Sustainable bivalve farming can deliver food security in the tropics

Bivalve shellfish represent a nutritious and low-impact food source that is underutilized. New innovations in production in this sector could fulfil the protein needs of nearly one billion people in the most vulnerable global regions.

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Suboptimal global food production is directly related to poor diets, nutrition-related disease and environmental pressure. The tropical regions bear the brunt of this crisis, concentrating the fastest population growth[1] and the greatest problems related to food production, distribution and loss. Over-reliance on processed food imports is also driving a rapid increase in obesity in the developing tropics relative to the Global North[2].

Livestock meat, though nutrient rich, has a limited potential to solve these issues. Current production methods are unsustainable, and consumption must be halved by 2050 to avoid a catastrophic overstep of planetary environmental boundaries[3]. Sustainable diets are primarily plant-based[3], yet many nutrients vital to human health are far less bioavailable in plant crops than in meat[3] while rising CO_2 is dramatically reducing the absolute content of these nutrients in plant crops[4]. Without new food sources and productivity increases, tropical regions may be forced to open up new land to unsustainable agricultural development, or face economic debt and public health problems through unsustainable food imports[5].

Bivalve shellfish aquaculture represents a key opportunity for sustainable diets, and has been identified as an alternative to fill the gap left by livestock meat[3,6,7]. Bivalves, which include clams, oysters, mussels and scallops, have a higher protein content than many meats and plant crops, high levels of essential omega-3 fatty acids, and micronutrients such as zinc, iron, vitamin A and vitamin B12 (ref. [7]) (Table 1). Bivalve farming also has a smaller environmental footprint than most other foods, using up almost no land or freshwater, relying on seawater instead, having lower carbon emissions than many cereal crops, and helping to restore and protect coastal ecosystems[7] (Table 1). Bivalve reefs (and bivalve farms, during the period between harvests) can buffer estuaries and coastal waters against phytoplankton blooms caused by anthropogenic nitrogen loading, increase water clarity, provide a nursery habitat for fish, provide coastal flood and storm protection, and shell production acts as a form of carbon capture[8]. The ecosystem services yielded from bivalve aquaculture are currently estimated at US$30.5 billion per year and only set to grow as the industry expands[8]. From a nutritional and environmental standpoint, bivalve shellfish represent a promising choice for farmers in the coastal tropics (Table 1).

There is great potential to expand bivalve aquaculture in the tropics. Today, bivalve production in tropical regions is almost non-existent, providing just over 2 Mt of meat annually[9,10] (Fig. 1). Low levels of knowledge, funding, infrastructure and consumer acceptance are key contributing factors. Yet, worldwide, over 1,500,000 km^2 of currently undeveloped coastlines are suitable for productive bivalve aquaculture, two-thirds of which are in the tropics (Fig. 1)[11]. If just 1% of the area in the tropical regions alone would be developed, over

Table 1 | Nutritional properties and environmental footprints of selected food items that can be farmed in the tropics

	Beef	Pork	Chicken	Tilapia	Bivalves	Shrimp	Rice	Soya	Wheat
Nutrient									
Protein (mg kcal^{-1})	98	64	121	205	**150**	242	19	88	33
Omega 3 (mg kcal^{-1})	0.5	0.3	0.7	1.9	**4.8**	0.3	0.1	2.6	0.2
Iron (µg kcal^{-1})	10.1	3.3	5.7	5.4	**34.3**	5.2	11.8	24.1	9.9
Zinc (µg kcal^{-1})	23	8	10	3	**61**	17	3	7	8
Vitamin B12 (ng kcal^{-1})	10	3	4	15	**126**	15	0	0	0
Vitamin A (IU kcal^{-1})	0.1	0.1	0.1	0.1	**2.30**	0.51	0	1.2	0
Environmental footprint									
Land use (ha per t protein)	50	2	3	7.5	**0**	16.4	21.2	0.578	4.62
Greenhouse gas emissions (tCO_2 per t protein)	337.2	57.6	42.3	40.7	**11.1**	161.7	2.36	1.04	3.54
Freshwater use (m^3 per kg protein)	112.5	56.5	34.3	15.9	**0**	4.4	19.81	5.76	11.84
Eutrophication potential (kg P per t protein)	180	120	40	82	**−148**	104	109	17.8	30

Bold values indicate that bivalves provide maximal nutritional value for minimal environmental footprint. Environmental footprints are based on today's production methods and fresh consumption of bivalves. Production intensification and increased food processing are expected to increase footprint values, but sustainable development methods could minimize environmental costs. IU, international unit. Data on beef, pork, chicken, tilapia, bivalves and shrimp were obtained from ref. [6], data on rice, soya and wheat were obtained from refs. [33,39], and ref. [9] was used for unit conversion.

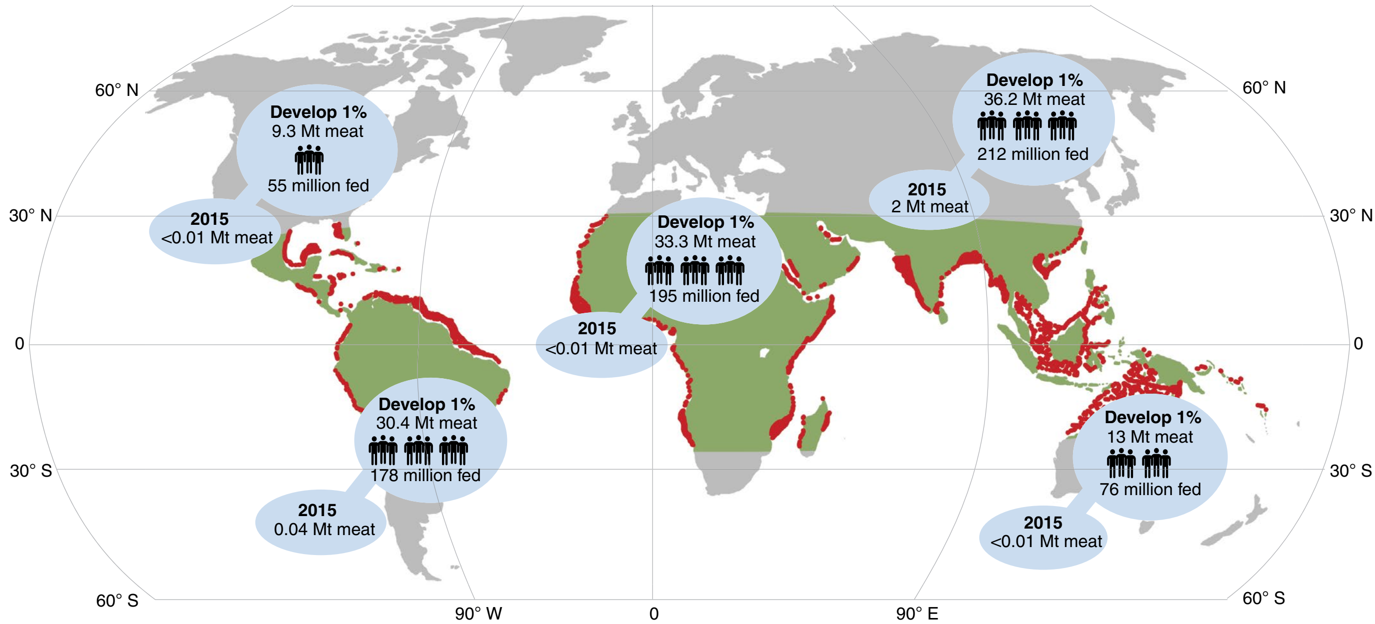

Fig. 1 | Potential for bivalve coastline production in the tropics. Areas of coastline suitable for the development of productive bivalve farming shown in red were determined based on the satisfaction of physical factors — that is, depth (<200 m), chlorophyll *a* concentration (annual mean > 2 mg m^{-3}) and oxygen concentration (>1.99 mg l^{-1}) — and the exclusion of areas dedicated to activities such as shipping and oil rigs. The tropical zone is shown in green. Blue circles show the quantity of bivalve meat produced in 2015 (in Mt), the potential additional quantity if 1% of the suitable coastline that is not yet in use was developed (in Mt), and the number of people (in millions) that could potentially be fed on bivalves as their only protein source for each of the following regions: Central America, South America, Africa, Asia and Oceania. Data on coastline suitability including physical factors and exclusion zones were obtained from refs. [11,24], data on 2015 production were obtained from ref. [10], and projection data were calculated using refs. [9,11,25]. Publ. note: Springer Nature is neutral about jurisdictional claims in maps.

120 Mt of bivalve meat could be produced annually — enough to satisfy the protein demands of approximately 715 million people (Fig. 1). Production costs are also relatively low, making bivalve farming an accessible venture for both large businesses and also small-scale farmers in the developing world[12,13]. The economic viability of bivalve farming in a rapidly developing nation has been proven in China, which began extensive bivalve farming in the 1950s and now yields over 85% of global production[12]. Mirroring this development in the rest of Asia, Africa, the Americas and Oceania could generate considerable human health and environmental benefits.

To meet and expand its potential, the bivalve industry in tropical regions requires development across the entire value chain. As discussed below, major challenges must be overcome across hatchery, grow-out and depuration stages of production, as well as in infrastructure and consumer marketing — but innovations and technologies can turn these challenges into exciting opportunities for success.

Hatcheries

The need for research and investment in hatchery systems represents a major challenge for establishing bivalve aquaculture in the tropics. Lack of seed (juvenile bivalves) is severely constraining industry expansion[12]. Seed from natural reefs is in very limited supply and its collection has detrimental ecosystem impacts, making hatcheries crucial for seed provision[12]. Research and breeding programmes akin to those performed in China for the Pacific oyster *Crassostrea gigas* are needed to produce broodstock with high reproductive output and resulting good quality seed (that is, triploid genetics for faster growth and enhanced disease resistance[13] and other desirable characteristics). There is a particular need for greater knowledge and expertise in breeding species such as *Perna perna*, *Perna viridis*, *Crassostrea gasar* and *Ruditapes decussatus*; these are suitable species to farm in unexploited tropical areas and offer high potential productivity (Box 1). Hatcheries also require affordable and sustainable feed for juveniles and broodstock. Current methodologies make inefficient use of natural and economic resources, and only minor development has occurred since the 1990s; the live microalgae used today is disease prone and of variable quality, energy intensive to grow and accounts for 50% of hatchery costs[7,14–16]. Investment in grow out, distribution and marketing of bivalves is all at risk without industry investment in hatcheries that underpins the production process[17].

Solutions that can provide investment, high-quality broodstock and feed for hatcheries are emerging. Overseas investment from private companies such as China's Tongwei Co., the nation's industry leader in aquaculture for 20 years, could play an important role in establishing hatcheries in the tropics. From 2005–2018, China invested US$300 billion in Africa (primarily into the production of arable crops, cattle, poultry and enabling resources including power and infrastructure), and has indicated that additional investment could go towards bivalves[6,18]. Better collaboration of bivalve hatcheries with the rest of the seafood industry can also increase resource use efficiency and reduce costs; a working example is the Chinese National Fisheries Corporation who implement legislation across the entire value chain[19]. Advances in DNA analysis and increasing affordability can enable accelerated selective breeding programmes in tropical areas in need of rapid aquaculture development, including sub-Saharan Africa[6]. Additionally,

Box 1 | Opportunities for bivalves in the tropics

Each of the coastal regions presented has a mean annual chlorophyll *a* concentration above 2 mg m^{-3}, suitable to support highly productive bivalve grow-out. Production data in 2017 were obtained from ref. [10]. 'Additional nutrients' refer to sources of N and P that can support phytoplankton proliferation and bivalve growth, with data obtained from refs. [11,24,25]. 'Suitable species' are bivalve species that would be most economically feasible and environmentally appropriate to farm in the given region, with data obtained from ref. [25]. Considerations on food safety and socioeconomic factors were taken from refs. [1,12,13,22], with 'GDP per capita' referring to the gross domestic product per person in 2015[1].

East Asia (China)
Production in 2017: 14.6 Mt (85% of global bivalve production).
Additional nutrients: integrated multi-trophic aquaculture.
Suitable species: *C. gigas*, *P. viridis*, *Ruditapes phillippinarum*, *Siliqua patula*.
Food safety: marine functional zoning, bivalve meat bacterial load regulations.
GDP per capita: US$10,000.
Socioeconomic considerations: in 1960, GDP per capita was US$100 (current equivalent US$) and bivalve consumption 4.8 kg per capita. Heavy investment in hatcheries and breeding followed; by 2015, consumption reached 35.7 kg per capita.

West Africa (Sierra Leone, Senegal)
Production in 2017: 563 t
Additional nutrients: by 2050, agricultural N and P runoff will triple, and intervention is needed to avoid eutrophication.
Suitable species: *R. decussatus*, *C. gasar*, *Mytilus edulis*.
Food safety: sewage runoff is increasing, and improved waste infrastructure and food safety regulations are needed.
GDP per capita: <US$1,000.
Socioeconomic considerations: facilities and marketing investment is required and available — since 2005 China invested US$300 billion in Africa in food and resource production with further investment planned.

South America (Venezuela)
Production in 2017: 8 t
Additional nutrients: industrial and urban discharge.
Suitable species: *P. perna*, *C. gigas*, *Crassostrea rhizoporae*.
Food safety: marine functional zoning and regulation on oil spill detection and food safety required due to active oil industry.
GDP per capita: US$10,000.
Socioeconomic considerations: competing marine shrimp industry is already lucrative and productive, but combined coastal shrimp and bivalve farming could tackle eutrophication.

South Asia (India, Myanmar)
Production in 2017: 13,000 t
Additional nutrients: discharge from agriculture on the Ganges delta and intensive shrimp aquaculture.
Suitable species: *Crassostrea madrasensis*, *P. viridis*, *C. gigas*.
Food safety: nearshore plastic and sewage pollution means offshore farming is preferable over intertidal farming.
GDP per capita: US$1,000–2,000.
Socioeconomic considerations: potential conflicts with the active fishing industry, but current fishing infrastructure could help service offshore farms.

innovations in algal production and microencapsulation technology can provide sustainable low-cost feed for hatcheries. Recently developed microencapsulated diets containing *Schizochytrium* algae grown on food waste have facilitated accelerated bivalve growth and sexual development with a 100-fold reduction in energy usage and costs relative to conventional live algae hatchery feeds[7,14].

Grow out

Productive bivalve farming in the tropics requires the identification and management of suitable grow-out areas. High levels of primary production or eutrophication from nutrient runoff are needed to support bivalve filter feeding and growth, yet many tropical waters are relatively oligotrophic, thus making these resources less available[11,12]. In some areas, integrated multi-trophic aquaculture can provide additional but not always adequate resources, and the availability of these resources is also dependent on water exchange rates[20]. Waste streams from urban and industrial areas can provide a further source of nutrients, but without adequate treatment hazardous substances such as cadmium, lead and microplastics can accumulate in bivalves intended for food[21,22]. Careful consideration is also needed regarding species selection for grow out, as production and conservation interests can conflict. For example, *C. gigas* has received investments in production efficiency and now dominates global oyster production, yet must be managed carefully so that it does not displace native species and modify natural ecosystems[23].

Careful site selection and management can enable expansion of bivalve grow-out in the tropics. Regions of West Africa, South Asia and South America have particularly good potential (Box 1), with mean annual chlorophyll *a* concentrations above 2 mg m^{-3} to support bivalve grow-out, alongside additional nutrient sources from human activities[24,25]. Knowledge exchange with established grow-out operators in the United States, Western Europe and China could help farmers with poor experience in these new grow-out regions improve the economic viability of their own farms[19]. Offshore production methods such as longlines can be chosen to reduce accumulation of hazardous pollutants by bivalves, as many pollutants are most concentrated nearshore to urban areas[22,25]. Regulatory approaches, such as the marine functional zoning already used in China, can further reduce food safety concerns and minimize conflict between bivalve aquaculture and other activities (such as the oil industry in Venezuela[12]). Increased hatchery breeding and grow out of native species could reduce risks of ecosystem modification from farming non-natives (Box 1)[26]. In addition, to ensure that the ecological carrying capacity of a given region is not exceeded when developing 1% of the potential productive coastline for bivalves, it may be pertinent to distribute development across the entire tropics rather than focusing on one given region[11,12,26]. This would likely result in increased infrastructure costs, but may still be favourable for small-scale fisheries and in supporting local livelihoods.

Depuration

Bivalve food safety is a major hurdle. Even if human-derived pollutants are avoided through careful grow-out site selection, there is still potential for toxic cyanobacterial blooms or other bacteria to contaminate food[27]. Depuration facilities, where bivalves are held for a minimum of 48 hours after harvest in clean water, play a crucial role in ensuring food quality — but are lacking in regions trying to develop bivalve aquaculture such as Africa and India[12].

Established and emerging methodologies can provide bivalve food safety solutions.

Information transfer and investment from the European Union, United States and Australia could accelerate depuration facility development in the tropics — for example, the introduction of low-cost, solar-powered, ultraviolet depuration systems[12]. Surveillance programmes such as those used in the United States can monitor toxic algal blooms and enforce increased depuration times when contamination occurs[27]. The use of probiotics and antimicrobial peptides such as *Phaeobacter inhibens* and tachyplesin, respectively, during depuration are new potential approaches for tackling bacterial contamination[28,29]. In areas where funds are more limited, establishment of food safety monitoring programmes in relevant culture areas, as has been done through China's 2009 food safety legislations, may be the most efficient approach to cover multiple forms of contamination[30]. A thorough economic assessment would still be required for any target region since each method may increase production costs and, if designed improperly, create a production bottleneck.

Infrastructure

The upscaling of bivalve aquaculture in the tropics and the establishment of necessary infrastructure raise important challenges. Increasing production will require significant investment in facilities, including harbours, transport, cooling and processing — and may be amplified in the tropics as high ambient temperatures and humidity mean food spoils more rapidly[1,17,31]. Intensification will likely also raise the currently low environmental footprint of bivalve production (Table 1).

Innovative financial approaches, research and industry development provide an opportunity to develop an effective sustainable infrastructure. Microfinance institutions such as those utilized in India[25], overseas private investment from major producers in China and World Bank programmes such as PROFISH are suitable funding routes[32]. An example of recent success is Peru, where a 50% reduction in corporation tax for aquaculture companies, incentives for investment from nationally prominent agri-businesses including Camposol Ltd and private investment in innovation centres allowed the bivalve industry to grow sevenfold between 2003–2015[10,12,25]. Careful modelling and design of upscaled systems can ensure bivalve farming remains environmentally favourable relative to other food systems[6,33]. Integrated facilities combining hatchery, grow-out, depuration and processing functions in urban areas could enable further productivity increases whilst providing additional infrastructure to support coastal production[12]. At the same time, waste streams from aquaculture and other industries could support bivalve aquaculture in recirculating aquaculture systems[6,26]. Farming bivalves in a closed environment might even permit the safe usage of fast-growing non-native bivalves to reduce production timescales, minimize accumulation of pollutants and increase production output[34].

Consumer acceptance

Driving consumer uptake of bivalves as an appealing, nutritious and sustainable food source is a key hurdle; unless properly tackled, it may render improvements across the rest of the value chain expendable. Societies in many tropical regions including Africa do not traditionally consume shellfish, contributing to a reinforcing loop between low production and low consumption[12]. Additionally, fears around food safety, and a lack of familiarity and knowledge around choosing, preparing and cooking seafood are serious barriers to consumption[35]. Other types of meat and dairy can simply be more attractive[36].

A multi-pronged approach is required to stimulate consumer demand for bivalve shellfish. Pivotal to China's success were state-organized promotion of aquaculture as an affordable protein source and reform policies leading to the creation of a wide range of convenient, highly palatable, non-perishable processed bivalve products[13,25]. The increased consumer demand underpinned rapid aquaculture industry growth and will have contributed to the nation's economic expansion — a model other tropical nations could build on (Box 1). Looking into the future, consumer co-creation in food product development — possibly using new avenues such as social media — can drive innovations in bivalve food processing to meet the tastes of specific populations[37]. Replacing conventional meat with bivalve meat within recipes or familiar processed foods may play a key role, for example shellfish paella in South America, clam stew in Africa and battered bivalve meat in tropical urban areas[35–37]. Food processing developments could reduce the time and distance over which fresh bivalves need to be stored as well as the need for cooling infrastructure, and improve consumer perceptions of food safety (although an increased environmental footprint could result[6]). Seafood quality certification offers promise to increase uptake and might lead consumers to pay more for this assurance[38]. There may also be opportunities for chefs and entrepreneurs in developing nations to improve their own livelihoods, establish bivalve-focused food outlets and promote the consumption of bivalve meat in novel and creative ways[6].

A blue horizon

The global community is in great need of nutrient-rich food sources that can be produced without overburdening the environment. Bivalve shellfish are a promising alternative, particularly in the tropics. Vast areas of coastline are available for sustainable development, but several challenges must still be tackled for bivalve aquaculture to meet its potential. Leveraging new innovations and technologies can overcome these challenges, enabling bivalve aquaculture to provide a new source of income with the potential to feed nearly a billion people in the developing world. ❐

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Published online: 09 July 2020
https://doi.org/10.1038/s43016-020-0116-8

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Acknowledgements
This research was supported by the Biotechnology and Biological Sciences Research Council.

Competing interests
The authors declare no competing interests