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Global yield from aquaculture systems

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ABSTRACT

Aquaculture is expected to expand significantly in the coming decades to meet growing demand. A key variable for understanding the potential benefit of and impact from this growth is efficiency, yet a comprehensive assessment of on-farm area use and yield is limited. Much like land-based agriculture, range and variation in yields across space, species, and practice provide insights into area use and production efficiencies. Current estimates of aquaculture yields (production per area per time) aggregate on-farm and off-farm land use into one 'land use' category; in contrast, we disaggregate this category to provide on-farm yield estimates and account for water area use. We use a quantitative review of scientific literature to synthesize and compare on-farm area use and yield patterns across countries, taxa, aquatic systems, data source, and production mode (n=378). Because recirculating aquaculture systems (RAS) have been touted as a particularly efficient production mode, we also found estimates for RAS from industry (n=4). Median, mean, and range in yields among countries and taxa vary by orders of magnitude, with algal production greatly exceeding that of crustaceans, fishes, and molluscs. Yields in marine systems were on average roughly 5x greater than yields in freshwater systems. RAS had particularly high yields but sparse data and estimates from private corporations were approximately 3.7x higher than literature estimates on average. This comprehensive assessment of global aquaculture yields offers critical insight into the production efficiencies of different aquaculture forms and the large amount of variability, which could help guide aquaculture policy and practice.

KEY WORDS: yield, area use, global patterns, mariculture, efficiency

1. Introduction

Approximately 40% of habitable land has been transformed for food production[1], with additional conversion expected in the future to support a growing population. This transformation of natural terrestrial ecosystems has resulted in loss of species diversity and habitats[2], freshwater scarcity[2–4], pollution[5,6], and greenhouse gas emissions[7]. The magnitude of these impacts is related to production volume, efficiency, and production type. While we have a robust understanding of land use requirements and efficiencies for production of staple crops[8], land animals[9] and animal feed[10], we have a more limited understanding of aquaculture yields. This gap is significant considering aquaculture provides ca. 9% of total animal production for human consumption globally, and significantly more for many countries[11]. Further, the industry is the fastest growing global food sector, and is expected to grow an additional 15% by 2030[11]. To understand how food production is affecting landscapes and seascapes, we need better estimates of the range and variability of aquaculture yields—the amount of food produced per area per unit time.

Life cycle assessments (LCAs) are often used to compare yields across foods, production modes, and geographies; while useful and appropriate in many cases, LCAs can obscure important sources of variation. Food LCAs estimate environmental pressures such as land, nutrient, water, and energy requirements by collapsing multiple subcategories into larger categories to allow comparison[7,12,13]. For example, on- and off-farm area requirements are typically aggregated into a general 'land use' category to allow comparison across farming practices. 'On-farm' or 'farm-to-gate' typically refers to the extent of land needed to physically grow the animal or crop, while 'off-farm' typically represents other external land use, typically related to land-based feed crops that are usually not co-located with animal or crop production. Indeed, intensive and extensive farming practices represent a trade-off between more on-farm use versus more off-farm use, and farms can lie anywhere along this continuum[14,15]. Additionally, 'land use' is not the same as 'area use'-- in many cases, water area used for aquaculture is excluded from 'land use'-- however, this is still a use of space that must be accounted for to understand yields in aquaculture. Thus, disaggregating multiple types of area (land and water, on- and off-farm) allows a deeper understanding of the environmental costs of food production. While there have been recent efforts to quantify the environmental impacts of blue food production—foods produced in aquatic environments—existing yield estimates aggregate on- and off-farm land use and do not account for on-farm water area use, and there is a need for better estimates of on-farm area use to quantify sources and magnitude of variation in yields.

A significant barrier to a comprehensive assessment of yields in aquaculture is the relative nascent nature of the industry and resultant paucity of comprehensive data across locations, taxa, environment, and production mode, all of which likely influence yield[6,7,12,13,13,16,17]. For instance, recirculating aquaculture systems (RAS) are on the extreme end of the intensive-extensive farming spectrum, and can have extraordinarily high yields per unit area, but are typically highly controlled, costly, and emissive[18,19]. On the other extreme, large enclosed bodies of water that utilize natural ecosystems like pond aquaculture is a particularly extensive form, requiring minimal intervention and no feed, and has been practiced for thousands of years[20]. Additionally, there are key differences in production in freshwater compared to marine environments for finfish that could lead to differences in yield. For example, the infrastructure requirements can be higher for finfish and crustacean marine production compared to some inland freshwater aquaculture due to high energy environments and the requirement for artificial containment structures, which generally make intensive production modes more common for marine finfish and crustacean aquaculture and thus increase yields. In addition to broad divisions between intensive/fed and extensive/unfed production systems, there is also substantial variation in general production strategy used by farmers. For example, farmers that grow rice simultaneously with crustaceans (e.g., crayfish in the United States[21] and shrimp in China[22]) need to optimize production across both foods, which could reduce yield; in contrast, monoculture production only needs to optimize production of a single species. These hypotheses, while reasonable, remain broadly untested due to data scarcity.

2. Methods

Here, we compile the first comprehensive dataset of on-farm area use and yield for aquaculture. We systematically reviewed the literature to compile and assess the most comprehensive dataset of on-farm aquaculture yield estimates across different taxa (finfish, crustacea, mollusc and algae), countries, environments (freshwater and marine), data source (farm, experiment, country, and/or region), and production mode (on or off bottom, ponds, conservation, crop rotation, lakes, cages, pens, or nets, and RAS or tanks). To standardize yield estimates, we converted all yields to tonnes produced per hectare per year; area could include both land and water area used, depending on what was reported by the source. We also compared edible yield, grams of protein, and calories by using conversion factors available in the literature (see Supplement of [13]); this conversion comparison excludes seaweeds because seaweeds are used for both food and bioproducts, requiring very different degrees of processing and refinement and are less robust. Additionally, we compared our yield values for RAS systems to those made publicly available by private corporations to broaden our limited data on this production mode and highlight potential differences between the scientific literature and industry.

To systematically review the literature, we used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol[23]. We used Web of Science to search the literature using key terms and boolean logic [(aquaculture OR mariculture) AND (production OR yield) AND (tonnes OR tons OR volume) AND (area OR hectare* OR acre* OR kilometer*)] on March 25, 2023; our search was not constrained to a subset of years. Of note, our search only returned results in English, which may inherently bias and limit our findings, particularly given many major producers are non-English speaking countries.

We compared yield estimates from RAS systems from our dataset to data made publicly available by the aquaculture companies Samherji, Sashimi Royal, and Blue Sapphire because 1) RAS has been identified as a particularly high-yield production system and 2) we were only able to identify limited estimates in the literature. We identified these companies with the Google search “aquaculture recirculating system RAS yield” and these were the only companies for which we could find publicly available estimates. Corporate data are not peer reviewed or validated, so these estimates were used for the cross-system comparisons but excluded from overall results out of concern they may not be representative.

To better understand the factors that influence on-farm yield, we compared estimates across a variety of factors; of note, data limitations preclude analysis with fully crossed, interactive effects among factors. Additionally, we assessed the relationship between year and yield to determine if efficiency changed over time. When sample size was sufficient, we used rank ANOVAs to compare yield estimates. In many cases, replication was too low and sample sizes were too variable to allow for formal statistical analyses. All figures are presented with a log y-axis (yield) to improve readability. All analyses were performed and all figures were constructed in R 4.1.2. Box-and-whisker plots were constructed with the *ggplot* function in the *ggplot2* package while ANOVAs were performed in base R.

3. Results

We found 414 studies, all of which were screened for eligibility. Studies were excluded if they 1) did not report yield data in units that could be converted to mt/ha/year (n=329), 2) were book chapters or conference abstracts (n=31), or 3) were inaccessible or not reported in English (n=9). If the authors reviewed aquaculture yields in their paper that were not included in our search, we included those values. We evaluated the distributions of yields and removed a single outlier (defined as an order of magnitude higher than the next highest yield and two orders of magnitude higher than mean yield across all estimates). We also removed 14 yield estimates from failed crops (yield=0). In total, we identified 45 studies which yielded a total of 378 estimates of yield.

Our dataset included values from 25 countries, with the number of estimates per country ranging from 1 to 184 (mean=15 per country across all taxa; Figure 1). Overall, we found the fewest estimates for mollusc yields (n=33), almost double the estimates for fish (n=64), triple for crustaceans (n=91), and the most estimates for algae yields (n=190). Overall, half the yield data came from China (n=184), four times the number from India (n=45), the country with the next highest number of estimates. Of the remaining countries, most, (n=20) had 10 or fewer estimates. Thus, our dataset was highly biased toward Asian countries (Figure 1). We assessed the relationship between yield and year to determine if efficiency increased over time, but found no pattern; thus, year was not included as a cofactor in any analysis (Figure S1).

Algae had the highest mean (18,395 mt/ha/year) and variation (SD= +/- 127,642 mt/ha/year), and yield estimates ranged from 0.28 to 1,400,000 mt/ha/year, from China and the Philippines respectively. Molluscs had the second highest mean yield (617 mt/ha/year) but much lower variability (SD = +/- 123 mt/ha/year); yield ranged from (0.0007 to 617 mt/ha/year in Japan and India, respectively). Fish mean yield was modest (34 mt/ha/year) with lower variation (SD= +/- 94 mt/ha/year; range 0.1 (Spain) to 525 (China) mt/ha/year). Finally, crustaceans had the second lowest mean yield (7 mt/ha/year) with the lowest variation (SD= +/-17 mt/ha/year; range 0.02 mt/ha/year to 120 mt/ha/year, in China and Singapore respectively).

Overall, edible tonnes, grams of protein, and calories produced annually per hectare were similar to each other and reflected overall yield patterns—e.g. relative mean, median, and range across taxa—though seaweeds were excluded from these metrics (Figure 1, 2). For brevity, we describe patterns for edible yield in detail, but patterns hold for grams of protein and calorie yields. For edible yield, median yields followed the same rank order as overall yields, where fish were the most productive (3.7 mt/ha/year) followed by crustacean (3.2 mt/ha/y) then molluscs (0.005 mt/ha/year) (Rank ANOVA; df=2, F-ration=37.59, p<0.0001; Figure 3a). Average edible yields showed a slightly different pattern, such that fish were the most productive (23.9 edible mt/ha/y) followed by molluscs (7.2 mt/ha/y) then crustaceans (6.4 mt/ha/y); differences in rankings between medians and means is driven by the high variability in mollusc yields.

Saltwater yields were consistently greater than freshwater (rank ANOVA, taxa and environment main effects $p<0.0001$, n.s. interaction; note, molluscs only had saltwater values and were excluded from statistical analysis) (Fig. 3). Algae estimates were heavily weighted toward saltwater (n=180) compared to freshwater (n=10); notably, mean yield estimates for saltwater algae were > 700x greater than freshwater. Crustacean estimates were also more common in saltwater systems, though to a lesser extent than algae (saltwater=58, freshwater =33). For crustaceans, saltwater mean estimates were ~20x higher compared to freshwater systems, while median estimates were approximately 50x higher. In contrast to algae and crustaceans, we found more estimates in freshwater (n=51) compared to saltwater (n=13) for fish. For fish, saltwater average and median estimates were 5x higher on average than freshwater.

We found variation in number of data source estimates (country, experiment, farm, region) across taxa (Table 1). Replication was uneven, precluding formal statistical analysis and severely constraining comparison and limiting conclusions. The most common type of estimates for algae were at the country level, which is the coarsest scale, while farm estimates were rare. For crustaceans, estimates were well distributed across country, region, and farms, but with limited experimental estimates. For fish, estimates were biased towards regional and farm level estimates, while for molluscs estimates were heavily weighted toward farm estimates. Of note, this imbalance in number of estimates may influence overall yield estimates across taxa; the taxa with the highest yield estimates, algae, were most heavily weighted by the coarsest data collection resolution, while the taxa with the lowest mean estimates, molluscs, was most heavily weighted by the finest data collection resolution.

The frequency of production mode varied across taxa, as did the yields; however, data scarcity precludes formal statistical analysis and comparison (Figure 4). Molluscs were only cultured with one production mode – on or off bottom – which is the fewest types of production modes of any taxa. Seaweeds were only cultured with two production modes: on or off bottom and ponds. In contrast, crustaceans and fishes were cultured with all six production modes. While data are sparse for fishes, RAS or tank systems generally had higher yields, followed by cages, pens or nets, then ponds, lakes, with crops, and in conservation wetlands, which follows the general pattern of increasing yield as production mode became more intensive. These patterns were similar, yet not as clear, for crustaceans, but had limited data.

We found four RAS yield estimates provided by three companies, with yields ranging from 363 to 2242 mt/ha/y. Atlantic Sapphire[24], a corporation based in Denmark, farms salmon (putatively *Salmo* salar) and reports yields of 2242 mt/ha/y (Atlantic Sapphire 2020), which is higher than any other estimate in our dataset. Another company in Denmark, Sashimi Royal[25], farming Yellowtail (putatively *Seriola quinqueradiata*), reported yields of 363 mt/ha/y. Finally, Samherji[26] is a company based in Iceland that farms Arctic char (putatively *Salvelinus alpinus*), and reports yields of 544 mt/ha/y and 479 mt/ha/y for two different facilities. There is no external validation of these values. These corporate estimates all exceed our mean estimate for fish yields in RAS or tanks of 242 mt/ha/y, though many corporate estimates are within our estimate range of 13 and 437 mt/ha/y.

4. Discussion

Better estimates of on-farm area requirements can improve our understanding of the range and variation in aquaculture production requirements, in particular as the sector expands to meet growing seafood demand. Here, we provide a systematic overview of yields—here, metric tonnes produced per hectare per year—collected from the literature to provide better estimates of on-farm area requirements and efficiencies of production. We found large variability in yield across taxa, aquatic system, data source, and production modes. This considerable variability indicates that as aquaculture expands, the on-farm area required could vary by several orders of magnitude; for example, with low on farm area for fish RAS farming and comparatively higher on farm area for unfed bivalves. These differences have important implications for understanding and assessing environmental impacts of food produced by aquaculture that should be further explored, as well as delineate the lower and upper ends for potential improvement. While the yield values are highly variable, they provide a better understanding for farmers and managers on what is feasible across the various forms of aquaculture, as well as aid in decision making of setting expectations and standards for improving aquaculture overall.

We found mariculture had higher yields than freshwater aquaculture, which adds to the growing evidence that mariculture expansion can help bridge the gap between production and consumption to feed the growing population. The higher yields from marine systems supports the growing call to consider expanding foods grown in the ocean to support broader sustainable food goals[10,13,27–29]. While our data are not resolved enough to identify why this pattern emerges, we suggest three possible drivers. First, marine taxa are often cash crops of high value with substantial infrastructure investment, both motivating and facilitating higher yields[29,30]. Second, marine farmed fishes may rely more on exogenous feed inputs to provide adequate nutrition compared to freshwater aquaculture (e.g. salmon versus carp), which can increase growth and condition of the fed species. Third, marine algae may outperform freshwater algae (*Spirulina*), due to a taxonomic focus on large brown seaweeds and rapidly growing reds (e.g., *Laminaria saccharina* and *Gracilaria spp*). Irrespective of the underlying mechanism for these differences between marine and freshwater aquaculture, our research adds to the growing evidence that sustainable aquaculture expansion, particularly in marine systems, has the potential to revolutionize the food production sector and help meet global food demands[6].

While some have suggested RAS systems could be a solution to producing significant amounts of aquatic food in the future[19,31], in part because of their relatively small on-farm land use, limited data are available to assess these assertions. In the scientific literature, we found only three estimates for RAS production, and estimates only included fishes, which purportedly produce vastly more seafood compared to fish production from all other fish production modes. The yield estimates made publicly available by private corporations were somewhat in line with the values in the literature, with estimates ranging from 363 to 2242 tonnes per hectare per year (n = 4). Although corporate estimates should be treated with caution because they are provided by the corporation itself and not independently verified, alignment with the literature is notable. While these values do indicate RAS could be a highly effective production mode, sample size and replication is extremely low, which challenges the certainty of such high outputs. Additionally, RAS systems are also more energy intensive and, in the absence of being part of a clean energy grid, emit significantly more greenhouse gas emissions compared to other farming modes[1,2]. Finally, commercial RAS may not be a sustainable business model; in the United States, nearly all US RAS attempts between 1991 to 2018, across 23 states, have failed[32]. Thus, more research on the viability and yield consistency of RAS systems is warranted, ideally through transparent and open partnerships and data access between scientists and industry.

Our estimates of yield are for on-farm area requirements only, and are thus fundamentally different from most other analyses of the footprint of food production, deepening our understanding of variation in aquaculture yields and highlighting the need to improve data collection and availability to informed decision making. Our estimates for fishes and crustaceans were consistently lower than those using LCA approaches, which is undoubtedly a result of those authors' inclusion of land use required for feed[7,12,13]. However, our estimates were higher for molluscs and seaweeds–for example, Gephart et al.[13] estimate no land use for molluscs or seaweed production–because those authors reasonably do not include water area use in on-farm land use estimates. Our dataset does match estimates derived from pairing estimates of farm area to national production statistics[33], likely because both of these approaches were constrained to on-farm area use for marine production. Thus, the explicit separation of on- vs off- farm use, provides a fuller picture of yields in aquaculture, but those data are not routinely collected or publicly available. Given the global nature of aquaculture production, and commodity production broadly, collection and publication of land use data will require intergovernmental cooperation, standardization, a centralized and digitized database, and supplementation with satellite data[17,33,34]. Better data are essential for understanding all components of area use, and will be key information for industry and policymakers as aquaculture continues to expand in the coming decades.

Our dataset is inherently unbalanced across regions, environment, data source, and production mode. However, there is the potential to build more robust datasets moving forward through collaborations and knowledge transfer across scales and organizations (e.g., industry and science) to increase our understanding of yields and potentially better meet both efficiency and sustainability goals. Overall, ~50% of our estimates came from China and 82% of our estimates come from Asia more broadly. This reflects global patterns of production, where Asian nations produce over 90% of aquaculture products by value, and China specifically produces the most aquaculture products by volume of any nation[11,35]. Thus, the weighting of our yield estimates toward a handful of countries should be explicitly considered if these yield estimates are applied to future area estimates for blue food production. Additionally, estimates across production mode ranged four orders of magnitude, yet were not comprehensive. Farm based estimates are likely the most robust, compared to estimates aggregated at the regional or country level, or estimates arising from experiments; however, farm-based estimates comprised less than 25% of the dataset, with substantial variability across taxa (e.g., one farm estimates for algae). Thus, we caution that application of these yield estimates be interpreted and applied with taxa, production mode, and country in mind.

There are large ranges of yield within and among taxa, and while we were able to disaggregate across environment (freshwater and marine), we were unable to disentangle the effects of country/region, species, or production mode due unbalanced reporting in the literature—all of which undoubtedly influence yield. We might expect variation across countries for a variety of reasons, including industry age[36] and environmental conditions[37]. Countries with a longer history of aquaculture, e.g., China, may reasonably have more advanced practices and technology[38] and thus higher yields. Further, different countries clearly have different environmental conditions and degrees of variability, though linkages to aquaculture production can be tenuous[39]. Additionally, we expect variation in yield across species. For example, within finfish aquaculture, the grow-out time can vary significantly, influencing yield in a given year; for example, grow out time for fast growing, yet inexpensive species like tilapia are short (5-8 months[40]), whereas the grow-out time for slow growing/maturing, yet high value species like sturgeon are long (7 years for caviar[41]). We also expect production mode to influence yield. For fed species (e.g., marine fish, shrimp), there are relationships between intensity of farming, density, and feed required[42]. However, for both fed and unfed species (e.g., bivalves, seaweeds), there are trade-offs between stocking density and disease risk[43], which will influence a farms yield, even within the same production mode. Thus, while we provide some foundational information for comparing yield across different facets of aquaculture, more information on farming practices and environmental conditions are needed to fully understand drivers of variability of on farm yield in aquaculture systems.

While there are current shifts to increase sustainability of aquaculture practices in China[44,45], we find no evidence for increased efficiency over time (see Supplement Figure S1); though this may be because this dataset does not have the resolution to detect changes in efficiency over time. Of note, the aquaculture industry, and particularly mariculture, is relatively nascent compared to terrestrial agriculture counterparts. Evidence from agriculture suggests yields, and efficiency generally, should increase over time with technological innovations and refined practices[38].

5. Conclusion

In the coming decades, feeding a growing population will demand more from our food production systems and put increasing pressure on social and natural systems. Increasing production of seafood has been identified as part of a sustainable solution to help meet future gaps between food production and demand[46–50]. In the seafood sector, meeting the production gap will mostly come from aquaculture development[13,27,46]. If well managed, aquaculture can potentially be more efficient and sustainable in terms of land required, greenhouse gas emissions, freshwater use, and nitrogen and phosphorus pollution[6,10,13,27,51]. Here, we advance our understanding of aquaculture production systems by providing the first systematic review of aquaculture on-farm yields across taxa, regions, environments, data source, and production modes.

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TABLES:

Table 1. Yield estimates by taxa (algae, crustacean, fish, mollusc) and data source (country, experiment, farm, region), including number of estimates, 25th (Q1), 50th (median), and 75th (Q3) quantiles, and means. — indicates no data available. Country data were aggregated data reported at the country level, experimental data typically come from scientific experiments (often to test new practices), farm data are individual holdings, and regional data describe a subsection of a country or a group of countries.

Taxa	Data Source	# estimates	Q1	median	Q3	mean
algae	country	146	68.8	158.7	226.2	157.0
	experiment	22	31.4	54.5	161.0	116.4
	farm	1	---	---	---	1,566.7
	region	12	29.1	35,500	281,250	260,837.1
crustacean	country	31	1.0	1.3	5.4	3.2
	experiment	4	4.4	4.5	4.5	4.4
	farm	30	1.4	5.9	12.8	12.1
	region	26	0.04	0.08	5.5	7.0
fish	country	2	4.0	7.8	11.6	7.8
	experiment	4	192.9	259.9	312.3	245.2
	farm	26	0.22	2.09	7.4	31.0
	region	32	4.4	7.0	16.8	11.6
mollusc	country	0	---	---	---	---
	experiment	0	---	---	---	---
	farm	29	0.0007	0.01	0.05	0.03
	region	4	195.1	271.5	368.8	292.4

FIGURE LEGENDS:

Fig. 1 Yield by taxa and country, presented as tonnes per hectare per year. Note, the axis has been log transformed. Points are individual estimates colored by taxa and arranged by country. Countries are ordered from the most to the fewest number of estimates. Solid lines indicate mean yields while dashed lines indicate median yields, colored by taxa.

Figure 2. Boxplots of edible yield, grams of protein, and calories produced per hectare annually for taxa by taxa boxplots of yield; all data are presented on a log axis. Median values are provided as the middle line while the 25th and 75th quartiles bound the lower and upper ends of the box. Open circles indicate mean estimates. Conversion factors were unavailable for algae as this is a nascent and variable production mode (e.g. food and additives).

Fig. 3 Yield (tonnes per hectare per year) by taxa and aquatic environment. Boxplots of yield (tonnes per hectare per year (log)) for the four broad taxonomic groups separated by farmed environment, freshwater (fw) versus saltwater (sw) or marine. Median values are provided as the middle line while the 25th and 75th quartiles bound the lower and upper ends of the box.

Figure 4. Yield (tonnes per hectare per year) estimates across production mode. Boxplots of yield (tonnes per hectare per year (log)) for the four broad taxonomic groups separated by production mode. Median values are provided as the middle line while the 25th and 75th quartiles bound the lower and upper ends of the box.