PERSPECTIVE
https://doi.org/10.1038/s43016-020-0127-5

Sustainable aquaculture through the One Health lens

G. D. Stentiford[1,2] ✉, I. J. Bateman[3], S. J. Hinchliffe[2,4], D. Bass[1,2], R. Hartnell[5], E. M. Santos[2,6], M. J. Devlin[7], S. W. Feist[1], N. G. H. Taylor[1,2], D. W. Verner-Jeffreys[1,2], R. van Aerle[1,2], E. J. Peeler[1,2], W. A. Higman[1], L. Smith[1], R. Baines[1], D. C. Behringer[8,9], I. Katsiadaki[1,2], H. E. Froehlich[10,11] and C. R. Tyler[2,6]

Aquaculture is predicted to supply the majority of aquatic dietary protein by 2050. For aquaculture to deliver significantly enhanced volumes of food in a sustainable manner, appropriate account needs to be taken of its impacts on environmental integrity, farmed organism health and welfare, and human health. Here, we explore increased aquaculture production through the One Health lens and define a set of success metrics — underpinned by evidence, policy and legislation — that must be embedded into aquaculture sustainability. We provide a framework for defining, monitoring and averting potential negative impacts of enhanced production — and consider interactions with land-based food systems. These metrics will inform national and international science and policy strategies to support improved aquatic food system design.

Aquaculture is one of the fastest growing and highly traded food sectors globally — Asia accounts for 90% of production[1] and volumes are predicted to double by 2050[1] (Supplementary Section 1). Enhanced sustainable production (ESP) in aquaculture features within the Rome Declaration of the Second International Conference on Nutrition (ICN2), the United Nations Framework Convention on Climate Change (COP21) and in the 2030 Agenda for Sustainable Development[2]. Achieving ESP is technically, socially and politically complex: the sector spans small homestead-scale production systems — underpinning food security in rural settings in low- and middle-income countries — to medium-sized farms that contribute to exports and high-technology industrial-scale production of globally traded products. More than 500 aquatic species are farmed in widely divergent social and legislative infrastructures — with different end goals. Thus, a holistic approach to the design and implementation of aquaculture systems is needed[3] — framed within the broader context of sustainable food systems[4].

The sector offers many positive aspects: poverty alleviation in some of the lowest-income regions[5], production increases from technological advances and selected species lines[6], the use of non-fed (for example, molluscs) and extractive (for example, seaweed)[7] species with benefits of farms for proximate marine biodiversity[8], comparatively lower environmental impact of some types of aquaculture[9,10], and smaller spatial footprints compared with both capture fisheries[11,12] and land-based agriculture[13]. However, numerous sustainability challenges must be addressed across the diverse range of aquaculture sectors. For example, economic gains in the global shrimp sector have been prioritized in spite of evidence of major mangrove forest degradation[14], bonded labour and social inequities[15], and potentially high carbon footprints[16,17]. The profitable Northern Hemisphere Atlantic salmon aquaculture industry farms native stocks, but claims of subsequent pathogen spillover[18], loss of genetic integrity of native populations[19] and wider environmental degradation of sensitive habitats[20] persist. Similarly, antibiotic overuse in Southern Hemisphere Atlantic salmon production[21] remains disproportionate to the economic benefits in otherwise deprived rural communities[22]. The principles of One Health — defined as the collaborative, multisectoral and transdisciplinary approach to achieving beneficial health and well-being outcomes for people, non-human organisms and their shared environment (Supplementary Section 2) — offer a practical framework to achieve aquaculture ESP. Governments, producers, wider industry, scientists and the public must engage to facilitate the design of food systems to decouple the human health benefits of consuming aquatic protein from negative environmental, organismal and societal impacts that may develop around a rapidly expanding, unregulated sector. Interaction and integration of independent accreditation schemes, such as the Best Aquaculture Practice standards (https://www.bap-certification.org/), with traditional governmental regulation could deliver greater positive impacts[23].

Here, we propose a practical means to implement the One Health approach to aquaculture ESP within national and international policy, legislation, evidence provision and research (Fig. 1) that can be tailored to industry sub-sectors to address specific sustainability requirements.

Success metrics

Sustainability measures must be rigorously applied across all food sectors if aquaculture is to become part of regional and global

[1]International Centre of Excellence for Aquatic Animal Health, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Dorset, UK. [2]Centre for Sustainable Aquaculture Futures, University of Exeter, Exeter, UK. [3]Land, Environment, Economics and Policy Institute, University of Exeter, Devon, UK. [4]Department of Geography, University of Exeter, Exeter, UK. [5]International Centre of Excellence for Seafood Safety, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Dorset, UK. [6]Biosciences, University of Exeter, Exeter, UK. [7]Environment and People Theme, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft Laboratory, Lowestof, UK. [8]Fisheries and Aquatic Sciences, University of Florida, Gainesville, FL, USA. [9]Emerging Pathogens Institute, University of Florida, Gainesville, FL, USA. [10]Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, Santa Barbara, CA, USA. [11]Environmental Studies, University of California, Santa Barbara, Santa Barbara, CA, USA. ✉e-mail: grant.stentiford@cefas.co.uk

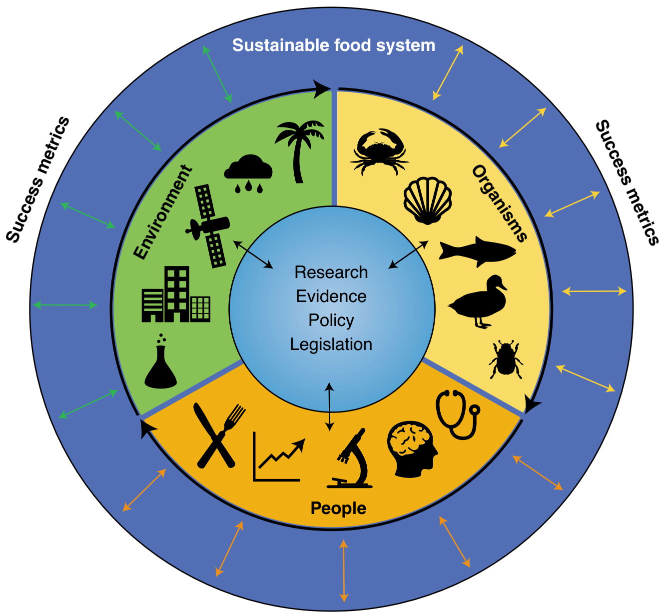

Fig. 1 | One Health approach to sustainable food system design and analysis. Research, evidence, policy and legislation (centre) are focused on a co-designed set of success metrics (outer circle) relating to environment, human and organism health — the interlinked components of the One Health philosophy. Using this simple framework, government, industry and society can assess specific sectors, such as aquaculture, according to the principles of sustainability. Sub-optimal conditions can be measured and the data used to guide research, evidence collection, and policy or legislative change. Perceived benefits to human society (for example, nutritional supply, employment, profit) are considered in the context of broader environmental cost-benefits, allowing nuanced trade-offs between success metrics in different sections of the model to be more easily identified and rebalanced using policy and legislative solutions. The systems-based approach draws upon a wider array of specialist input than may previously have been applied to sustainable food system design and is likely to be an efficient means of communicating food system policy to society.

sustainable food systems. Evidence-based success metrics indicate producers', co-operatives', sub-sectors' or the regional industry's compliance with the One Health principles (Table 1 and Fig. 2) and aid metric-specific policy and legislation development. Metrics that are fully achieved gain the highest score of 5, corresponding to policy and legislation being in place and consistently applied. The lowest score of 1 is given for unsuccessful metrics when no supporting research or evidence is in place to support policy and legislative design. This approach allows tailored sub-sector evaluation, highlighting specific areas for improvement and directing future research and evidence to support design of policy and legislation (Fig. 3).

Human health. Aquaculture can provide a range of public health, economic and social benefits. The One Health approach might result in a series of decisions on investment and health quality that make 'optimization' closer to a set of trade-offs between economic gain and productivity, animal welfare or system-wide health. Market preferences or social aspirations to sponsor or tolerate certain levels of health will become crucial in establishing practical health. In Bangladesh, for example, finfish consumption increased by 150% between 2000–2010, while adjusted prices for cultured catfish and tilapia fell by 40% — largely as a result of expanding freshwater pond production[24] — with considerable impact on human health and well-being[25]. Simultaneously, rapidly urbanizing populations can suffer from the coexistence of food poverty and overconsumption of processed foods[26] — aquaculture products could alleviate some of these issues. While producers may choose more profitable and sometimes less nutritious cash- and export-oriented crops, aquaculture as a component of polyculture traditions in many low- and middle-income countries can contribute to the local availability of nutritious products. An estimated 20 million people are directly employed in aquaculture worldwide, mostly in Asia, while supporting industries and services contribute to 100 million jobs globally. Trade, meaningful employment, gender equity, increasing rural production (which further benefits rural schooling), diet and infrastructure can be included in human success metrics. Early evaluation of public health risks is fundamental within the principles of One Health. For example, whilst the perceived increased gross domestic product (GDP) gains from international trade have driven rapid growth in bivalve mollusc production since the 1950s, a systemic absence of mature legal frameworks, robust data on origin, prevalence and levels of putative human pathogens in aquatic systems, and scarce expertise at the food business operator or official services level have underestimated hazards and severely impacted value chains, limiting exports for many low- and middle-income countries[1].

Between 70 to 80% of production is undertaken by a "missing or squeezed middle" of commercial producers[27] who "enjoy none of the benefits of investments in biosecurity or pathogen control characteristic of intensive systems nor, the low input/low risk/low output typical of extensive systems"[28]. These producers are adopting practices such as commercial feed use, water and livestock treatments, but are also loosely tied to value chains, subject to little or no veterinary oversight and are weakly regulated by buyer and/or state organizations. Disease is a persistent threat — constituting an estimated US$6 billion loss per annum in the global industry[29] — meaning these producers will be key in improving health outcomes globally. Developing accreditation and consumer trust can be a challenge, particularly as production starts to shift from a bipolar South–North export model (with relatively well-developed buyer driver governance) to a trade pattern that is increasingly South–South with growing production for domestic markets[30]. Enhancing animal and environmental health requires a programme of engagement with producers to develop ownership of and compliance with ESP goals. The burden of risk and rewards is unevenly distributed within many aquaculture value chains, providing disincentives for innovative and sustainable practices — equitable value chains and rewards for sustainable production will be fundamental to achieve ESP. We outline five success metrics for the human health component of the One Health approach to aquaculture ESP in Table 1 and Fig. 2.

Organism health. Production occurs within complex ecological systems physically embedded within an environment differing from the farmed species' wild habitat. Farmed animals or plants interact with communities of viruses, bacteria, small eukaryotes, and other animals and plants within the aquaculture system. Microbes within the system include known and unknown pathogens with potential to cause infection and disease in farmed species. Crop-growing ponds are highly modified, 'artificial' ecosystems that can unintentionally create an environment for rapid pathogen propagation and epidemic disease outbreaks — and have been a source of many emergent diseases. For example, the incidentally discovered microsporidian *Enterocytozoon hepatopenaei* found at low levels in a pond in Thailand over 10 years ago is now one of the most widespread and impactful pathogens in shrimp aquaculture[31]. Thus, stock management must be considered in terms of health and disease

Table 1 | Success metrics for aquaculture ESP

One Health success metric (SM)	Abbreviation	Descriptor
People		
Nutritious and safe food	People SM1	The food produced from aquaculture and sub-sectors is nutritious, is an acknowledged contributor to a planetary sustainable diet[56] and is safe to consume, with negligible risk of exposure to harmful microbial and chemical contaminants by human consumers.
Equitable income generation	People SM2	The income generated from the whole industry and sub-sectors is shared equitably across the stakeholder web, economic risks of production are considered and income contributes to employment and development of producer communities. Income generated within sector contributes directly to local poverty alleviation and wealth generation.
Gender equalization	People SM3	The whole industry and sub-sectors contribute demonstrably to improving opportunities for women, not only in terms of income generation and wealth sharing but also in access to high-quality foods and other opportunities.
Quality employment	People SM4	The whole industry and sub-sectors contribute to enhanced employment opportunities in direct food production and in subsidiary sectors. Employment is safe, meaningful and high quality. A sustainable production (and consumption, waste) ethic is built into jobs across the whole industry, sub-sectors and its subsidiaries.
Knowledge and skills generation	People SM5	Technical knowledge and skills generation relating to the whole industry and sub-sectors are underpinned by continued professional development and the co-ownership of a sustainability narrative by workers throughout the food web.
Organism		
Healthy stock	Organism SM1	High health and welfare status of stock is promoted by controlling entry of pathogen and non-native species hazards, by deployment of stock management procedures (for example, genetics, stocking and feed strategies) and promoting environmental conditions conducive to low disease susceptibility in farmed stock.
Minimal chemical hazards	Organism SM2	Farm management procedures that involve chemical and physical treatments are carried out to impart minimal (zero) disruption on the surrounding environment and native biodiversity. Measures are in place to minimize antimicrobial usage in the farm environment and to negate the negative impacts of antimicrobial spillover to the surrounding environment, wildlife and humans.
Biosecure farms	Organism SM3	High health status of wildlife is promoted by negating the risks of pathogen and non-native species spillover from the farm to the surrounding environment. Trade of live animals and their products takes account of animal welfare, risk of pathogen and non-native species transfer via these movements. Biosecurity protocols followed at farm, catchment and national levels complement those in place to control cross-boundary risks of transfer via trade.
Safe farms	Organism SM4	Potential for the transfer of zoonotic and environmental pathogens from stock to humans is negated (including potential for transfer of AMR). The stock produced on farms should be safe to handle and to eat.
Optimized farm systems	Organism SM5	Farms are stocked with species appropriate to the conditions in which they are being produced and consider their origin in the context of surrounding biodiversity. The genetic structure of stocks being farmed is known and taken into account relative to potential genetic spillover to native wildlife. Mixed species and multitrophic systems should be considered where suitable, in attempt to optimize farm systems.
Environment		
Optimal water usage	Environment SM1	Freshwater resources are used efficiently to optimally reduce any detrimental effects to the functioning and productivity of natural aquatic systems, balancing use of water for aquaculture with the benefits of freshwater supply for other human needs.
Optimal water quality	Environment SM2	Minimize (or avoid) discharges of animal pathogens, chemicals, antibiotics, excessive nutrients or other factors with potential to adversely impact the physicochemical environments on/around farms. Minimize potential for AMR carryover to biodiversity.
Protected biodiversity and natural capital	Environment SM3	Minimize (avoid) negative impact of aquaculture on natural biodiversity. To include the protection of natural (wild) genetic resources (including species grown in aquaculture settings in the context of their current and future economic and ecological benefits). Utilize aquaculture production to boost natural capital in surrounding environments.
Low-energy production	Environment SM4	Aquaculture systems designed to be energy efficient with a low or negative carbon cost relative to other food production systems. To include full consideration of energy costs associated with production, feed inputs, operational engineering, and transport of aquaculture products for human consumption.
Low spatial footprint	Environment SM5	Spatial footprint of aquaculture production systems is minimized relative to yield, relative to other food production systems. Location of aquaculture systems promotes enhanced biodiversity and natural resource productivity (for example, mangroves) while protecting areas of cultural and heritage importance, or areas of natural beauty.

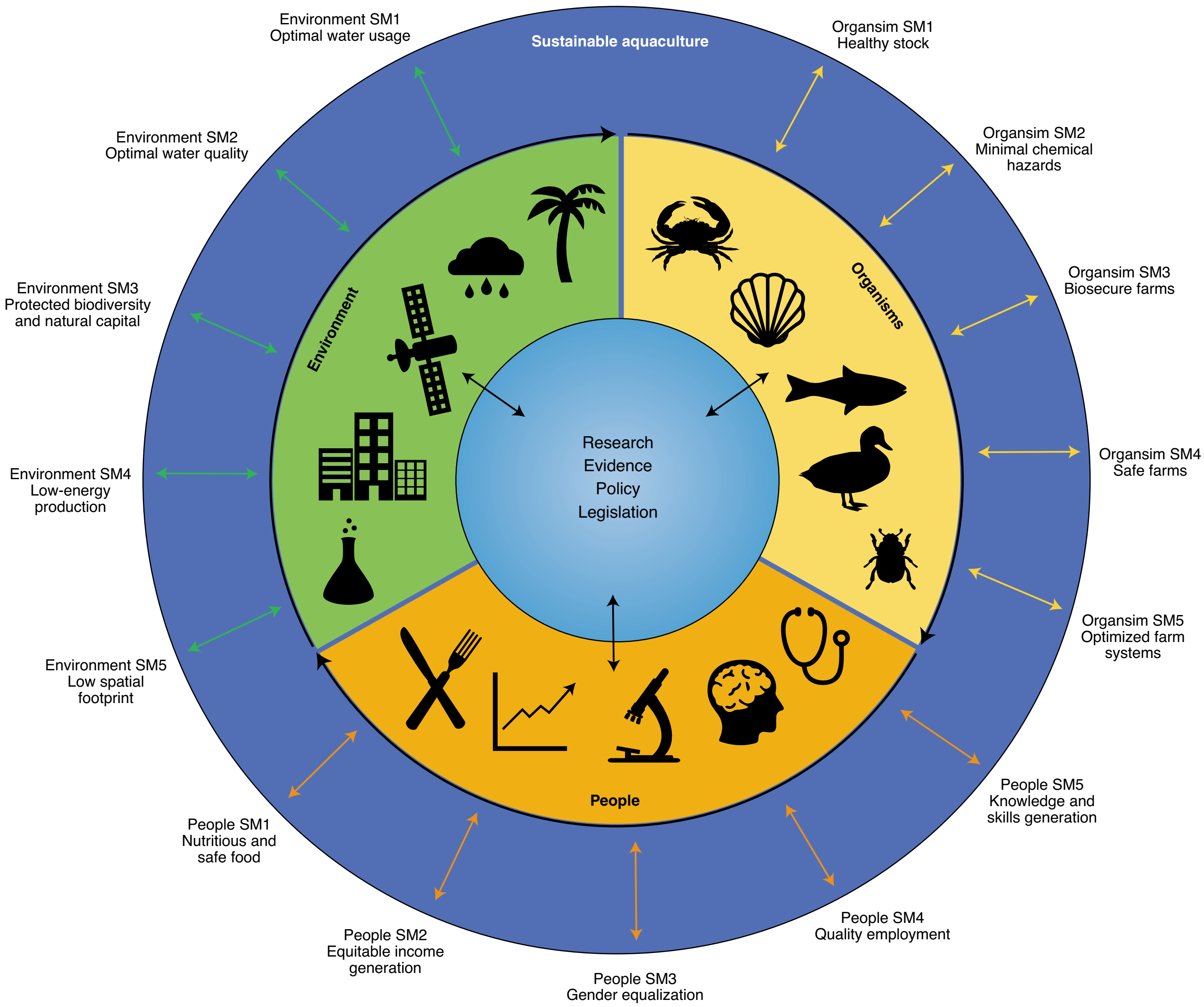

Fig. 2 | One Health success metrics for sustainable aquaculture. A One Health approach (Fig. 1) to the design and assessment of ESP in aquaculture and related sub-sectors requires success metrics (SMs) spanning environment, organism and human health. Descriptors for SMs (Table 1) are applied to hypothetical sub-sectors of the aquaculture industry in Fig. 3.

manifestation, zoonoses, biosecurity, genetics, and treatments' or interventions' impact on the local environment.

Creating growing conditions conducive to high stock health and welfare is critical for aquaculture ESP — perhaps the most important barrier to development of the industry to 2050[29]. Profiling microbial hazards, even in a preventative manner, utilizing emergent technologies such as high-throughput sequencing of water, sediment, feed and host tissues is increasingly an option[32]. These technologies can also identify broad biosecurity risks that aquaculture farms pose to the surrounding environment. Preventing pathogen spillover to the environment and wildlife, and vice versa, is a critical measure that must be built into aquaculture systems.

Aquaculture feeds alter the ecology of aquaculture systems and can introduce other compounds such as antimicrobial residues (AMR), which can potentially influence stock health and the physicochemical properties of the system. Feeds range from natural pond fertilizers to formulaic feeds for enhancing stock performance. Pharmaceuticals, liming or sterilization between cropping cycles, and biocides can create favourable conditions for disease development by eutrophication, leading to hypoxic stress, or by environmental dysbiosis, whereby disease agents may be preferentially selected and become pathogenic for resident hosts[33]. Chemical spillover into the surrounding environment, to other farmed stock, wildlife and humans via zoonotic diseases and AMR must be prevented in future One Health design of aquaculture systems. AMR genetic elements within aquaculture systems is of great concern largely due to the intensive and often inappropriate use of antibiotics to treat disease. While some aquaculture sub-sectors, such as Norwegian salmon, are exemplars of antibiotic use reduction, other sub-sectors require substantial improvement[34].

The choice of farmed species can be determined by their capacity for their maintenance with minimal ecological modification to the farm environment and a low potential to impact the surrounding environment. While the benefits of sourcing seed stock from natural environments may encourage propensity for disease in captive settings[29], conversely, the use of specific-pathogen-free stock may not always be an appropriate choice, particularly when animals are stocked into open systems in which a native microbial community may rapidly exploit microbiologically naive hosts[35]. Genetic structuring at farm population level must aim to reduce

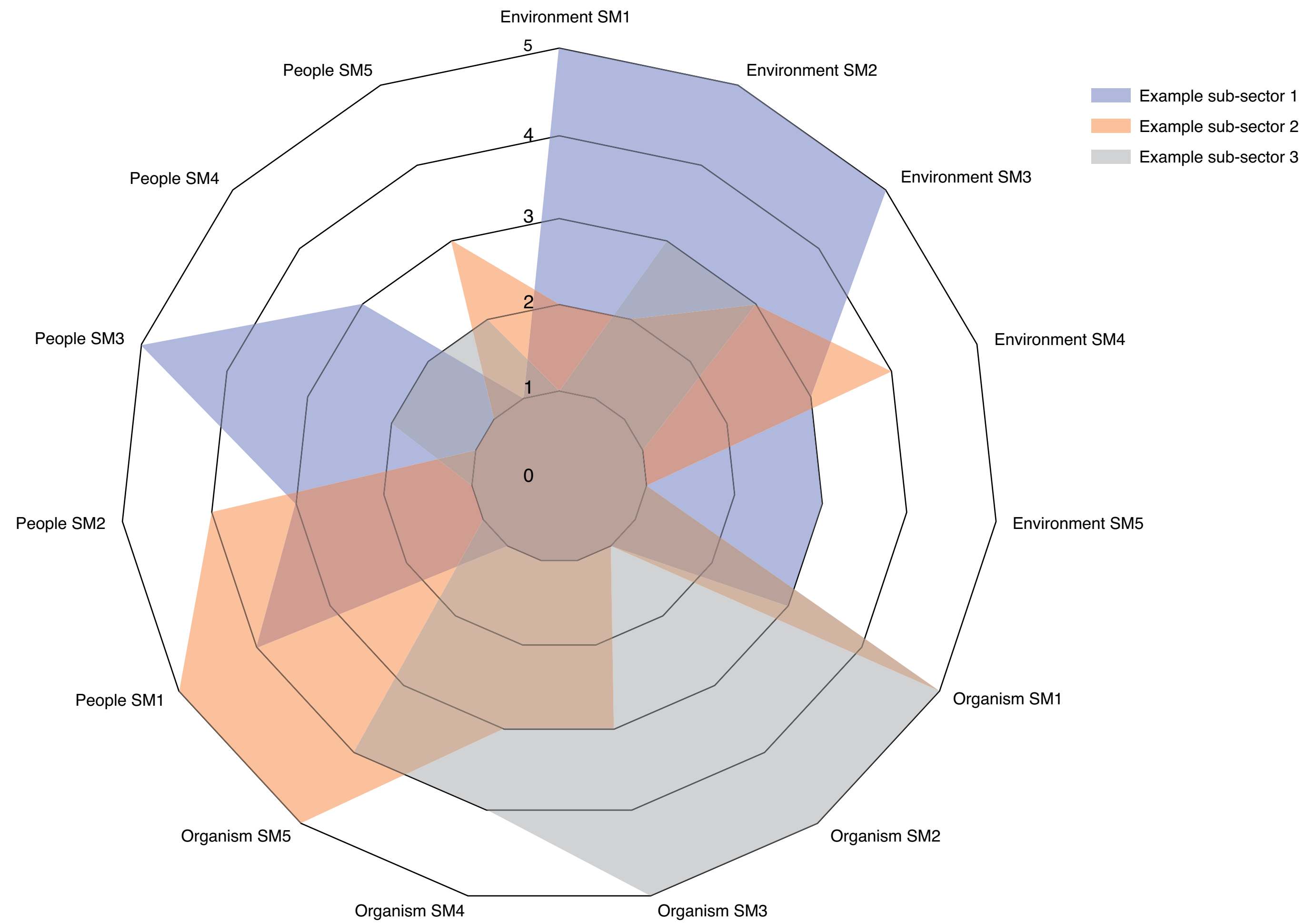

Fig. 3 | Application of One Health success metrics to aquaculture and related sub-sectors. Demonstrable fulfilment of success metrics (SMs) takes account of research and evidence available on which to base policy and legislation, and how consistently that policy and legislation is applied. When specific SMs are being consistently fulfilled but others are performing poorly, research, evidence and policy design can be altered to support and improve poorly performing metrics. Specific SMs for environment, people and organisms are provided in Table 1 and illustrated in Fig. 2. Key to scale: (1) no research, evidence, policy, or legislation is in place to allow delivery of SM; (2) basic research outputs are available but have not been applied to policy formation and legislation to allow delivery of SM consistently; (3) applied research has been conducted and used for policy formation and legislation to deliver SM, but not yet applied; (4) policy and legislation is in place, is continually refined by further research and evidence but SM has not been consistently achieved; (5) policy and legislation is in place and applied consistently, research and evidence contribute to further refinement, or SM being consistently achieved.

the likelihood of disease epidemics and create resilience to challenges encountered within and between cropping cycles. Mixed species or multitrophic culture systems can be considered for managing health of other stock, minimizing environmental impact and may be more ecologically stable and resilient than monocultures[36]. Introducing non-native, invasive species to the local environment should be avoided to prevent the risk of hybridization and genetic introgression with native species, and the introduction of pathogen spillover[37].

Close attention to national and transboundary spread of hazards — particularly via trade — must extend beyond live animals and include the risk of distributing pathogens via end-products, even those destined directly for human consumption that would not normally interact further with the environment[38]. The organism health component of the One Health approach is outlined by five broad success metrics in Table 1 and Fig. 2.

Environmental health. Sixty-three per cent of aquaculture occurs in fresh waters, with 29% in marine and 8% in brackish habitats[39] — relatively similar projections are expected in future production (Supplementary Section 1). Aquaculture ESP is constrained by the amount and quality of freshwater available. Inland aquaculture globally withdraws around 429 km^3 freshwater per year, representing 3.6% of Earth's surface flowing water[40]. Future freshwater demands must be balanced against other needs, including for land-based agriculture that currently uses 70% of the readily accessible supply[40]. The IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* indicated that climate change will result in warming seas and the expansions of hypoxic zones, affecting where marine aquaculture may operate and which species can be farmed[41]. Climate models indicate many tropical regions of the world — where most aquaculture takes place — will become hotter and drier, which is likely to limit available freshwater supply and influence which species can farmed in those environments[42]. In contrast, temperate regions may be expected to become warmer and wetter, potentially opening new aquaculture development opportunities. Up to 60% of water withdrawn for inland aquaculture could be re-used with adequate pollution control measures for purification of effluents, re-use of nutrients and control of percolation losses[39]. Highest production to 2030 and beyond will occur in freshwater systems in Asia[1]. Sustainable management of pollution and effluent discharge is essential; special attention must be given to sub-regions where little or no freshwater operational control measures exist. Freshwater ecosystems are especially vulnerable to biodiversity impacts — 35% of freshwater fish are classified as vulnerable or threatened[43], which are vital for providing feed, broodstock, seed (eggs/larvae/fry) and genetic resources for many farmed species.

Although all aquaculture animals are ectotherms, some forms of aquaculture currently operate with a relatively high carbon footprint. For example, shrimp produced on land formerly occupied by mangroves has a carbon footprint of 1,603 kg CO_2 per kg of shrimp produced — a figure similar to the production of beef (1,440 kg CO_2; ref. [16]). Feed inputs are a major environmental and economic cost for many species in aquaculture — an estimated 15.6 million tonnes of wild fish harvested globally is used in the production of fish meal and fish oils (FMFO), almost half of which is used in aquaculture feed[44]. Alternative feeds, including those based on insect, plant or algal proteins, show promise[45], but are yet to offer consistent replacement of FMFO-based feeds. The comparative efficiency at converting protein and energy from feed sources and toleration of species such as carp and tilapia to challenging physicochemical environments have led to significant expansion in the global production of these species[1], demonstrating their potential for future aquaculture ESP. Similarly, extractive, non-fed species such as filter-feeding bivalves, algal grazers, detritivores and autotrophic plants (mainly macroalgae) are considered some of the lowest impact aquaculture organisms (Supplementary Section 1). Culture platforms for seaweeds and bivalves can simultaneously act as nurseries for native biodiversity and boost productivity of wild fisheries, while helping to control nutrient and microbial levels in the water column[8]. Alternatively, the contained nature of onshore recirculating aquaculture systems hold potential for greater environmental control, better biosecurity and a smaller environmental footprint in terms of land space and water use compared with open systems, particularly when aligned with terrestrial food and energy systems[46].

Land-space allocation for future aquaculture must take into account the impacts on biodiversity and natural resource productivity. Globally, approximately 8.7 million hectares is used for freshwater aquaculture production and a further 2.3 million hectares for brackish water production[39]. Future inland aquaculture will likely compete for space with terrestrial agriculture, which occupies more than one-third — or 5 billion hectares — of the Earth's surface[47]. Open oceans provide ample space but offshore systems present considerable operational challenges more suited to larger industry operations. Nevertheless, current US seafood consumption could be met by extending offshore marine aquaculture into less than 1% of exclusive economic zones belonging to coastal states[48]. Lessons must be learned from the detrimental environmental effects of mangrove removal for shrimp aquaculture — countries such as Bangladesh have destroyed nursery grounds for important commercial wild fisheries and rendered large tracks of land unsuitable for agriculture due to the resulting saltwater intrusion[49]. Finally, aquaculture ESP must consider areas of cultural and (inter)national heritage importance and must not impose on areas of outstanding natural beauty. The environment component of the One Health approach to aquaculture ESP is outlined in five metrics in Table 1 and Fig. 2.

Interactions between success metrics. The success metrics presented here comprise a research, evidence, policy and legislative package that can guide governing bodies' aquatic food strategies. Importantly, aquaculture production must not be considered in isolation but rather as a food system with intricate linkages to wild-capture fisheries and terrestrial agriculture systems[9]. Individual metrics will benefit aquaculture ESP, but it is the interactions and dependencies between individual metrics that may have the greatest capacity to elicit positive change. Conversely, interactions may elicit unforeseen negative feedback loops, which must be guarded against. Such examples include the metrics organism SM2, organism SM3 and organism SM4 (Table 1 and Fig. 2): policy and legislation promoting farm biosecurity can reduce chemical, AMR and zoonotic hazards from entering the environment. The metrics environment SM3, environment SM5 and people SM4 (Table 1 and Fig. 2) interact where lowering the spatial footprint of aquaculture has positive impacts on protecting biodiversity, optimizing water quality and providing people with quality employment. However, if a metric is perceived as requiring excessive regulation, counterproductive actions may be taken by stakeholders to evade the metric, thereby negating its intended impact.

Future directions

The One Health approach captures detailed aspects of the ecosystem aquaculture approach[50] and broader targets from the United Nations Sustainable Development Goals[51]. The extension of the One Health approach beyond zoonotic diseases — to address grand societal challenges such as food security — was proposed in programmes such as the Network for Evaluation of One Health (Supplementary Section 2). Our approach enables national policies to collectively contribute to aquaculture ESP.

Data collection for monitoring success metrics will require interaction across government departments and a broad range of aquaculture stakeholders. Accountability must extend beyond national borders, particularly where high-income countries obtain food from medium- to low-income and/or less stable regions at the cost of those ecosystems and people[52]. Given seafood is one of the most traded commodities[53], the unaccounted burdens of international, unsustainable socio-ecological practices require attention within the aquaculture sector — and seafood in general. Success metric achievement at national levels, coupled with international cooperation, forms the cornerstone of widespread One Health adoption.

Aquaculture can mitigate the negative consequences associated with land-based food production systems — particularly where land- and water-based systems are integrated — to protect terrestrial habitats from the impact associated with some current farming systems[54,55]. The One Health principles will facilitate increasing production of aquaculture species with efficient food production and sustainable environmental footprints — while supporting local socio-economic needs. If put into practice, the success metrics presented here will serve as an example for the design and assessment of not just aquaculture, but whole food systems.

Received: 3 January 2020; Accepted: 7 July 2020;
Published online: 3 August 2020

References

1. FAO *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals* (Food and Agriculture Organization of the UN, 2018).
2. FAO *Fishery and Aquaculture Statistics Yearbook 2016* (Food and Agriculture Organization of the UN, 2016).
3. Stead, S. M. Using systems thinking and open innovation to strengthen aquaculture policy for the United Nations Sustainable Development Goals. *J. Fish Biol.* **94**, 837–844 (2018).
4. Berry, E. M., Dernini, S., Burlingame, B., Meybeck, A. & Conforti, P. Food security and sustainability: can one exist without the other? *Publ. Health Nutr.* **18**, 2293–2302 (2014).
5. De Silva, S. S. & Davy, F. B. (eds) in *Success Stories in Asian Aquaculture* https://doi.org/10.1007/978-90-481-3087-0_1 (Springer, 2010).
6. Midtlyng, P. J., Grave, K. & Horsberg, T. E. What has been done to minimize the use of antibacterial and antiparasitic drugs in Norwegian aquaculture? *Aquacult. Res.* **42**, 28–34 (2011).
7. Carboni, S. et al. Mussel consumption as a "food first" approach to improve omega-3 status. *Nutrients* **11**, 1381 (2019).

8. Gentry, R. R. et al. Exploring the potential for marine aquaculture to contribute to ecosystem services. *Rev. Aquacult.* **12**, 499–512 (2019).
9. Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T. & Walsworth, T. E. The environmental cost of animal source foods. *Front. Ecol. Environ.* **16**, 329–335 (2018).
10. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
11. Jennings, S. Aquatic food security: trends, challenges and solutions for a single nation embedded in a dynamic global web of producers, processors and markets. *Fish Fisher.* **17**, 893–938 (2016).
12. Lester, S. E., Gentry, R. R., Kappel, C. V., White, C. & Gaines, S. D. Offshore aquaculture in the United States: untapped potential in need of smart policy. *Proc. Natl Acad. Sci. USA* **115**, 7162–7165 (2018).
13. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl Acad. Sci. USA* **115**, 5295–5300 (2018).
14. de Graaf, G. & Xuan, T. Extensive shrimp farming, mangrove clearance and marine fisheries in the southern provinces of Vietnam. *Mangroves Salt Marshes* **2**, 159–166 (1998).
15. Nakamura, K. et al. Seeing slavery in seafood supply chains. *Sci. Adv.* **4**, e1701833 (2018).
16. Kauffman, J. B. et al. The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. *Front. Ecol. Environ.* **15**, 183–188 (2017).
17. Henriksson, P. J. G., Järviö, N., Jonell, M., Guinée, J. B. & Troell, M. The devil is in the details—the carbon footprint of a shrimp. *Front. Ecol. Environ.* **16**, 10–11 (2018).
18. Price, M. H. H. et al. Sea louse infection of juvenile sockeye salmon in relation to marine salmon farms on Canada's west coast. *PLoS ONE* **6**, e16851 (2011).
19. Crego-Prieto, V. et al. Aquaculture and the spread of introduced mussel genes in British Columbia. *Biol. Invasions* **17**, 2011–2026 (2015).
20. Sugiura, S. H. Phosphorus, aquaculture, and the environment. *Rev. Fish. Sci. Aquacult.* **26**, 515–521 (2018).
21. Higuera-Llantén, S. et al. Extended antibiotic treatment in salmon farms select multiresistant gut bacteria with a high prevalence of antibiotic resistance genes. *PLoS ONE* **13**, e0203641 (2018).
22. Ceballos, A., Dresdner-Cid, J. D. & Quiroga-Suazo, M. A. Does the location of salmon farms contribute to the reduction of poverty in remote coastal areas? An impact assessment using a Chilean case study. *Food Policy* **75**, 68–79 (2018).
23. Vince, J. & Haward, M. Hybrid governance in aquaculture: certification schemes and third party accreditation. *Aquaculture* **507**, 322–328 (2019).
24. Toufique, K. A. & Belton, B. Is aquaculture pro-poor? Empirical evidence of impacts on fish consumption in Bangladesh. *World Dev.* **64**, 609–620 (2014).
25. Toufique, K. A., Farook, S. & Belton, B. Managing fisheries for food security: implications from demand analysis. *Mar. Resour. Econ.* **33**, 61–85 (2018).
26. GBD 2017 Diet Collaborators. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **393**, 1958–1972 (2019).
27. Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L. & Chookolingo, B. How much of the world's food do smallholders produce? *Glob. Food Sec.* **17**, 64–72 (2018).
28. Little, D. C. et al. Sustainable intensification of aquaculture value chains between Asia and Europe: a framework for understanding impacts and challenges. *Aquaculture* **493**, 338–354 (2018).
29. Stentiford, G. D. et al. New paradigms to solve the global aquaculture disease crisis. *PLoS Path.* **13**, e1006160 (2017).
30. Belton, B., Bush, S. R. & Little, D. C. Not just for the wealthy: rethinking farmed fish consumption in the Global South. *Glob. Food Sec.* **16**, 85–92 (2018).
31. Stentiford, G. D., Bass, D. & Williams, B. A. P. Ultimate opportunists—the emergent *Enterocytozoon* group microsporidia. *PLoS Path.* **15**, e1007668 (2019).
32. Bass, D., Stentiford, G. D., Wang, H.-C., Koskella, B. & Tyler, C. The pathobiome in animal and plant diseases. *Trends Ecol. Evol.* **34**, 996–1008 (2019).
33. Egan, S. & Gardiner, M. Microbial dysbiosis: rethinking disease in marine ecosystems. *Front. Microbiol.* **7**, 991 (2016).
34. Henriksson, P. J. G. et al. Unpacking factors influencing antimicrobial use in global aquaculture and their implication for management: a review from a systems perspective. *Sustain. Sci.* **13**, 1105–1120 (2018).
35. Alday-Sanz, V. et al. Facts, truths and myths about SPF shrimp in Aquaculture. *Rev. Aquacult.* **12**, 76–84 (2020).
36. Ying, C. et al. The effects of marine farm-scale sequentially integrated multi-trophic aquaculture systems on microbial community composition, prevalence of sulfonamide-resistant bacteria and sulfonamide resistance gene *sul1*. *Sci. Total Environ.* **643**, 681–691 (2018).
37. Peeler, E. J. & Taylor, N. G. The application of epidemiology in aquatic animal health—opportunities and challenges. *Vet. Res.* **42**, 94 (2011).
38. Oidtmann, B. & Stentiford, G. D. White spot syndrome virus (WSSV) concentrations in crustacean tissues—a review of data relevant to assess the risk associated with commodity trade. *Transbound. Emerg. Dis.* **58**, 469–482 (2011).
39. Ottingera, M., Claussa, K. & Kuenzerb, C. Aquaculture: relevance, distribution, impacts and spatial assessments—a review. *Ocean Coast. Managem.* **119**, 244–266 (2016).
40. Verdegem, M. C. L. & Bosma, R. H. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. *Water Policy* **11**, 52–68 (2009).
41. IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H.-O. et al.) https://www.ipcc.ch/srocc/home/ (in the press).
42. Fu, R. Global warming-accelerated drying in the tropics. *Proc. Natl Acad. Sci. USA* **24**, 3593–3594 (2015).
43. Grooten, M. & Almond, R. E. A. (eds) *Living Planet Report 2018: Aiming Higher* (WWF, 2018).
44. Halpern, B. J. et al. Putting all foods on the same table: achieving sustainable food systems requires full accounting. *Proc. Natl Acad. Sci. USA* **116**, 18152–18156 (2019).
45. Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M. & Froehlich, H. E. Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nat. Food* **1**, 301–308 (2020).
46. Badiola, M., Mendiola, D. & Bostock, J. Recirculating Aquaculture Systems (RAS) analysis: main issues on management and future challenges. *Aquacult. Eng.* **51**, 26–35 (2012).
47. Ramankutty, N. et al. Trends in global agricultural land use: implications for environmental health and food security. *Annu. Rev. Plant Biol.* **69**, 789–815 (2018).
48. Gentry, R. R. et al. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **1**, 1317–1324 (2017).
49. Hossain, M. & Hasan, M. R. *An Assessment of Impacts from Shrimp Aquaculture in Bangladesh and Prospects for Improvement* http://www.fao.org/3/a-i8064e.pdf (Food and Agriculture Organization of the UN, 2017).
50. Brugère, C., Aguilar-Manjarrez, J., Beveridge, M. C. M. & Soto, D. The ecosy stem approach to aquaculture 10 years on—a critical review and consideration of its future role in blue growth. *Rev. Aquacult.* **11**, 493–514 (2019).
51. Hambrey, J. *The 2030 Agenda and the Sustainable Development Goals: The Challenge for Aquaculture Development and Management* (Food and Agriculture Organization of the UN, 2017).
52. Hicks, C. C. et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–96 (2019).
53. Gephart, J. A. & Pace, M. L Structure and evolution of the global seafood trade network. *Environ. Res. Lett.* **10**, 125014 (2015).
54. Lamb, A. et al. The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nat. Clim. Change* **6**, 488–492 (2016).
55. Pretty, J. et al. Policy challenges and priorities for internalizing the externalities of modern agriculture. *J. Environ. Plan. Manag.* **44**, 263–283 (2001).
56. Willett, W. et al. Food in the Anthropocene: the EAT–*Lancet* Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).

Acknowledgements
We acknowledge the Centre for Sustainable Aquaculture Futures (a collaboration between the Centre for Environment, Fisheries and Aquaculture Science and the University of Exeter) for funding under contract Cefas Seedcorn contract no. SP003 to host a workshop 'Sustainable Aquaculture through the One Health Lens' at the Department for Environment, Food and Rural Affairs (Defra) London, on 1 July 2019. The input to that workshop by colleagues from across Defra provided significant guidance for the material contained within this article.

Author contributions
G.D.S. conceptualized the manuscript and led the development of the text, I.J.B., S.J.H., D.B., R.H., E.M.S., M.J.D., S.W.F., N.G.H.T., D.W.V.-J., R.v.A., E.J.P., W.A.H., L.S., R.B., I.K. and C.R.T. attended and presented at the 'Sustainable Aquaculture through the One Health lens' workshop in London on 1 July 2019 and wrote elements of this manuscript. D.C.B. and H.E.F. wrote elements of the manuscript and were involved with wide-ranging discussions on integration of One Health principles within aquaculture and sustainable food system design.

Competing interests
The authors declare no competing interests

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s43016-020-0127-5.

Correspondence should be addressed to G.D.S.