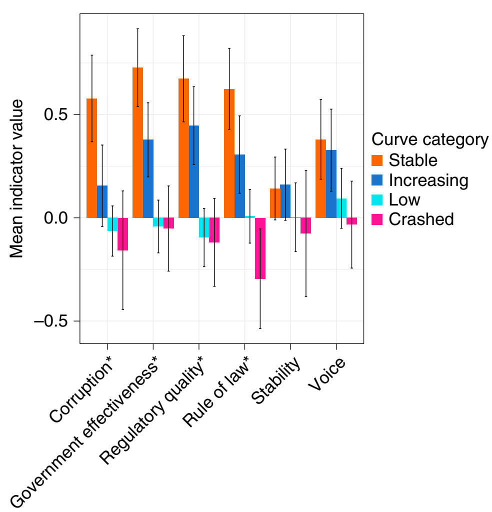

Fig. 3 | The mean indicator value for each of the six World Governance indicators by curve category. Error bars show the standard error of the mean. An asterisk after the name of the indicator variable signifies a significant ($P < 0.05$) difference between the mean value of development and governance indicators across curve categories.

of mariculture to reach its potential may mean that much of the demand is met by less sustainable production methods.

We analyse time series of mariculture production for all mariculture-producing countries. We consider total mariculture and broad taxonomic groupings, measured as volume of production as a proxy for innovation adoption. We categorize each country's development trajectory into one of four curve categories that describe its development stage. We then examine how a country's curve category relates to key national economic and governance attributes and to the taxonomic composition and diversity of farmed seafood produced in each country. Further, we investigate whether development patterns are consistent with diffusion of innovation theory and explore how this theory can inform sustainable mariculture development, in addition to limitations of the theory for understanding mariculture. We aim to improve understanding of when, where and how countries adopt mariculture and what economic, governance and farmed species attributes are associated with different temporal patterns of production (for example, stable, crashed or increasing). Understanding these patterns has important implications for managing our changing global food systems to ensure economic development, food security and environmental sustainability.

Results

Development trajectories. We found that mariculture development often follows a general S-curve pattern, as predicted by diffusion of innovation theory (Fig. 1). Of countries that have at least 1,000 t of production ($n = 67$; countries <1,000 t labelled as 'low production', $n = 44$), some show a pattern of increasing growth (31%), while the production of other countries has slowed or levelled out near or below maximum observed production and is now relatively stable (47%). Countries in both of these curve categories share a similar pattern of low production for several years after adopting mariculture practices, before reaching a point where the rate of production increases more sharply. The frequency of these development trajectories suggests that the S-curve pattern is relatively common for mariculture development. However, countries appear to be at different locations on this curve—some are still increasing production, while others have levelled out. Despite the frequency of the S-curve pattern, 22% of countries do not follow it—14% have experienced a crash in production and 8% had unusual patterns that did not fit any of our categories (Supplementary Table 1). There was no clear geographical pattern to the distribution of country curve categories (Supplementary Fig. 1).

Country-level curves for each taxonomic group often followed similar patterns to the aggregate country-level production data (Supplementary Table 2). We identified a marginally significant association between taxonomic group and curve category ($X^2 = 15.808$, d.f. $= 9$, $P = 0.071$). Mollusc production was most often categorized as stable production (35.7% of mollusc production curves) and the least likely of all taxonomic groups to have crashed production (9.3%). Fish had the highest percentage of production curves with production continuing to rise (20.5%), followed closely by algae (19.5%). Algae was the most likely to be classified as having crashed production (19.5%). Crustaceans were the least likely to have production categorized as continuing to rise (8.7%) and the most likely to be characterized as having low production (58.7%).

Taxonomic composition. We found significant differences in the total number of species produced in countries with different curve categories (analysis of variance, ANOVA: $F(3, 105) = 11.78$; $P < 0.001$). Countries with stable production farmed the highest mean number of species (15.2 species), followed by countries with continued growth in production (11.3 species), countries with crashed production (6.5 species) and those with low production (3.5 species) (Fig. 2).

The taxonomic composition of production varied across curve categories and at different periods of production (Supplementary Table 2). Using logistic regression, production volume of molluscs as a percentage of total production in a country was significantly associated with curve category ($P < 0.05$). Specifically, high levels of mollusc production early in a country's mariculture development are associated with that country experiencing stable or increasing production later in its trajectory; a 1% increase in the percentage of molluscs (as opposed to fish) produced in the first three years of production was associated with a 0.012 increase in the log odds of a country being classified as either stable or increasing production (Supplementary Table 3; pseudo $R^2 = 0.052$). We did not find a

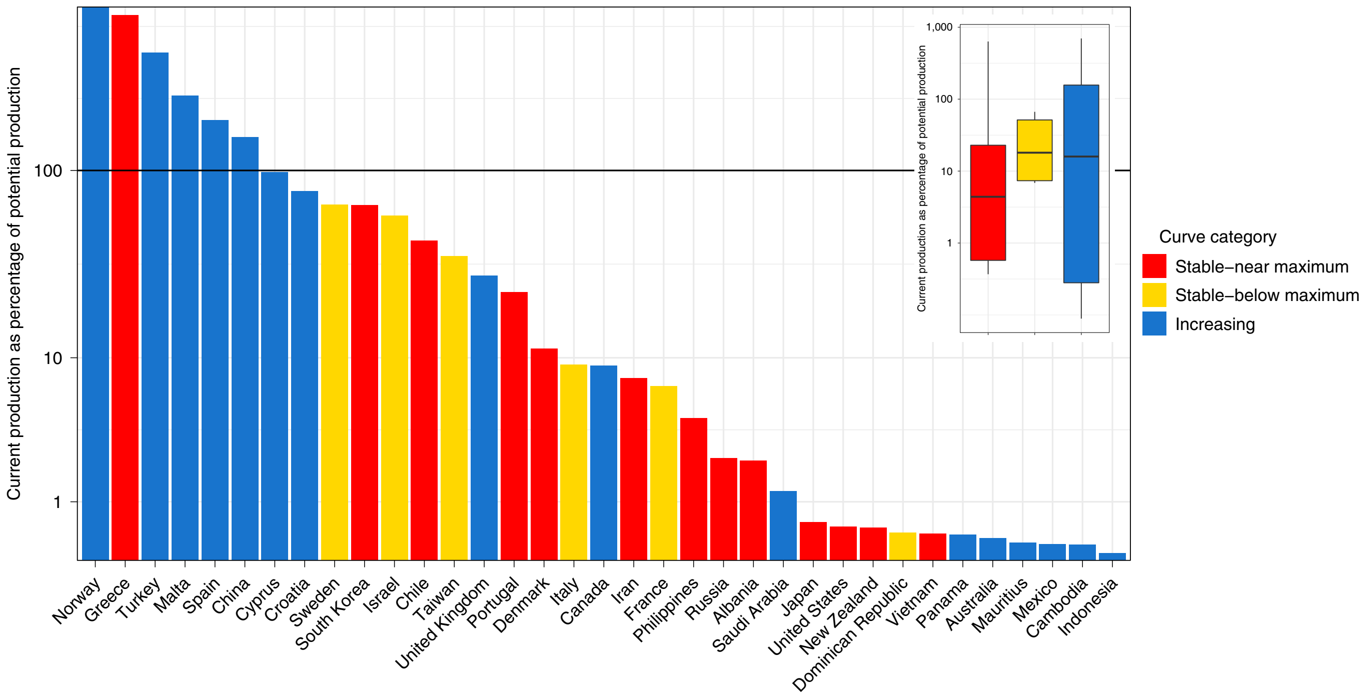

Fig. 4 | The relationship between current marine fish production and a conservative estimate of fish production potential for countries categorized as stable or increasing and for which potential production data are available. The inset boxplot shows the 25–75% range of values, with the median marked with a horizontal line for each curve category; the whiskers indicate the furthest data point within 1.5 times the interquartile range and outliers beyond the whiskers are indicated with a dot. Note that the *y*-scale is logarithmic. Fish production potential is based on ref. [10].

significant relationship between taxonomic composition of production and curve category at maximum production.

Governance and development indicators. Certain governance and economic development indicators, specifically gross domestic product (GDP), the World Bank doing business index, Internet connections per 1 million people, regulatory quality, government effectiveness, corruption and rule of law, varied significantly across country curve categories (Fig. 3 and Supplementary Table 4). Post-hoc analysis showed that countries with crashed production and low production have a significantly lower annual GDP and rule-of-law score than do countries whose production is stable. Countries with low production have a significantly less business friendly environment (lower doing business index score) than countries whose production is stable. Several governance indicators—regulatory quality, corruption and government effectiveness—also showed significantly lower scores for low-production countries than for stable-production countries. Finally, low-production countries have significantly fewer Internet connections per 1 million people than crashed-production countries. The other development and governance indicators that we examined did not show a significant relationship with country curve category (Supplementary Table 4).

Logistic regression indicated that governance and business environment were significantly ($P < 0.01$) and positively related to the likelihood of a country being classified as having stable or increasing production. The other variables in our regression (Internet connectivity and foreign direct investment) did not have a significant relationship with a country's aquaculture development trajectory (pseudo R^2 value, Tjur test = 0.10) (Supplementary Table 5).

Mariculture potential. In most countries, fish aquaculture production is far below each country's production potential. This is based on a conservative measure of fish production potential (as calculated by Gentry et al.[10]) that we use here as an indicator of sustainable production potential. For a few countries (five out of six of which are categorized as having increasing production), current production exceeded these production potential estimates (Fig. 4).

Discussion

We have provided insights into an important shift in global food production by studying mariculture development through the lens of innovation diffusion. Patterns of mariculture development are generally consistent across countries and reflect theories of innovation diffusion seen across other sectors. Our results demonstrate a positive relationship between stability of production and diversity of species produced. These patterns allow us to suggest probable trajectories for countries at varying stages of mariculture development. Specifically, countries in the production-increasing category may be in the portion of an S-curve with the quickest diffusion and will probably continue to experience growth until they reach an unknown limit. Countries whose production has levelled off are unlikely to experience significant growth unless a limiting force is relaxed and the capacity for new adoption or expansion of mariculture increases.

Mariculture could play a major role in contributing to more sustainable food systems in the future. However, the development trajectory we identified for each country does not necessarily indicate whether a country's mariculture production is sustainable. A country with long-term stable production may be more likely to be within sustainable limits, although even in that case, stable production could be hiding unsustainable practices, such as changing the location of farms once environmental conditions degrade. We attempted to assess sustainable limits by looking at a country's current fish production relative to its production potential (as calculated in Gentry et al.[10]). These limits were calculated using conservative assumptions and so can be loosely interpreted as sustainable potential but they were not developed based on determinations of the environmental and social carrying-capacities of each country.

Table 1 | Classification criteria for curve categories

Curve category		Criteria	Consistent with theoretical S-curve?
Low production		Peak production is less than 1,000 t.	Difficult to ascertain due to low production volumes. These countries may be at the first part of the S-curve before more rapid levels of adoption occur.
Production increasing		Maximum production (using a 3-yr moving average) must be 2015 (the most recent year) and the average production between 2012 and 2016 is greater than the average production between 2007 and 2011.	These countries may be on the middle part of the S-curve where rapid increases in adoption are occurring.
Production crashed		Production in 2016 is less than 20% of maximum production.	These countries are not consistent with an S-curve pattern.
Stable production	Near maximum	The 3-yr moving average in 2015 is within 20% of the maximum moving average.	These countries may be showing an S-curve pattern and have reached the top part of the S, where further adoption has slowed resulting in stable production.
	Below maximum	The coefficient of variation of production between 2012 and 2016 is less than 20%.	These countries have stabilized production somewhat below maximum. This could be a variation of the S-curve where adoption overshot capacity and has stabilized at a level less than peak production.
No category		Does not fit in any of the above categories.	These countries do not seem to be showing an S-curve pattern.

Notably, many countries, including most countries with stable production, are producing far less mariculture than their ocean environment could sustainably support (Fig. 4). This indicates that governance, regulatory or economic changes could unlock further opportunities for growth. For example, Denmark experienced relatively stable mariculture production throughout the 1990s; however, a new period of growth began in the 2000s, coinciding with a renewed emphasis by the government to promote sustainable aquaculture growth via technology development and education, among other factors[25]. Environmental regulations are important for preventing significant environmental degradation, local overdevelopment and unsustainable farm practices. However, for those countries that are in the increasing production category but are below their potential, policies to encourage thoughtful growth may be appropriate. Some countries, such as China and Norway, have exceeded their conservatively estimated finfish mariculture potential and continue to have increasing production (Fig. 4), raising concerns about whether this growth is environmentally and socially sustainable. Understanding both environmental and social sustainability limits to production is challenging and warrants continued investigation[26]. Future research will require integrated examination of both the environmental components (for example, ecosystem health and greenhouse gas emissions) and social components (for example, wages and ownership) of sustainability.

In general, we found that indicators of high-quality governance and more advanced economic development were correlated with countries that have stable production trajectories. Furthermore, governance and economic policies that streamline development or that provide a conducive environment for innovation, may facilitate stable or increasing production. For example, in 2013 the Dominican Republic established a national fund for sustainable development of fisheries and aquaculture that seems to have created a stabilizing force for mariculture production[27]. One approach to promoting sustainable development is to design integrated governance approaches that allow for more communication between all those involved in and affected by aquaculture activities and allowing for systems that can encourage and integrate feedback through time[14]. For instance, efforts such as the European Commission's Blue Growth Strategy aim to encourage development of sustainable mariculture by facilitating dialogue between stakeholders, mobilizing investments and streamlining application procedures[28].

Our results also show that the types of species grown are correlated with a country's mariculture development trajectory. Specifically, countries that initially adopted mariculture by farming molluscs were more likely to have stable production than countries that began farming fish and the curve categories for mollusc production are the most likely to be categorized as stable. Fish farming has long been associated with environmental risks such as pollution[29], parasite transmission[30] and sustainability of feeds[31]. As a result of this, farmers are also often faced with problems of community opposition to expansion[32,33]. In countries such as New Zealand and Canada, negative public attitudes towards aquaculture, specifically towards salmon farming, have slowed the mariculture expansion[34,35]. Although mollusc farming can also be controversial, public impressions are often more positive[36]. This may be due to a generally smaller environmental footprint and the potential for bivalve farming to improve the health of the surrounding environment in some cases[37,38]. The potential sustainability of mollusc farming may help to explain the correlation between stable production curves and higher production of molluscs in the first years of farming.

Another difference between fish and mollusc farming is the upfront costs of establishing a farm. Mollusc farming has a relatively low barrier to entry due to the low cost of farming infrastructure (particularly for artisanal production)[39]. Lower barriers of entry have been suggested as important in facilitating the uptake of new innovations both generally and in aquaculture specifically[21]. Indeed, across all curve categories, molluscs were the taxonomic group most commonly adopted in the first three years of production, possibly due to these lower costs of entry. In comparison, fish operations can have higher initial costs due to the required cage infrastructure, hatcheries and feed. These high initial costs coupled with the potential for lucrative profits due to the high value of some fish products might help explain the seeming anomaly of fish production in early years being associated with low-production countries but also being the most dominant species in countries that are experiencing continued growth (Supplementary Table 2). Further research on overcoming initial barriers and developing fish farming that is both socially and environmentally sustainable should be prioritized.

Further, we also demonstrate that the number of species farmed is correlated with the development trajectory of a country. Notably, countries with relatively stable production have farmed, on average, the most species over time. This finding is supported by portfolio theory, which posits that creating a more diverse portfolio of investments can reduce risks and improve financial outcomes[40]. More recently, portfolio theory has been applied to managing natural capital such as wild fisheries[41,42] and biodiversity[43,44]. Additionally, crop diversity has been shown to be an important driver of stability in land-based agriculture[45] and diversity of aquaculture species can provide some protection from both environmental and economic shocks[46]. Promoting diversity in mariculture species and methods could be an important element of governance frameworks that seek a balance between sustainable food production, economic development and environmental health.

Despite the usefulness of diffusion of innovation theory for understanding patterns of mariculture development, aspects of this theory are more relevant to processes operating at smaller scales than we were able to examine with global country-level data sets. For example, due to the coarse nature of global data, we were unable to determine whether changes in production are due to expansion of existing farms or through adoption and spread of innovation into new farms. While these different pathways to growth do not inherently change our results or the lessons learned from them, they do have important implications for applying theories of innovation diffusion to mariculture, since expansion of a single farm does not necessarily mean that there has been any new uptake of an innovation. Growth in production is probably due to both the expansion of existing producers as well as new farmers adopting mariculture practices but it would be worthwhile to study these trends on a more regional basis where farm-level data are available. In addition, many of the factors that shape technological and business expansion, along with the social and environmental effects of this expansion, operate at local and regional scales that are not captured in our analysis. However we suggest that the insights gained through this wider scale analysis provide an important macro-level view that could then be tested and refined at a more local scale; these local insights could then further refine our understanding of country-level trends.

On the other hand, some factors potentially affecting mariculture development are operating at scales larger than the country level and would therefore not be apparent in this analysis. For example, environmental pressures such as global warming or emerging diseases could affect mariculture development across many countries. Markets for both terrestrial meat and seafood often operate on a global scale and therefore changes to demand (for example, due to decreases in wild fisheries landings) could have far-reaching effects on mariculture development. The adoption and consequent development of mariculture within a country does not happen in isolation—it is intimately intertwined with economic, social, environmental and governance frameworks at both large- and small-scales. As such, applying diffusion of innovation theory is but one useful lens through which to view mariculture development trajectories.

While we have focused on the adoption and subsequent development of mariculture, it is worth noting that the potential for innovation continues long after the initial establishment of a farm and that this continued innovation can have a profound impact on social and environmental sustainability[14,21]. New methods (such as farming further from shore and novel feeds that reduce reliance on wild fisheries) and new farmed species can create opportunities for better environmental and economic performance[47]. Indeed, the diversity of species and taxonomic groups farmed in some countries is evidence of continued innovation and adoption of new farming practices. Considering the patterns of initial mariculture adoption alongside emerging research on technology innovation within the aquaculture sector[21] is important for understanding the dynamics of this rapidly expanding and changing industry and its effects on food systems and the environment.

Our findings provide an important foundation from which to further test and explore questions related to potential pathways for sustainable food production. Hypotheses explored above, specifically links between stability, sustainability and mariculture development, are worthy of future study. A better understanding of mariculture production trajectories and the overall effects of mariculture on global food systems is important for guiding policy that promotes sustainable use of natural resources while providing for long-term economic development.

Methods

We used Food and Agricultural Organization of the United Nations (FAO) mariculture production data[48], classified at the country level and filtered to include all types of marine production. We included all available years of data, allowing us to build country-level production time series from 1950 to 2016 for 115 mariculture-producing countries.

Classification of development patterns. Each country was classified into a pattern of development, referred to as 'curve categories' based on specific criteria (Table 1). Countries whose maximum production is under 1,000 t were classified as 'low production' since under this threshold the shape of the curves was difficult to discern and was strongly affected by relatively minor shifts in production. In total, 44 countries fell under the 1,000-t threshold so were not classified further. Next, countries were evaluated to determine if their production has crashed, whether it is continuing to rise or is relatively stable. For stable production, we assigned two subcategories: production is near (within 20% of) the country's maximum historic production and production has levelled out below maximum historic production. Countries that do not fit into any of these categories were labelled as 'no category'. Many of the classification criteria used a 3-yr moving average to minimize the effects of an anomalously high- or low-production year, which may be due to isolated events rather than indicative of general trends.

To examine patterns of mariculture production for specific taxonomic groups, we performed a similar classification exercise for fish, crustaceans, molluscs and aquatic plants in each country. The only change in the classification rules for the taxa-specific curves was that 'low production' was defined as under 500 t maximum production. A chi-square test was performed to assess whether curve categories were represented across all taxonomic groups in equal proportion.

Taxonomic composition. We calculated the total number of species produced in each country since 1950 and assessed, using ANOVA and a post-hoc Tukey's test when applicable, whether there were significant differences in the total number of species produced by countries in each curve category. For this analysis, countries with stable production near or below maximum were combined since these two categories represent a similar place on the theoretical S-curve. Countries that did not fit any category were not included in this analysis.

We also examined the percentage of mariculture production contributed by each major taxonomic group (mollusc, fish, bivalve and aquatic plants) at certain points in a country's development (in the first three years of production and at maximum production) and whether the relative contribution of certain species groups was related to a country's development trajectory. We used a logistic regression with curve category as the dependent variable and percentage contribution of each taxonomic group to total production (with total production calculated as the sum of that for the four major taxonomic groups) as the independent variables. The percentage of fish was excluded as an independent variable (and was therefore absorbed into the intercept) so that it would serve as the reference category in the regression output. For the dependent variable (called 'development trajectory'), all of the curve categories that are consistent with an S-curve diffusion of innovation model were grouped together (stable production and increasing production), as were curve categories that are not consistent with an S-curve pattern (low development, crashed production and no pattern). Our regression took the following form:

$$\text{Development trajectory} = \beta_0 + \beta_1 \times (\%\,\text{mollusc}) + \beta_2 \times (\%\,\text{aquatic plant}) + \beta_3 \times (\%\,\text{crustacean})$$

Where β_0 represents the y-intercept and β_1–β_3 represent the estimated coefficients for each independent variable. To understand the fit of our model to the data we calculated a pseudo r-squared value following the method described in ref. [49].

Development and governance indicators. We examined whether certain development and governance indicators at the country level, specifically GDP, the World Bank doing business index, foreign direct investment (FDI), Internet connections per 1 million people and the Worldwide Governance Indicators (regulatory quality, government effectiveness, corruption, rule of law, voice and stability) were related to a country's curve category. These indicators are related to factors that have been suggested to effect innovation adoption. For example, Internet connectivity may be related to information availability and the doing business index indicates whether a country has economic policies that could enable new business development. All indicator data were downloaded from the World Bank[50–52]. On the occasion that indicator data were not available for a specific country, that country was not included in that particular analysis. ANOVA analysis and post-hoc Tukey's tests were performed to determine if there was a significant difference between the development and governance indicators for each curve category.

To gain a more holistic assessment of the combined influence of development climate and governance on mariculture production, we specified a logistic regression with curve category as the dependent variable and governance and development indicators as the independent variables. As many of these independent variables are highly correlated and describe related aspects of governance, we performed a principal components analysis to identify one or more components that could be used as independent variables in the regression. All ten governance and development indicators (six World Bank Governance Indicators, the World Bank doing business index, GDP, FDI and Internet connections per 1 million people) were included in the principal components analysis. The first component explained 61.6% (eigenvalue 6.16) of the variability and had strong and even factor loadings from eight out of ten of the indicators. Only Internet per 1 million people and FDI contributed less than 5% to the first factor. The second factor had an eigenvalue of 1.05 and all subsequent factors had eigenvalues less than 1. Given that FDI explained over 80% of the variance in the second factor we decided not to include the second factor in our regression and instead perform a subsequent principal components analysis excluding Internet per 1 million people and FDI and include these two indicators separately in the regression. For the second reduced principal components analysis, which included the six governance indicators, the doing business index and GDP, the first component explained 73.7% of the variance and had factor loadings of over 10% from all of the indicators except voice and stability (which contributed 7.9 and 8.8% respectively). The second factor had its strongest loadings from voice and stability (40.9% and 22.9%) but was not included in the regression as its eigenvalue is below 1 (0.83) (Supplementary Fig. 2). The first component from the reduced principal components analysis represented 'governance and business environment' (GOV) in the subsequent regression:

$$\text{Development trajectory} = \beta_0 + \beta_1 \times \text{GOV} + \beta_2 \times \text{FDI} + \beta_3 \times \text{Internet connections}$$

As in the logistic regression described above under Taxonomic composition, stable production and production that is increasing were grouped together and low development, crashed production and no pattern were grouped together for the dependent variable (called 'development trajectory'). We then calculated a pseudo r-squared[49] to test the fit of our model to the data.

Mariculture potential. To determine whether current mariculture development trajectories are above or below a country's biophysical mariculture potential, the current fish production of all countries classified as either increasing or stable was compared to their production potential as calculated by Gentry et al.[10]. These production potential calculations use assumptions that result in a very conservative estimation of production potential and as such could be considered a proxy for sustainable production potential. Thus, this metric allows us to compare aquaculture development trajectories in the context of the environmental suitability for mariculture at a country level. Detailed methods can be found in Gentry et al.[10] but we provide an overview of the methodology here.

The calculation of finfish mariculture production potential used a three-step process[10]. First, the relative finfish productivity for each 0.042 degree^2 patch of the global ocean was determined. This involved constraining 120 consumable farmed marine finfish species to patches within their respective upper and lower thermal tolerance thresholds using long-term (1982–2011) sea-surface temperature data. An average multispecies growth performance index was then calculated for each patch based on individual species' Von Bertalanffy growth parameters (K and L_{inf}) for those species found within that patch. The multispecies growth performance index was used instead of predicting a single species most likely to be farmed in each ocean patch. Second, unsuitable patches, based on environmental and social constraints, were removed from the results. Suitable patches included areas less than 200 deep that did not conflict with existing uses such as shipping, oil rigs or marine protected areas and had environmental conditions suitable for fish culture based on dissolved oxygen concentrations. Third, to understand how relative productivity relates to aquaculture production, the average multispecies growth performance index was used to estimate the time that it would take a farmed fish to grow to harvestable size in each ocean patch. Potential finfish production for each patch of ocean was calculated assuming a fixed farm design of $24 \times 9{,}000\ m^3$ cages per 1-km^2 area, each with a low stocking density (20 juveniles per m^3) and immediate restocking of a farm after harvest. Calculation of potential finfish production per country assumed development of only 1% of a country's suitable area, with the most productive areas developed first.

All analyses were performed in R v.3.51 (ref. [53]), using the following packages: dplyr[54], tidyr[55], ggplot2[56], factoextra[57], FactoMineR[58], DescTools[59], nnet[60] and rworldmap[61].

Data availability

All data used in this paper are publicly available and can be accessed through: http://www.fao.org/fishery/statistics/global-aquaculture-production/en; https://data.worldbank.org/; www.govindicators.org; http://www.doingbusiness.org; and https://doi.org/10.5063/F1CF9N69. Figure 1 uses raw aquaculture production data downloaded from http://www.fao.org/fishery/statistics/global-aquaculture-production/en.

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R.R.G. and S.E.L. developed the research. R.R.G. performed the analysis with input from S.E.L. and E.O.R. All authors interpreted the results. R.R.G. wrote the manuscript with significant contributions from S.E.L. and E.O.R.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to R.R.G.

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