Supplementary Materials

Appendix A: Pilot Study to Identify and Develop GAPI Indicators

The first step in the initial development of ecological indicators for GAPI was a scoping exercise of current seafood sustainability initiatives to assess indicators already in use. Initiatives (and indicators) were assessed for data quality, relevance, performance orientation and transparency. Each initiative was assessed for its efficacy measuring the performance of a given production system, specifically in regard to its relevance to sustainability, the quality and scope of an indicator and most importantly if the indicator is expressed quantitatively. Those initiatives which lacked clear indicators, targets or thresholds for these indicators, or were based on vague/qualitative standards were excluded from further assessment. In addition, those initiatives focused on a narrow division of criteria rather than broader sustainability criteria, such as meeting an organic standard, were excluded [1]. Many of these excluded initiatives were developed for farm level assessments of specific species being cultured in particular environments; meanwhile GAPI's focus was to develop criteria for assessing environmental performance across all finfish globally.

Included Initiatives

Blue Oceans Institute
Global Aquaculture Alliance
Greenpeace Criteria for Aquaculture
MBA Seafood Watch Program
Marine Conservation Society
Whole Foods
WWF Benchmarking Study

Excluded Initiatives

ABCC- Shrimp Quality Guarantee Brazil
AB France
Audobon Seafood Lover's Guide
BioAustria - Austria
Bio-Suisse
CoC Certified Shrimp - Thailand
Debio Norway- Norway
Irish Quality Salmon and Trout
Krav - Sweden
Label Rouge - France
La Truite Charte Qualité - France
Marine Stewardship Council
Naturland
Norway Royal Salmon- Norway
Norge Seafood- Norway
Scottish Code of Good Practices
Sea Choice Qualité Aquaculture de France- France
Soil Association UK
SSOQ- Shrimp Seal of Quality
Marine Aquaculture Task Force
Tartan Quality Mark
Thai Quality-Thailand

Based on these criteria only seven of the 30 assessed initiatives were found to meet these expectations [1]. These seven were further examined to identify those environmental impacts that were commonly addressed across these efforts (see Table A1). These seven initiatives together with their respective informants and stakeholders span the breadth of the seafood sustainability community. If an issue is addressed within one or more of these seven initiatives we conclude there is a global consensus that this issue is critical for evaluating the environmental performance of marine finfish aquaculture. However, it is crucial that GAPI remain focused on selecting criteria relevant only to the environmental performance of marine aquaculture; therefore any non-ecologically relevant issues such as human health, social issues and the use of genetically modified feed ingredients were not included within the GAPI indicators (see Table A1 for a more detailed list). While these indicators were not included within the GAPI methodology they still remain important in the overall assessment of marine aquaculture but are not specific to ecological performance. Two expert panels comprised of internationally recognized leaders in particular issue areas were assembled to help further develop quantitative indicators. Further, extensive input was sought from individual leaders within ENGO, producer and retail communities. The product of this extensive consultative process was 10 robust yet concise indicators (Appendix B).

Table A1. Initiative assessment: indicators included and excluded from development of GAPI framework.

	Greenpeace Red Criteria	**Global Aquaculture Alliance**	**Marine Stewardship Council**	**Whole Foods**	**Blue Ocean Institute Guide**	**Aquaculture Stewardship Council**	**MontereyBay Aquarium Seafood Watch Program**
Antibiotics	✓	✓	✓	✓	✓	✓	✓
Biochemical Oxygen Demand	✓	✓	✓	✓	✓	✓	✓
Capture Based	✓			✓	✓	✓	✓
Antifoulants (Copper)	✓		✓	✓	✓	✓	✓
Ecological Energy			✓	✓	✓	✓	✓
Escapes	✓		✓	✓	✓	✓	✓
Feed	✓	✓	✓	✓	✓	✓	✓
Industrial Energy						✓	
Parasiticides	✓	✓	✓	✓	✓	✓	✓
Pathogens	✓	✓	✓	✓	✓	✓	✓
Excluded Indicators Groups							
No genetically or chemically modified feed ingredients	✗		✗	✗		✗	
Human health concerns				✗			
Level of disturbance (hydrology/ soil *etc.*) & regional sensitivity	✗			✗	✗	✗	
Impact on wildlife species / marine mammals.	✗			✗	✗	✗	✗
Social issues including workers rights *etc.*	✗	✗	✗	✗	✗	✗	✗

Appendix B Detailed Derivation of GAPI Scores

The methodology, which produces a final score for each species-country pair assessed (e.g., Atlantic salmon–Norway) ranging from 0 to 100, consists of eight steps:

Step 1: Identifying critical indicators of environmental performance
Step 2: Constructing formulas to objectively assess performance in each indicator
Step 3: Setting a "zero-impact" target for each indicator
*Step 4***:** Data collection
Step 5: Winsorization
Step 7: Weighting indicators
Step 8: Calculating the final country score

Step 1: Selecting Key Indicators of Environmental Performance

Emphasis has been placed on identifying a suite of indicators that sufficiently describes the major ecological impacts of marine finfish aquaculture while using the fewest indicators possible. Each additional indicator increases the complexity of the analysis, the likelihood of significant data gaps, and the effort required to collect data. Therefore, rather than attempting to measure all conceivable impacts from production systems, the *most significant* and *measurable* environmental effects were evaluated. In order to determine the suite of GAPI indicators, we examined existing aquaculture assessment efforts and pinpointed those environmental impacts that were commonly addressed across these efforts (Appendix A).

Step 2: Constructing Formulas for Each Indicator

The next step was to determine how best to measure actual performance within each indicator category. We developed specific criteria to ensure that each indicator is:

- Relevant and measures the environmental impact at hand;
- Has a performance orientation which tracks actual, on-the-water performance;
- Transparent (both formulae and data); and
- Assessable utilizing high quality data.

A pilot project to identify what specific issue areas should be addressed and to identify the optimal performance measure for each is described in Appendix A. Following exhaustive literature review and convening numerous expert panels, 10 issue areas and their associated performance metrics were identified (Table 1).

In the same way that it is valuable information to know a country's GDP and its GDP *per capita* or its overall contribution to carbon dioxide emissions *vs.* its per capita contribution, both absolute and normalized performance are assessed within GAPI. The absolute score of each country reflects the overall environmental impact of marine aquaculture production in that country. However, because absolute scores take into account the volume of fish produced, they can be greatly affected by differences in production volume (e.g., large producers will tend to have high cumulative scores given their sheer volume of production). Thus, in order to level the playing field among the range of performers as well as to highlight intrinsic performance differences between species, performance in each indicator is divided by the production volume (mT, live-weight equivalents). These normalized values for performance within each indicator are used to obtain a normalized score for each country and allow for direct comparison between producers of various scales. This paper focuses on the normalized scores (per unit of production), which better characterizes China's environmental performance relative to other producing countries and is not inflated by differences of production volume between countries. Further, normalized scores offer decision makers greater insight not only into how players are performing compared to their peers, but also into what indicators are they leading or lagging, and where effective solutions might lie.

Step 3: Setting Targets for Each Indicator

One of the major strengths of GAPI is that it enables aquaculture performance to be judged against a set of targets that would be unrealistic as certification standards but provide crucial information regarding how close marine finfish aquaculture comes to meeting an ecological ideal. By setting a zero-impact target for each indicator, GAPI permanently sets the environmental performance at the ecological ideal rather than continually recalibrating the goal as the performance of the industry improves or as viewpoints of what is an "acceptable" level of impact shift. As such, GAPI provides a robust tool to assess any real progress or decline in environmental performance over time.

Step 4: Collecting Data

A wide range of data drawn from international organizations, regulatory bodies, conservation organizations, academia, seafood industry groups, and seafood industry trade press were used. All data used are publicly available and traceable. Data sources are referenced within the indicator summaries. All data included within the GAPI dataset are from 2007, unless otherwise indicated.

As with any effort to assess aquaculture performance, challenges related to data availability and quality were faced. Limited data coverage, methodological inconsistencies, low-quality metrics, and poor (or nonexistent) reporting structures pose problems for all assessment efforts. While GAPI is focused at the country level, where most aquaculture data are collected and reported by regulatory authorities, data inaccuracies are still likely. Where questions regarding data accuracy or where gaps in data remain, the treatment of these potential inaccuracies and gaps are treated in a transparent manner (see the "data gaps" section within each indicator, Appendix C) within each indicator.

Lastly, while the preference is to use data that track on-the-water performance, in some cases there is simply a lack of direct empirical data. In keeping with the approach of the Environmental Performance Index [2], GAPI aims to stimulate discussion on defining the appropriate metrics and methodologies for evaluating environmental performance in addition to highlighting the need for improved data collection.

Step 5: Winsorization

With indicators identified, targets defined and the relevant data collected, performance scores can be calculated. The first step of this process is winsorization; a common statistical approach [2] to dealing with extreme outliers so those values do not distort the distribution of the entire data set. In winsorization, if any performance lies outside of the normal distribution of data for the entire group of performers, that outlier performance value is adjusted so that it lies two standard deviations from the mean (the edge of the normal distribution). Since the target performance is set at zero, however, no performer can over perform (*i.e.*, do better than zero impact). Thus, winsorization is only used to adjust for extreme underperformance (*i.e.*, performing far worse in any one indicator than the data set would suggest is plausible). Winsorization then adds a level of conservatism to the analysis. Extraordinarily poor performance relative to peers in an indicator is assumed to be erroneous and is adjusted, even though such a poor performance may be accurate.

Step 6: Proximity-to-Target Calculation

In order to directly compare performance among two or more disjunct indicators (*i.e.*, escaping fish and the sustainability of feed sources) in a statistically meaningful way, it is necessary to standardize the data for each indicator on the same 0-to-100 scale. Proximity-to-target calculates how close each performer is to meeting zero-impact for each indicator using the following formula:

$$\text{Proximity-to-target} = 100 - \frac{[100 \times (\text{Actual Performance} - \text{Target}}{(\text{Maximum Winsorized Value} - \text{Target})]} \quad (1)$$

This results in an initial, unweighted score for each individual indicator. Since the worst performer in the analysis sets the floor for performance, the score is partially dependent on the pool of performers included in the analysis. Thus, in order to properly characterize Chinese performance it is important that this pool of performers accurately represents the global marine finfish aquaculture industry. The performers included here comprise approximately 94% of marine finfish aquaculture by production and 91% by value.

Step 7: Weighting Indicators

At this point, the overall score could be calculated by simply taking the average of the 10 individual indicator scores. However, doing so would ignore the fact that some indicators are more important than others in explaining the difference in performance among two or more players. A recent review of sustainability assessment methodologies [3] demonstrated that normalization and weighting of indicators used in sustainability assessments is typically associated with subjective judgments and reveals a high degree of arbitrariness without mentioning or systematically assessing critical assumptions. This dilemma is addressed by shifting away from weighting based on the assumed magnitude of environmental impact of each indicator to a weighting scheme where the data and not the investigator determine the degree of weighting for each indicator. A standard statistical procedure for such a task is the Principal Component Analysis (PCA). Within GAPI, the 10 indicators generate a large "cloud" of data. PCA essentially creates a lens through which we can view this complex set of data as simply and clearly as possible. In this case, the purpose of using PCA is to help find trends in the data in order to determine how important each indicator is in describing the difference in performance across many performers. PCA measures how much of the total variation in the data is explained by each indicator, thus providing a measure of each indicator's relative importance or weight.

PCA-derived weights for each GAPI indicator are listed in Table 3 (Column D). The larger weights identify those indicators with the largest differences in performance and lower weights indicate proportionally smaller discriminatory power among performances. Antibiotic use, ecological energy consumption, sustainability of feed, and pathogen impacts each explain 15% of the variation in performance across all countries. The remaining six indicators all add similar but more modest levels of insight each explaining between 5% to 8% of variation (Table 3)

Step 8: Calculating the Final County Score

The final country score is the average of the country's species scores after each was weighted according to its production volume. For example, in a given country with two assessed species, for which species #1 accounts for 65% of the country's assess production and species #2 accounts for 35% of assessed production, the final country score is a weighted average (65% and 35%) of the two species' scores (Table 4). Both normalized and aggregate scores are reported. Normalized scores are normalized by production, meaning they reflect environmental performance per ton of fish produced. Cumulative scores are not divided by production but instead reflect the aggregate effect of production.

Appendix C: The Indicators

Indicator 1—Antibiotics (ANTI)

A large percentage of marine finfish species are farmed in open nets or cages in the marine environment, which makes them especially susceptible to a host of pathogen-borne diseases. Given the open nature of most marine finfish production systems, a significant portion of the applied antibiotics are released into the ecosystem. Some of these antibiotics have been associated with a variety of ecological impacts including: selection for antibiotic-resistant bacteria [4,5]; persistence in sediments and the water column [4,6]; and potential toxicity to non-target organisms [7,8].

Formula:

$$\frac{\Sigma\text{ (Amount Active Ingredient (kg)} \times \text{WHO-OIE Score}}{\text{mT Fish Produced}} \tag{2}$$

Units: Kilograms weighted by the WHO-OIE Score per mT produced

Target: Zero

Sources: *Antibiotics used:* Producers; international, national, and regional aquaculture associations; FAO; seafood industry trade press; science literature

WHO-OIE Score: Report of Joint FAO/WHO/OIE Expert Meeting on Critically Important Antimicrobials [9].

Indicator Formula

The antibiotic indicator considers two primary factors: the absolute amount of antibiotics used in production and a measure of the environmental risk of each antibiotic. It assumes that antibiotic use is indirectly related to strong environmental performance; the fewer antibiotics used, the better the performer's score for this indicator. Since antibiotics have varying degrees of potential ecological impact, it was also deemed necessary to weight the use of each antibiotic by some measure of potential impact or risk. Through expert consultation, the most readily accessible, yet accurate, measures of the risk of antibiotic use related to human and veterinary use were the ratings of antibiotics by the World Health Organization (WHO) and the World Organization for Animal Health (OIE). Like all GAPI indicators, the antibiotics indicator is normalized by mT of fish produced.

WHO—IOE Score

In 2007, the U.N. Food and Agriculture Organization (FAO), the World Health Organization (WHO), and the World Organization for Animal Health (OIE) hosted a joint meeting in which they assessed the importance of key antibiotics in the treatment of human and animal disease. Attention was placed on those antibiotics for which overuse could lead to the development of antibiotic resistance. Two ratings emerged: a WHO rating of the importance of antibiotics in human use and an OIE rating of importance in veterinary use. WHO and OIE classify antibiotics as critically important, highly important, or important antimicrobials based on two criteria [9].

For antibiotics used in human medicine, the WHO classification criteria are:

Criterion 1: Sole therapy or one of a few alternatives to treat serious human disease.

Criterion 2: Antibacterial used to treat diseases caused by organisms that may be transmitted via non-human sources or diseases caused by organisms that may acquire resistance genes from non-human sources.

For antibiotics used in veterinary medicine, the OIE classification criteria are:

Criterion 1: Response rate to the questionnaire regarding Veterinary Critically Important Antimicrobials. This criterion was met when a majority of the respondents (more than 50%) identified the importance of the antimicrobial class in their response to the questionnaire.

Criterion 2: Treatment of serious animal disease and availability of alternative antimicrobials. This criterion was met when compounds within the class were identified as essential against specific infections and there was a lack of sufficient therapeutic alternatives.

If both criteria are met, the antibiotic is classified as critically important in that use category by WHO or OIE. For instance, if an antibiotic used in human medicine meets both WHO criteria, it is classified by the WHO as critically important. If one criterion is met, the antibiotic is classified as highly important in that category. If neither criterion is met, the antibiotic is classified as an important antimicrobial in that category. In order to assess the overall importance of antibiotics for both human and veterinary use, GAPI assigned scores to antibiotics based on their combined WHO and OIE classifications.

Table C1. The joint WHO-OIE antibiotic importance scoring system used by GAPI.

Category	Score
Critically important - WHO and OIE	7
Critically important in either	6
Highly important - WHO and OIE	5
Highly important in either	4
Important - WHO and OIE	3
Important in either	2

Addressing Data Gaps

- If there were no reported data regarding the type of antibiotics used, it was assumed that all producers in a country were using those antibiotics that are legal for use in that country. If no information was available regarding antibiotic regulations in the country, it was assumed that the country is using the same set of antibiotics used by neighboring countries farming the same species.
- If data on the quantity of antibiotics used were not available, it was assumed that use was equal to the recommended dosage (according to regulators in that country) for each antibiotic reported (or assumed) to be used.
- If data were not available for the assessment year an average value in kg/mT of fish produced from all known years was applied (for all antibiotics used for more than one year).
- In only a few cases, a WHO-OIE Score for a specific antibiotic was not available. In these cases, the WHO-OIE Score for the closest related antibiotic group was used.

Indicator 2—Biological Oxygen Demand (BOD)

Most marine finfish production systems are open which results in the discharge of uneaten feed and fish wastes directly into the marine environment. The impacts of nutrient loading on water quality as well as on the sea floor environment are well documented and include decreased benthic diversity on the sea bottom and changes to the macrobenthic community structure [10–12]. BOD is a measure of the relative oxygen-depletion effect of waste contaminants (uneaten feed and feces) and is defined as the amount of oxygen required to oxidize organic carbon (C) and nitrogen (N) from feed inputs that is not recovered in the biomass at harvest [13]. It was assumed that nutrient loading spread across a large area would, on average, have a lesser impact than the same loading concentrated in a small area and this was calculated in the Area of Overlap.

Formula

$$\frac{\text{BOD (mT } O_2) \times \text{Area of Overlap (km}^2)}{\text{mT Fish Produced}} \quad (3)$$

$$BOD = (\text{total N in feed} - \text{total N in fish}) \times 4.57 + (\text{total C in feed} - \text{total C in fish}) \times 2.67 \quad (4)$$

$$\textit{Area of Overlap}\ (\text{km}^2) = \text{sum of the area of overlap of the buffer zones}$$

Units: (mT $O_2 \times km^2$) per mT fish produced
Target: Zero
Sources: International, regional, and national legislation; FAO; Sea Around Us Project (SAUP); scientific literature (including [13])

BOD is calculated by assessing the total carbon and nitrogen per unit of feed. According to Boyd [13] the amounts of molecular oxygen necessary to oxidize 1 kg of organic carbon and 1 kg of ammonia nitrogen are 2.67 kg and 4.57 kg, respectively. These relationships allow us to estimate the biochemical oxygen demand of feed as demonstrated in the BOD equation above.

Area of Overlap

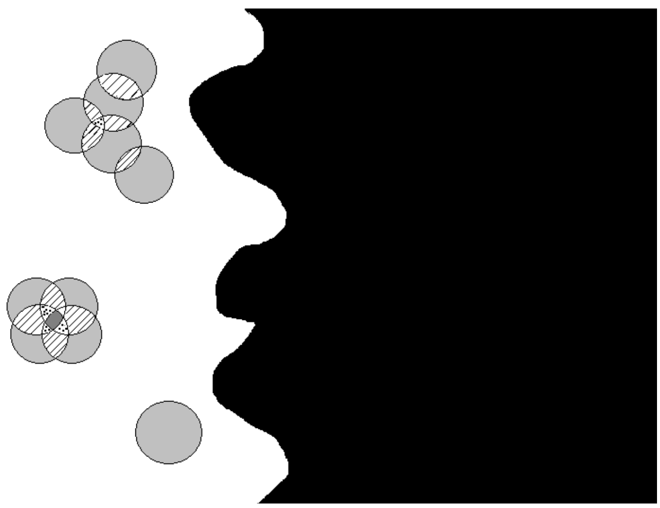
GAPI assumes that nutrient loading spread across a large area will, on average, have a lesser impact than the same loading concentrated in a small area. In order to establish the area of impact, GAPI first identified farm locations using Google Earth images (Google Inc. 2009) imported into ArcGIS 9.2. For each site, the area of impact is assumed to be a 3 km radius buffer around the farm site. The effect that farm-derived nutrients have on the water column is well documented [14] and has been measured up to and including distances of 1000 m [15]. It is likely that ecological impacts extend beyond this point and, as a result, farm-siting regulations in countries vary from 300 m (Nova Scotia) to 8 km (Scotland). Because there are very few systematic data regarding how ecological effects vary with distance [16] GAPI uses a median value of the siting regulations (3 km) to set the buffer for the area of overlap.

Area of Overlap value is the sum of the area of overlap of the buffer zones (Figure C1). A higher *Area of Overlap* indicates a more concentrated effluent release. Since we were unable to identify the type of species farmed at each site, the total *Area of Overlap* of all farms for a country was adjusted based on the proportion of production comprised by each species in a given country. Similarly, we could not quantify the production magnitude at any particular farm. Therefore, GAPI assumes negligible impact of any single farm located beyond 3 km from the next closest farm. For this reason, the BOD indicator is a very conservative performance metric.

Addressing Data Gaps

- If the percent of N and C were not available for the farmed species N and C values for the most closely related species for which values are available.
- If the C in feed is unknown, the 45% figure provided by Boyd was applied (Boyd, pers. comm. 2009).
- If the N in feed was unknown, the formula: % crude protein/6.25 was applied (Boyd, pers. comm. 2009).

Figure C1. Example of the Assessment of Area of Overlap in GAPI, where farms can either have no layers (light grey), two layers (lines), 3 layers (black dots) or 4 layers (dark grey).



Indicator 3—Capture Based Aquaculture (CAP)

Some aquaculture production systems, known as capture-based aquaculture (CBA), depend on the capture of wild fish either as a source of broodstock (mature fish used for breeding) or as farm stock that are raised to commercial size (*i.e.*, ranching). The capture of wild fish for use in aquaculture results in the same set of pressures as a conventional fishery. Specific impacts associated with ongoing CBA fisheries are the reduction of (wild) genetic biodiversity, stock depletion or collapse from low recruitment, habitat degradation from capture methods, and localized or wide-scale population disturbances [17]. This indicator is a measure of the sustainability of capture-based aquaculture. If the performer does not rely on the capture of wild fish to sustain its production, its score is perfect (100) for this indicator.

Formula

Area of Overlap (km2) = sum of the area of overlap of the buffer zones

$$\frac{\sum(\text{Amount from Wild Capture (kg)} \times \text{Sustainability Score})}{\text{mT Fish Produced}} \quad (5)$$

$$\textit{Sustainability Score} = (\text{harvest performance}) \times (\text{stock status}) \times (\text{management score}) \quad (6)$$

Units: kg × sustainability score per mT fish produced
Target: Zero
Sources: Amount from Wild Capture: FishSource [18]; FishStat Plus [19]
Sustainability Score: FAO; Sustainable Fisheries Partnership; FishSource

Harvest Performance

This measures the percentage of the actual catch of the fishery that is over the self-management catch limit. Where actual catch is above the management limit, the harvest performance is:

$$\text{Harvest Performance OF} = \text{Actual Catch} - \text{Mgmt Catch Limit/Actual catch} \times 100 \quad (7)$$

However, where actual catch is below the management limit, the numerator is transformed to 1. Thus, the equation for harvest performance is:

$$\text{Harvest Performance UF} = 1/\text{Actual Catch} \times 100 \quad (8)$$

Management catch limit information is largely taken from FishSource [18]. GAPI's first preference is to use the biological maximum sustainable yield (Bmsy) as the management catch limit for each species. However, if the Bmsy is unavailable, GAPI uses the total allowable catch (TAC). If the TAC is unavailable, GAPI uses the spawning stock biomass (SSB) or any other available management catch limit. If no management catch limit was set for the assessment year, GAPI uses the best of Bmsy, TAC, or other management catch limit (in order of preference) for the most recent year. If no management catch limit was ever set for the fishery, GAPI assumes that the management catch limit is zero. This leads to a harvest performance score where 100% of catch is considered to be over the management catch limit (*i.e.*, the worst-case scenario).

Table C2. GAPI Management Scores.

Biological Reference Points (BRP)		Management Score
BRP for Upper Limit	**BRP for Lower Limit**	
None	None	9
B20	None	8
B20	Bpa	7
None	Fecundity	6
B20	Fecundity	5
None	Bmsy	4
B20	Bmsy	3
None	Ecosystem	2
B20	Ecosystem	1

Amount of Wild Capture (kg)

Within the CAP formula, *amount of wild capture* measures the loss in future biomass of seed fish resulting from capture-based aquaculture. It is calculated accordingly:

$$\textit{Amount of Wild Capture (or Lost Future Biomass)} = \textit{Total Weight Removed From Wild} - (\textit{Total Weight Removed From Wild} \times \textit{Natural Mortality}) \tag{9}$$

This calculation measures the total amount of fish removed from the wild ecosystem, but it adjusts for natural mortality to account for the fact that not all fish removed from the wild would have survived if left in the wild. This avoids overestimation of the impact of wild fish removed. Once the amount of fish removed from the wild is calculated, it is multiplied by the Sustainability Score to obtain a measure of the total seed removed from the wild that are unsustainably fished and/or poorly managed.

Sustainability Score Calculation

The sustainability score of the fishery supplying the seed for an aquaculture system is the product of three factors: harvest performance, stock status, and an assessment of the management regime for that particular fishery.

Harvest Performance

This measures the percentage of the actual catch of the fishery that is over the set management catch limit.

Stock status

In 2005, the FAO assigned categorical values to the health of fish stocks. The four categories ranged from underexploited to overexploited-depleted. Within GAPI, these categorical scores are converted to numeric scores between one and four, with one being the best performance (underexploited) and four being the worst performance (overexploited-depleted).

Management Score

Sustainable Fisheries Partnership (SFP) examined the sustainability of world fisheries used for reduction purposes (e.g., aquaculture feeds) [20]. SFP used the setting of biological reference points (BRPs) as an indicator of the sustainability of reduction fisheries. BRPs can be derived using a variety of approaches.

Ecosystem-based management is considered to be the best approach for setting upper target reference points, while B20 or biomass/recruitment models are considered the best approach for setting lower limit reference points. Based on the BRP information provided in the SFP report, GAPI assigned a score between one and nine, where nine represents the worst possible performance (no upper and lower limits set) and one represents the best possible performance (use of ecosystem-based management and B20 to set upper and lower limits, respectively.

Fisheries Terminology

B20 and Biomass/Recruitment Models—Limiting fishing so that no more than 20% of the spawning stock biomass is removed from the total fish population

Bpa.—A fishing limit set slightly more stringently than the B20 level to create a buffer ensuring that the number of fish removed from the population does not meet or exceed 20% of the spawning stock biomass

Ecosystem-Based Management—According to the FAO Code of Conduct for Responsible Fisheries [21] management measures should not only ensure the conservation of target species but also of species belonging to the same ecosystem or associated with or dependent upon the target species

Fecundity—The fertility of the fish stock, or how quickly the stock can reproduce to sustain its population

Maximum Sustainable Yield (Bmsy.)—In theory, the maximum amount of fish (catch) that can be removed from a species' stock over an indefinite period while still maintaining the maximum growth rate of the population

Spawning Stock Biomass—The total weight of all sexually mature fish in a population

Total Allowable Catch (TAC)—The total catch of stock permitted to be removed in a specified period (usually a year), as defined in the management plan. The TAC may be allocated to stakeholders in the form of quotas representing specific quantities or proportions.

Addressing Data Gaps

- If the total weight removed from the wild was unavailable for the assessment year, then the average weight removed from the wild for known years.

Indicator 4—Antifoulant (COP)

Antifoulant coating and paint are applied to marine net pens to prevent the colonization of fouling organisms which can greatly reduce the flow of water through the net pen. Copper is the primary active ingredient in the vast majority of these applications [22]. Copper is highly toxic to a wide range of aquatic organisms including algae [23] copepods [24] amphipods [25], echinoderms [26], and larger microbial communities [27]. Copper in excess of recommended maximum concentrations has been found at aquaculture facilities [28]. Copper remains biologically active and therefore potentially lethal even when bound in marine sediments [28].

The antifoulant indicator is an estimate of metric tons (mT) of the species produced using copper-based antifoulants. Actual data regarding the on-farm usage of copper tend to be unavailable, either at the individual farm level or aggregated country level. Thus, GAPI uses the next best available data based on the proportion of production that used copper antifoulants.

Formula

$$\frac{\text{Production (mT)} \times \text{\% Production Using Copper-Based Antifoulants}}{\text{Production (mT)}} \tag{11}$$

Units: Proportion of production using copper-based antifoulants
Target: Zero
Sources: Producers; international, national, and regional aquaculture associations; FAO; seafood industry trade press, and scientific literature

Addressing Data Gaps

In the absence of verifiable data on the proportion of production using copper-based antifoulants an average value from known years. If this information was unavailable it was assumed that 100% of production used copper-based antifoulants.

Indicator 5—Ecological Energy (ECOE)

ECOE focuses specifically on how much ecological energy these systems take out of the marine environment (*i.e.*, NPP). Energy is converted up the food chain, from solar energy (sunlight) into forms that are biologically consumable. The ECOE indicator measures the magnitude of photosynthesis diverted away from the ecosystem and appropriated by an aquaculture production system. It is also necessary to account for the net primary productivity of the agriculture and livestock components of feed. GAPI uses the NPP of poultry as a proxy for the NPP of all livestock, since chicken is a major protein input of feed and typically displays similar feed conversion rates to swine and slightly higher than cattle [29]. For the plant proportion, a composite value is used, derived from NPP values for wheat, corn, and soy. Values for NPP can be easily obtained by converting the amounts of fish, plants and livestock consumed by each species into grams of Carbon (g C) per kilograms (kg) of farmed fish [29].

Formula

$$\frac{\sum \text{Net Primary Production of Feed Inputs}_{\text{(mT carbon)}}}{\text{mT Fish Produced}} \tag{12}$$

- *Net Primary Production of Feed Inputs (NPP)* = $(m/9) \times 10^{(T-1)}$ [29]
- *m* = Mass of feed components (mT)
- *T* = Trophic level of the feed components

Units:NPP (in mT C per kg -1) per mT produced
Target: Zero

Sources: National and regional statistics; FAO; seafood industry trade press; and scientific literature. *Feed Components*—The proportion of feed comprised of fish, livestock, and plants is calculated from either industry figures for feed composition or literature published on diet compositions.

Addressing Data Gaps

- It was assumed that no livestock components were present in feed mixtures consumed in all European Union countries due to EU regulations banning the use of these components in feed.
- If the proportion of fish, plant, or livestock was unknown the most recent data for that country and/or a similar species were applied.

Indicator 6—Escapes (ESC)

The inevitability of escapes from aquaculture facilities has led the U.N. Food and Agriculture Organization (FAO) to recommend that introductions of species in aquaculture should be considered an introduction to the wild, even if the facility is considered a closed system [30]. Negative impacts to community structure, biodiversity, genetic resources, and ecosystem function are well documented regardless of whether escapees are exotic species [31] or native species [32,33] farmed in the same waters as wild counterparts.

Impacts associated with inanimate wastes are relatively predictable. However, because escapees (and pathogens) are living organisms, the magnitude of their impact is greatly influenced by local biotic and abiotic conditions. An escape event may be devastating when it occurs in one region, yet produce only a modest disturbance in another. Therefore, assessing performance by the number of escapees alone is inadequate. Some species and country combinations carry a higher per capita escapee risk than others. For this reason, the escapes indicator is the product of the number of escapees and the GAPI Invasiveness Score, which provides an estimate of the per capita risk associated with an escape.

Formula

$$\frac{\text{GAPI Invasive Score} \times \text{\# Escaped Fish}}{\text{mT Fish Produced}} \qquad (13)$$

Units: Synthetic unit composed of the product of the number of escapees and per capita risk per mT produced

Target: Zero

Sources: FishBase; Sea Around Us Project (SAUP); FAO; industry reporting; country reports on escapes; seafood industry trade press; scientific literature

GAPI Invasiveness Score

Inspired by the Marine Fish Invasiveness Screening Kit (MFISK) tool developed by Copp *et al.* [33], the GAPI Invasiveness Score assesses the risks of impact of escape events within several broad categories. These include: domestication; climate; distribution; invasion elsewhere; undesirable traits; feeding traits; reproduction; and persistence attributes. For each species, a 26-question survey is completed. Responses, which are usually scored as either 0 or 1, are summed to obtain the total GAPI Invasiveness Score (Table B3).

Addressing Data Gaps

- If the number of escapes for a country and species combination was unknown the most recent data for that country or the average escape ratio for the species was applied.

Table C3. GAPI Invasiveness Score Questionnaire.

Question	Numerical Score
Is the species domesticated anywhere in the world?	No = 0 Yes = 1
Has the species naturalised (established viable populations) beyond its native range?	Native or No = 0, Few(<3) = 2, Many = 3
Does the species have invasive congeners?	No = 0 Yes = 1
Is the species poisonous or possess other immunochemical predation defenses?	No = 0 Yes = 1
Is the species parasitic of other species?	No = 0 Yes = 1
Is the species likely unpalatable to natural predators?	Yes = 1 No = 0
Is the species likely to be a novel predator to native forage species?	No = 0 Yes = 1
Does the species host, and/or is it a vector for, recognized pests and pathogens, especially non-native?	No = 0 Yes = 1
Does the species achieve a large ultimate body (> 30 cm FL)?	No = 0 Yes = 1
Does species tolerate a wide range of salinity?	No = 0 Yes = 1
Habitat diversity	(Value Range 0–1) × 3
Does feeding or other behaviours of the species reduce habitat quality for native species (*i.e.*, ecosystem engineer)?	No = 0 Yes = 1
Adult wild trophic level	SAUP Value
Does it exhibit parental care and/or is it known to reduce age-at-maturity in response to environmental conditions?	No = 0 Yes = 1
Do production fish produce viable gametes?	No = 0 Yes = 1
May the species hybridise with one or more native species?	No = 0 Yes = 1
Is the species hermaphroditic?	No=0 Yes =1
Is the species dependent on another species or specific habitat feature(s) to complete its life cycle (including diadromy)?	No = 1 Yes = 0
Does natural dispersal occur as a function of egg or larval dispersal?	No = 0 Yes = 1
Does the species tolerate or benefit from environmental disturbance?	No = 0 Yes = 1
Are there effective natural enemies of the species present in the risk assessment area?	Yes = 0 No = 1
Does the species tolerate a wide range of water quality conditions (e.g., hydrodynamics, pollution, oxygen)?	0-low, 3-high
If native, # generations from wild type	native = # generations (max = 3), exotic = 1
Resilience	Very Low = 0, Low = 1 Medium = 2 High = 3
Identified in IUCN Global Invasive Species Database	No = 0 Yes = 3
Effective distance	(Max range degrees)/60
FINAL SCORE	**/34**

Indicator 7 - Industrial Energy (INDE)

Industrial energy is energy as we commonly know it—resources such as petroleum and hydroelectric power that are used by aquaculture producers to support fish-farming activities and feed acquisition, processing, and transport [34,35]. Industrial energy consumption is calculated as the energy use (MJ) embedded in feed used and the type of production system to produce one mT of fish in that country. Using values from Life Cycle Analysis on salmon (a full "cradle to grave" analysis of environmental impacts), the knife coefficient represents the amount of industrial energy necessary for production of feed components and the type of production system [34,35]. The feed components are separated into livestock, plant, and marine. Production systems are categorized by type; cage, floating bag, land based flow through and land based recirculation. Energy input for each of these includes production, raw material processing/reduction, feed milling and on-growing of fish.

Formula

$$(\sum(\text{Proportion Fish/Livestock/Plant/System}) \times \text{Knife Coefficient} \\ (\text{megajoules/mT}) \times \text{Total Feed Consumed (mT)})) \,/\, \text{mT Fish Produced} \quad (14)$$

• *Knife coefficient* = Average energy of fish, livestock, and plant components in feed (Tyedmers, pers. comm. 2009)

Units: Megajoules (MJ) per mT fish produced
Target: Zero
Sources: National and regional statistics; FAO; seafood industry trade press; and scientific literature

Addressing Data Gaps

- It was assumed that no livestock components are present in feed mixtures consumed in countries of the European Union due to EU regulations banning the use of these components in feed.
- If the proportion of fish, plant, or livestock was unknown, the most recent data for that country and/or a similar species was applied.

Indicator 8 - Parasiticides (PARA)

In addition to antibiotic use to treat bacterial infection in farmed marine finfish, parasiticides are frequently used to reduce parasite infestations in farmed fish. Most parasiticides are applied in a similar manner to antibiotics, either in medicated baths or within formulated feeds. When used in open net pen aquaculture systems, the effects of parasiticides typically manifest beyond the fish farm, and thus it is important to consider the ecological implications of their application within the marine environment. Many parasiticides are toxic to non-target organisms, especially aquatic invertebrates [36]. Overuse of certain parasiticides can lead to chemical resistance, such as the documented resistance to parasiticides in Scottish sea lice [37].

While the amount of chemical used and the level of toxicity were considered key components of the indicator, consulted experts agreed that the persistence of the chemicals should also be incorporated.

LC50 and half-life, the major components of the formula, were chosen because they are both accepted and readily available measures of toxicity and persistence, respectively.

Formula

$$\frac{\sum(\text{Amount (kg)} \times [(1/\text{LC50}) + 1] \times \text{Persistence (Days)})}{\text{mT Fish Produced}} \quad (15)$$

- *Amount (kg)* = Amount of active ingredient of the parasiticide used
- *LC50 (mg/L)* = Lethal concentration of a chemical in water that kills 50% of the test animals in a given time (represents the organism most harmed by each substance)
- *Persistence (half-life)* = Residency time of a chemical in the environment measured by its half-life in that environment

Units: Kilograms per mT fish produced

Target: Zero

Sources: Producers; international, national, and regional aquaculture associations; FAO; Material Safety Data Sheets (MSDS); seafood industry trade press; scientific literature

Addressing Data Gaps

- If data on the amount of parasiticide used were not available it was assumed that the recommended dosage was being used for all parasiticides.
- If parasiticide use data were not available for a given year an average value (kg active ingredient/mT of fish produced) for known years was applied.
- The LC50 of active ingredient is standard regardless of the application. Where the LC50 for an aquaculture parasiticide was not available, the LC50 for the use of that parasiticide in other organisms/applications was used.

Indicator 9 - Pathogens (PATH)

Pathogen (disease and parasite) transfer among wild and farmed populations is a major issue not only for the farming industry but also for consumers concerned about the sustainability of aquaculture products. The impact of diseases and pathogens coming from the farm is estimated using three variables: on-farm production loss, pathogenicity (the degree to which the pathogen causes diseases in the host), and biomass (the mass of the total number of living organisms in an ecosystem) of susceptible species in the ecosystem around the farm. For each pathogen identified in a production system, the proportion of host range biomass in the ecosystem, pathogenicity, and life cycle are identified and used to predict the impact on wild populations (pathogen-specific wild losses).

The proportion of the host range biomass in the ecosystem is the proportion of species in the ecosystem that is susceptible to the pathogen in question. It is assumed that all members of a taxonomic *Family* are susceptible to a pathogen when two or more *Genera* are known to be susceptible (Kevin Lafferty, USGS, pers. comm. 2009).This estimate is derived from Ecopath models [38] using a trophic mass balance approach to quantify ecosystem biomasses of the world's 66 large marine ecosystems (LMEs). Two specific LME models were obtained from [7] and additional peer-reviewed Ecopath ecosystem models

Formula

$$\frac{\sum(\text{Pathogen-Specific Wild Losses (mT)})}{\text{mT Fish Produced}} \tag{16}$$

Units: mT pathogen-specific wild losses per mT fish produced
Target: Zero
Sources: Producers; international, national, and regional aquaculture associations; FAO; seafood industry trade press; scientificliterature. Producers and industry associations provided pathogen-related production loss data. Pathogens common to particular production systems are readily identified in scientific and trade journals, which are used to supplement interview data.

Addressing Data Gaps

If data on the total production loss from pathogens were not available:

- An average of the production loss from dead fish (not including other factors such as escapes and poor quality) for available years, or
- An estimated proportion of diseased fish calculated using the expected survival rate. For example, Species A have an expected survival rate of approximately 90%, with 25% of dead fish resulting from disease and parasites. Thus, the resulting production loss from pathogens would be 2.5%. If no proportional loss (relative pathogenicity) information is available, then one of the following were used:
- Frequency of pathogen occurrence and severity to represent each pathogen's contribution to the total losses due to disease;
- Economic loss due to disease/pathogen converted into a proportion of production loss; or
- If none of the above were available for a given year, pathogenicity was spread equally among pathogens known to be present.

Indicator 10—Sustainability of Feed (FEED)

Fish meal and fish oil continue to play an integral role in fulfilling the nutritional requirements of aquaculture raised species [39–43], particularly for carnivorous species fed compound feeds. Numerous and significant ecological impacts have been linked to these reduction fisheries and their increasing appropriation of marine productivity [42]. The targets of reduction fisheries tend to be fish species that not only constitute major components of marine ecosystems but also comprise the primary prey of economically important wild fish species.

Formula

$$(\sum \text{(Proportion of Feed by Species} \times \text{Sustainability Score of Each Species)} \times \text{Fish In: Fish Out Ratio} \times \text{Production (mT))} / \text{mT Fish Produced} \tag{17}$$

• *Proportion of Feed* = The fish meal and fish oil components of feed. This takes into account the species, country of origin, and the proportion of each component in the final feed formulation.
• *Sustainability Score* = (harvest performance) × (stock status) × (management score)
• *Fish. In: Fish. Out Ratio* = Calculated as the pelagic equivalent inputs to farmed fish outputs (kg wild fish inputs: kg farmed fish outputs) [43]

Units:	Metric tons (mT) modified by *Sustainability Score*
Target:	Zero
Sources:	Fish Source; Sustainable Fisheries Partnership; seafood industry trade press; FAO

Sustainability Score Calculation

The Sustainability Score calculation for fish meal and fish oil ingredients is the same formula used to determine the Sustainability Score of wild fish inputs in the capture-based aquaculture indicator (CAP). Please see the CAP section for sustainability score methodology.

Addressing Data Gaps

- If the composition of feed used in the country was unknown available data on the composition of feed from the most similar country producing that species was applied.
- If the species composition was unknown for any production country for a species being farmed a breakdown of species caught for reduction fisheries for that year was used.

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