Model inner workings - for methods and supplementary sections

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Introduction

Aquaculture is now the dominant form of aquatic animal food (herein 'seafood') production and is expected to be the primary way we meet future seafood demand. Freshwater systems will likely continue to provide the majority of farmed seafood but marine aquaculture is also poised to expand substantially in numerous areas. Farmed marine fish and invertebrates are produced near exclusively in coastal waters, and nearly three quarters of this production is dependent on human-made feeds. Nearshore locations and feed inputs are necessary to maintain profitable and productive farming operations but coastal aquaculture generates a number of challenges. In the crowded coastal zone, aquaculture operations can conflict with other stakeholder uses such as recreation, fishing, renewable energy, transport, and tourism. And while farming marine fish typically generates a far smaller nutrient footprint than livestock farming, the overt nature of aquaculture in nearshore regions and evidence of localised nutrient impacts around fish farms remains a primary public and scientific concern. Identifying strategies that reduce ecosystem impacts from fish farm waste therefore represents an important goal for improving marine aquaculture sustainability and maintaining the sector's social licence to operate.

Aquaculture feeds represent an important lever for reducing nutrient waste impacts around fish farms. Like all farmed animals, fish and invertebrates must digest the nutrients contained in feeds before they can be used for growth. Any nutrients left undigested are egested as solid waste, and dissolved wastes are excreted as metabolic waste products. Further, some feed inevitably remains uneaten and is lost to the surrounding ecosystem. Particulate organic matter (both feed and faeces) that settles can simplify benthic communities as the oxygen demand from its decomposition drives the production of sulphides that kill less mobile faunal, encouraging a lower diversity of opportunistic scavengers and the growth of bacterial mats (e.g., Beggiatoa spp). Thus, the chemical composition of the ingredients used in aquaculture feeds and their digestibility for the farmed species has significant implications for the nature and reactivity of the waste generate by marine aquaculture.

. Firstly the overall volume of nutrient waste is dictated by the nature and intensity of production, that is the farm size, the density of farmed animals and the feed requirements and efficiency of the species grown. SecondlDeposition of waste is heavily influenced by water depth and current speed at the farming site. Once

As farmed fish and invertebrates are fed, whatever

Nutand its impact on marine ecosystems is influenced by many factors. Farm size Depth Current speed Benthic impact - sediment type/faunal assemblages/wider marine community High turnover environments - nitrogen enriched areas Feed influences all of these things

The primary source of organic waste from fed aquaculture production comes from the excretion and faeces of the farmed animals and through uneaten feed that dissolves in the water column or settles on the benthos. The nature and impact of this waste are influenced heavily by the composition of the feeds fed to farmed animals.

P2 - Waste from aquaculture farms and it's impact is influenced by many things but the composition of feeds plays a central role. Waste from aquaculture farms has multiple sources. The primary source of organic waste comes from the faeces and excretion of the fish or invertebrates. Uneaten feed produced another key source. The nature and impact of this waste are influenced heavily by the composition of the feeds fed to farmed animals Many marine fish are naturally carnivorous so diets used to be high in fishmeal and oil but increasing fishmeal and oil prices along with concerns over the sustainability of marine ingredients have led to a reduction in their use across multiple farmed taxa In lieu of fishmeal and oil, many plant-based ingredients such as soy protein concentrate, canola oil, and wheat gluten have replaced them. Changes in feed composition influences the digestibility of the nutrients held in each feed and can alter the composition of waste. Of particular concern are changes (increases) to the presence of reactive nitrogen and phosphorus in coastal waters that could have an effect on eutrophication.

P3 Whether or not nutrients lead to eutrophication depends on the sensitivity of the receiving environment Ecosystems that are already enriched through natural processes and whose biota is well adapted to substantial fluxes in available nutrients (e.g. upwelling zones, dynamic coastal communities) may be less sensitive while oligotrophic ecosystem are likely to see considerable changes under nutrient enrichment scenarios. To understand the impact of aquaculture waste under present day or future scenarios we need to quantify the volume, nature, and location of mariculture waste and determine the sensitivity of the receiving environments to that waste. Yet only recent estimates even give us the estimated location of marine farms let alone the volume of nature of the waste produced. To address this gap, we use existing maps of mariculture location with a bioenergtic model

Temporary questions to answer:

- Do the fish reach harvest size within a reasonable amount of time?
  - If not, are they growing for the correct amount of time, starting at the correct weight?
- Is their FCE/FCR reasonably close to experimental data?
- Is their SGR reasonably close to experimental data?

Model approach

We adapted the methods of Baldan et al. (2018) to create a bioenergetic model that simulates individual growth and farm-scale production for Atlantic salmon and the resultant nutrient waste in the form of excess labile nitrogen and phosphorus. The model simulates growth at an individual level, calculating the change in individual weight through time using:

$$\frac{dw}{dt} = \frac{A - C}{\epsilon}$$

Where $w =$ is wet weight (t), $t =$ time (d), $A =$ anabolic rate (J t^{-1}), $C =$ the catabolic rate (J t^{-1}), $\epsilon =$ energy density of body tissues (J t^{-1}).

Individual models were then upscaled using monte-carlo simulations to simulate size structure in a population. Size differences were achieved through different initial starting weights and ingestion rates for different finfish species. All individuals have a fixed mortality rate to simulate stocking and harvesting.

- Parameterised for atlantic salmon

- Farms with mean temperature $< 8.5°$ were excluded

Water temp

Originally, all salmon were transferred to grow-out cages (model began) on January 1st. This isn't particularly realistic. Now, all farms begin the modelling period in spring (1st of May in the northern hemisphere, 1st of October in the southern hemisphere).

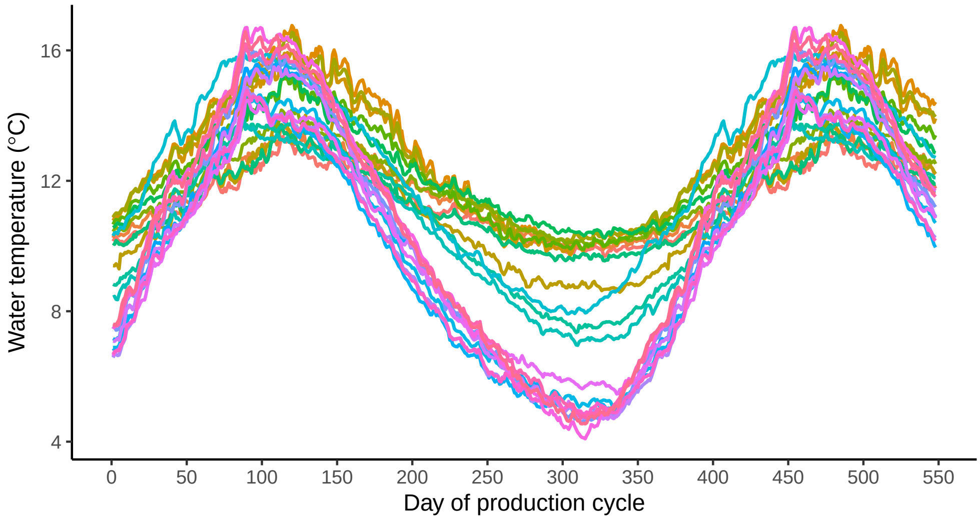

Figure 1: Water temperature for the production period, starting at either DOY 121 (1st May, northern hemisphere) or DOY 274 (1st October, southern hemisphere).

Weight

Figure 2 shows the change in weight for 25 individuals grown at different farms. Within the first 5 months (post-smolt period) the fish grow from 125g to 628.9g, or approximately 5× their starting weight. This is better than most production cycles. By the end of the production cycle (547 days, 18 months) the fish have grown to a mean of 2027.8 g, and a max of 3110.5 g. This is not quite what's needed - I'm expecting individual weights to at least approximate the mean commercial weight of 5kg.

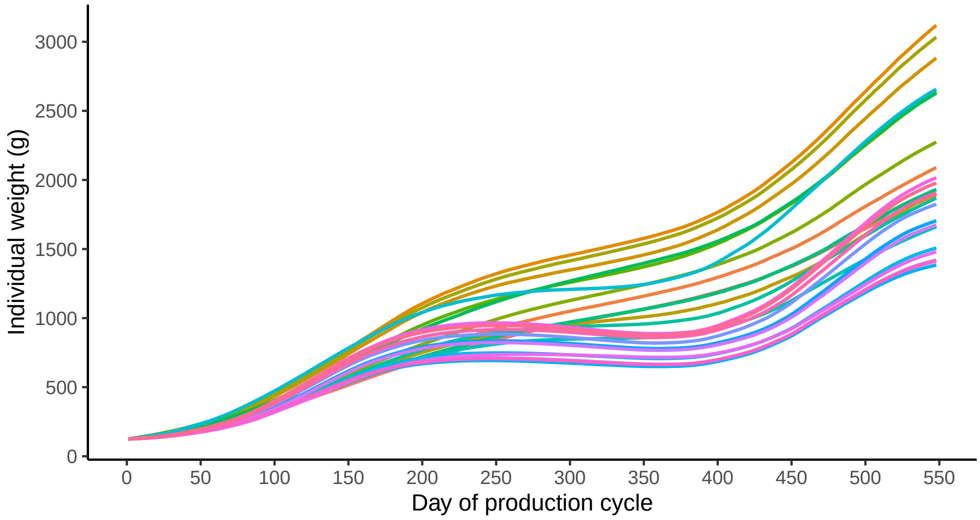

Figure 2: Weight of single individuals grown at 25 random farms across the production period, starting at either DOY 121 (1st May, northern hemisphere) or DOY 274 (1st October, southern hemisphere).

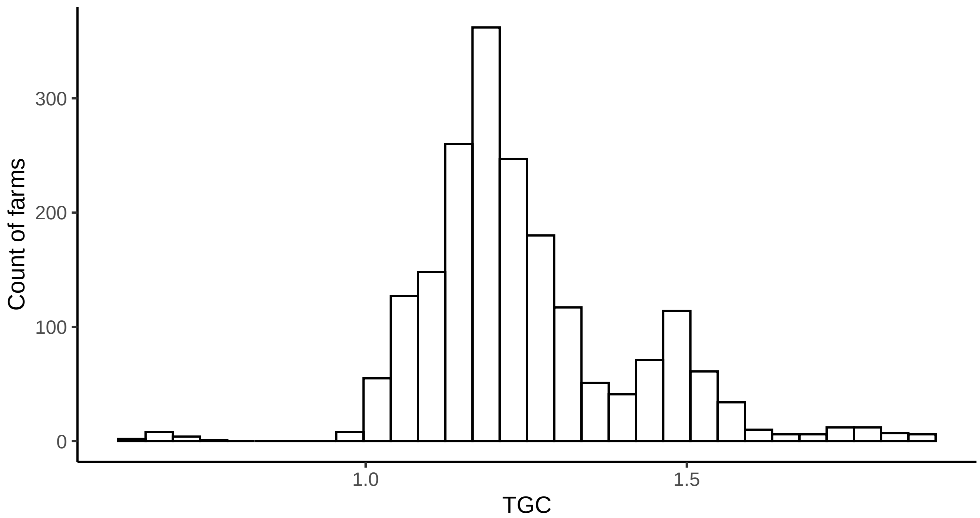

Figure 3: Thermal-unit Growth Coefficient (TGC) of all 2721 farms across the production period, starting at either DOY 121 (1st May, northern hemisphere) or DOY 274 (1st October, southern hemisphere).

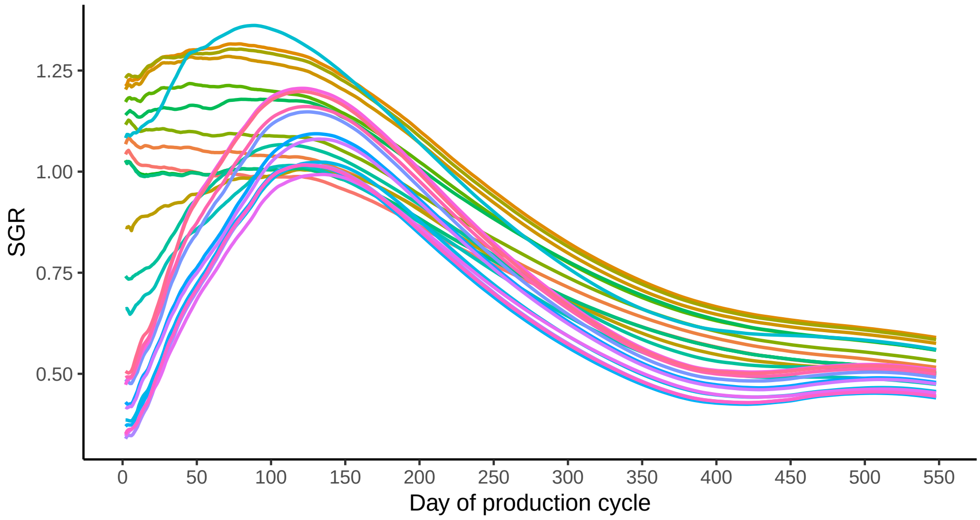

Figure 4: Specific growth rate of single individuals grown at 25 random farms across the production period, starting at either DOY 121 (1st May, northern hemisphere) or DOY 274 (1st October, southern hemisphere).

General fish functions

Figure 5 shows the metabolic response of all salmon to temperature (affecting their relative metabolism), and Figure 6 shows how the salmons' feeding rate changes with temperature.

$$cat = \epsilon_{O_2} \times k_0 \times T_{resp} \times W^n \times \omega$$

Relative feeding rate is temperature-dependent and calculated via:

$$FR_{rel} = e^{b(T_w - T_{opt})} \times \left[\frac{T_{max} - T_w}{T_{max} - T_{opt}}\right]^{b(T_{max} - T_{opt})}$$

where T_{opt} is the optimum feeding temperature, T_{max} is the maximum feeding temperature, T_w is the current water temperature, and b is a species-specific shape coefficient.

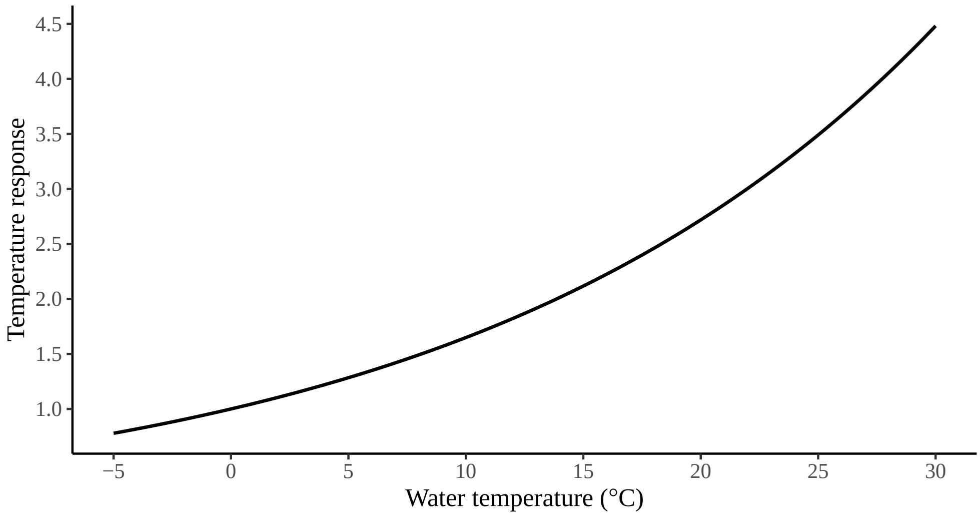

Figure 5: Metabolic response of all salmon to temperature within the model.

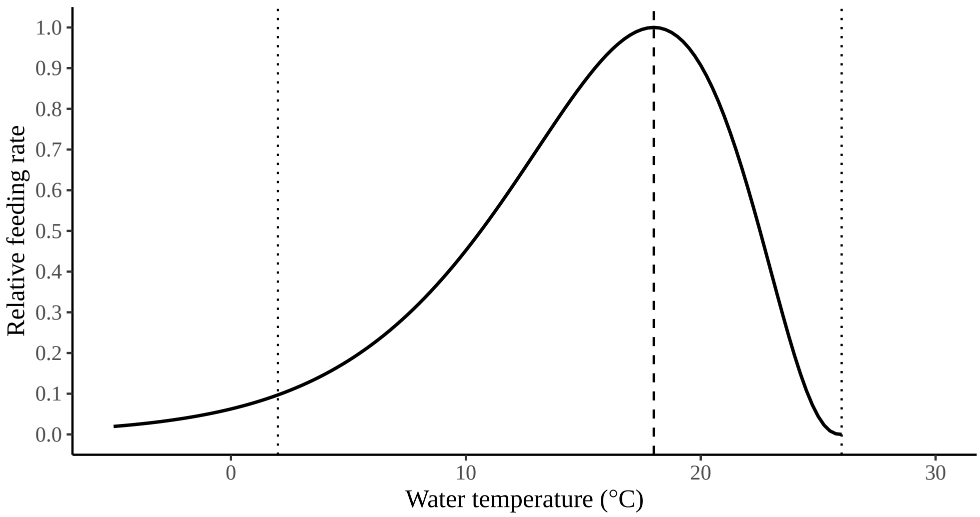

Figure 6: Changes in salmons feeding rate with temperature. The dashed line shows the optimum feeding temperature for salmon while the dotted lines show the minimum and maximum feeding temperatures.

Feed data

Incorporated the individual digestibility of each ingredient and switched to tracking ingredients separately instead of feed – this unfortunately makes the model run slower but I think it will be worth it once the digestibility coefficients from the experiments are incorporated.

Individual runs

I set up some "example fish" to speed up future model adjustments – basically fish that are the average of their whole farm, easier than running 5000 fish per farm while I'm making changes.

Food provided vs food eaten

Within the model, salmon have a maximum ingestion potential (based on their weight and individualised feeding rate). The actual food ingested is 97% of their ingestion potential (food encounter efficiency) or the total food provided, whichever is less. Figure 7 shows an example of how food provided scales with potential individual ingestion.

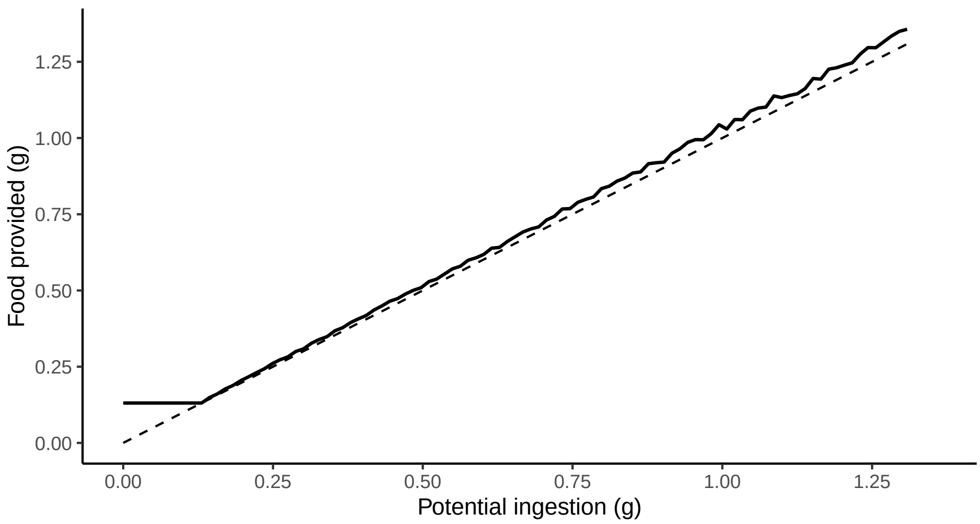

Figure 7: Example of food provided based on potential ingestion (where feeding rate ranges from 0 to 1). This curve is constructed with a single fish of mean starting weight (125 g) and average maximum ingestion rate (0.035). The dashed line shows food provision == potential ingestion.

Therefore, uneaten feed can be quite high (up to ~30%) when relative feeding is $ $10%. But generally, the median amount of uneaten food is 3.4% (Figure 8).

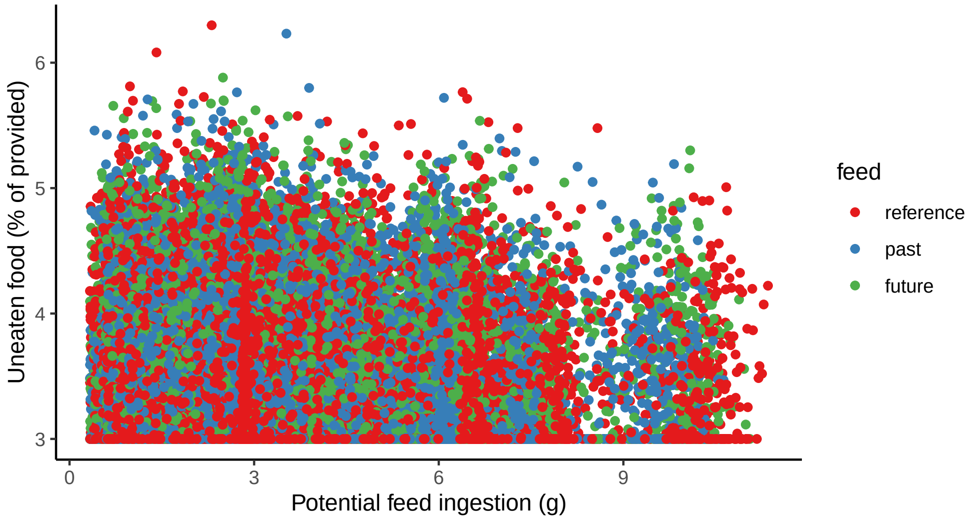

Figure 8: Difference between food provided and actual ingestion (i.e. total food ingestion efficiency) for 25 random farms.

References

Baldan, Damiano, Erika Maria Diletta Porporato, Roberto Pastres, and Daniele Brigolin. 2018. "An R Package for Simulating Growth and Organic Wastage in Aquaculture Farms in Response to Environmental Conditions and Husbandry Practices." *PLOS ONE* 13 (5): e0195732. https://doi.org/10.1371/journal.pone.0195732.