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## Response to a letter to editor regarding Kotta et al. 2020: Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea

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We thank Wikström et al. (2020) for their interest in our work and their recognition of the value of the data we present. We believe that we share with them a commitment to a healthy and sustainable Baltic Sea. In Kotta et al. (2020), we contributed to showing how blue mussel farming could be one of a bundle of measures for reducing excessive nutrient levels in the Baltic Sea. Blue mussel farming is a promising low-impact and native species-based internal method for eutrophication control in the Baltic Sea. We presented the first synthesis of a large number of recent measurements of farmed mussel growth in the Baltic Sea and a new model chain for predicting growth and nutrient removal potential across key environmental gradients.

While forty years of land-based measures have slowed the rate of increase of eutrophied areas in the Baltic Sea, they have failed to solve the problems of algal blooms, oxygen free dead zones and biodiversity loss caused by excessive levels of nitrogen (N) and phosphorus (P). Even if HELCOM nutrient reduction targets are ultimately reached, the time-scales of Baltic ecosystem recovery can still span from decades to hundreds of years (Savchuk 2018, Murray et al. 2019). The ongoing failure to adequately control Baltic Sea eutrophication through external nutrient load reduction measures highlights the need for complementary *in-situ* (internal) methods to lower nutrient concentrations in the water column.

Farming and harvesting of native plant and animal species that require no external inputs of nutrients, but rather take up nutrients from their environment, is likely to be the most effective internal measure for restoring the health of the Baltic Sea ecosystem. If such plants and animals are harvested, the nutrients they contain can, further, be reused for production of food or feed and make an important contribution to the circular economy.

Critics of blue mussel farming in the Baltic Sea have argued that yields were too low (Hedberg et al. 2018, Wikström et al. 2020). This was true when farms used inappropriate technology – systems designed for growing large mussels in the Atlantic simply do not work well for growing small mussels in the Baltic. New farm technologies which are adapted to growing small mussels are demonstrating that large volumes of mussels can be grown economically at many more locations throughout the Baltic than was previously thought possible. While these new technologies are at the pilot stage, they show a great deal of promise for all aspects of Baltic Sea sustainability.

In Kotta et al. (2020), we demonstrated that in the Baltic Sea region, mussels had a maximum production yield at  $14.7 \text{ kg m}^{-1} \text{ harvest}^{-1}$  (see Figure 5 or Supplementary Figure 3) which equals to  $7.35 \text{ kg m}^{-1} \text{ yr}^{-1}$  not  $1.5 \text{ kg m}^{-1} \text{ yr}^{-1}$  as erroneously stated in Wikström et al. 2020. In the Central Baltic Sea with declining salinity, the predicted biomass yields varied mostly between 1 and  $3 \text{ kg m}^{-1} \text{ harvest}^{-1}$ ; however, in its southern parts the values were locally much higher, at  $>5 \text{ kg m}^{-1} \text{ harvest}^{-1}$ . This is also a reason why we used a square in the map to visualize the predicted farm area needed to meet the whole nutrient reduction target in these high production areas (see Figure 1 in Kotta et al. 2020). However, we did not propose a single  $900 \text{ km}^2$  mussel farm, as seems to have been inferred by Wikström et al. (2020). Wikström et al. (2020) assumed incorrectly that we used a rope density of  $22 \text{ km ha}^{-1}$ . Instead, we used the Mussholm rope density ( $49 \text{ km ha}^{-1}$ ) in yield calculations for the southern Baltic Sea. This figure is similar to the rope density at the Kalmarsund farm ( $40 \text{ km ha}^{-1}$ ) located in the southern Baltic Sea (see <http://www.sea.ee/bbg-odss/ExtraInfo/Farms> for more details of the Baltic Sea mussel farms). When estimating farm area needed to meet HELCOM nutrient reduction targets for the Baltic Proper, we used modelled growth values for the southern Baltic Sea, which we estimated at close to  $5 \text{ kg m}^{-1} \text{ harvest}^{-1}$ . These numbers suggest an area of  $900 \text{ km}^2$  to remove the excess nutrients (Table 1).

In fact, we can emphasize in our response that this density is within a range used in the actual mussel farms in the Baltic Sea area (Holmer et al., 2015; Kraufvelin and Díaz, 2015). In the studied mussel farms of the Baltic Sea region, the growth of mussels was almost linear over time. Furthermore, the measured values of water chlorophyll *a* did not indicate any reduction of chlorophyll in the farm area. This very much indicates that mussel densities in the Baltic Sea farm area are far from carrying capacity (see, e.g., Smaal and Van Duren 2019) and physical environment (e.g. salinity, water exchange) rather than intraspecific interactions for

food defines the production yield of mussels. Thus, denser mussel farms and/or better farming technology are likely to yield even greater production of farmed mussels.

In their review of the environmental impacts of bivalve aquaculture, Burkholder and Shumway (2011) reported sustained, system level adverse impacts in 7% of cases, and these were all from large, intensive farms. The remaining 93% of farms they examined showed either negligible or localized negative effects related to eutrophication (Burkholder and Shumway 2011). The intensification we advocate to meet HELCOM nutrient reduction goals is based on many small farms, each situated in a locally optimal growth location, while minimizing potential negative environmental impacts. We agree with Wikström et al. (2020) that good maritime spatial planning is needed to ensure that farms are not located in areas having inappropriate environmental conditions, e.g., sheltered areas with inadequate water exchange. In such areas, adverse environmental effects (e.g. increased sedimentation and plausible oxygen deficiency) are expected. Mussel farming should preferably only be located semi-exposed or exposed areas in the Baltic Sea.

Importantly, blue mussels are among the most common benthic invertebrate species in the Baltic Sea and their habitats extend 75,000 km<sup>2</sup> (Figure 1) in which their average biomass is often estimated at 1–10 kg m<sup>-2</sup> in wet weight equalling 10–100 tons wet weight ha<sup>-1</sup> (values extracted from different spatial mapping datasets, for details see the subsection 2.3. in Kotta et al. 2020). At these natural densities, mussel beds have no documented adverse environmental effects. On the contrary, these habitats provide important ecosystem services (improving water quality, sustained biodiversity, Gentry et al. 2019). Thus, a farming density of mussels at 160 tons wet weight ha<sup>-1</sup> is not something artificial to the Baltic Sea. Moreover, owing to better water exchange provided in the water column, compared to the sediment-water interface of benthic mussel habitats, the expected effects of mussel farms on biodeposition rates and oxygen dynamics are lesser compared to natural mussel reefs.

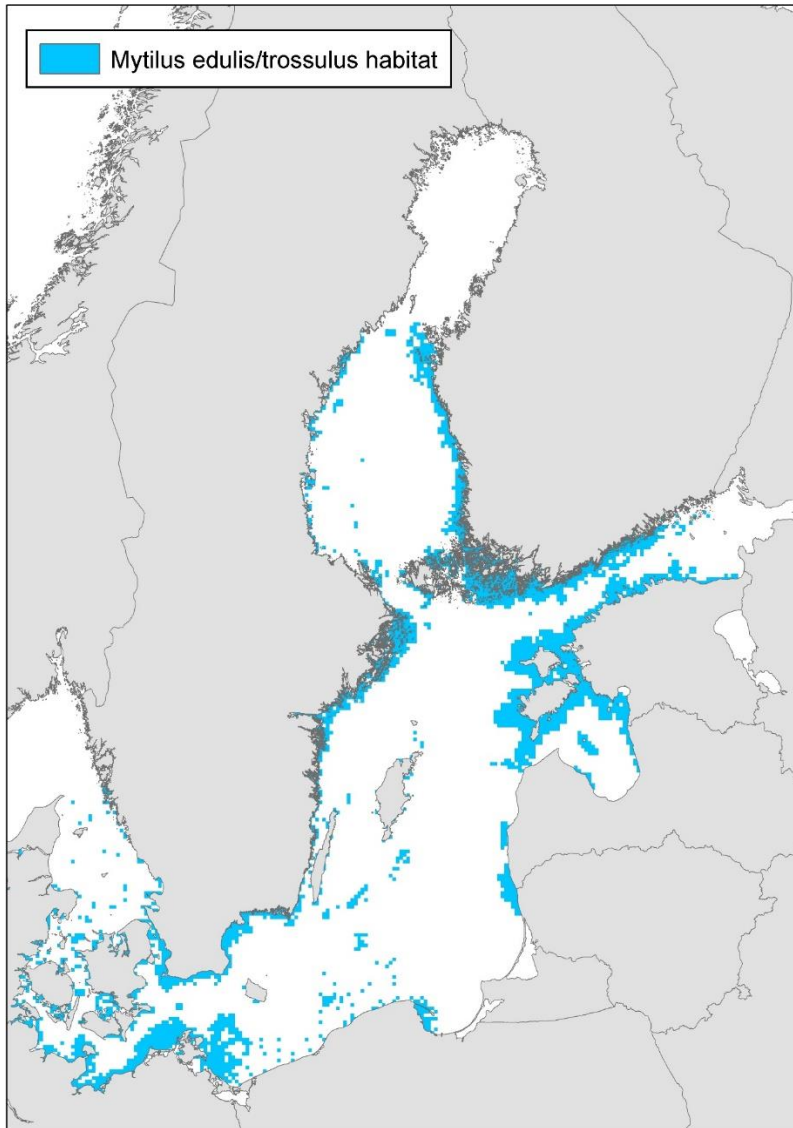
As we stressed in Kotta et al. (2020), before we can expand mussel farming, one has to solve legislation issues, develop farm technologies, etc. These are important questions that are outside the scope of our study. Several studies already show that the Baltic mussels are suitable for both fertilizer and a variety of feeds for, e.g., hens, pigs and different species of fish (Lindahl and Kolberg 2004, Jönsson 2009, Vidakovic et al. 2015); however, there needs to be a certain supply to create a market.

Finally, we agree with Wikström et al. (2020), that more data on the large-scale ecosystem effects of mussel farming are needed as well as new solutions to technical aspects of mussel use. Nevertheless, the problem of Baltic Sea eutrophication urgently requires local solutions and combining different promising measures such as mussel farming can help us reach future environmental targets in a more timely manner.

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**Figure 1.** Current distribution of the blue mussel *Mytilus edulis/trossulus* habitats in the Baltic Sea region (source: Helcom Map and Data Service at <http://maps.helcom.fi/website/mapservice/>).

**Table 1.** Summary of nitrogen (N) yield calculation in the central Baltic Sea region.

Variable	Value	Unit
N content in mussel tissue	0.7	%
Modelled biomass yield in the region of interest	2.4325	kg m <sup>-1</sup> yr <sup>-1</sup> (t km <sup>-1</sup> yr <sup>-1</sup> )
Long line density	49	km ha <sup>-1</sup>
Modelled areal biomass yield in the region of interest	11919.25	t km <sup>-2</sup> yr <sup>-1</sup>
Modelled areal N removal in the region of interest	83.4	t km <sup>-2</sup> yr <sup>-1</sup>
HELCOM regional N reduction target	75069	t
Total surface area of mussel farms needed to reach the N target	900	km <sup>2</sup>

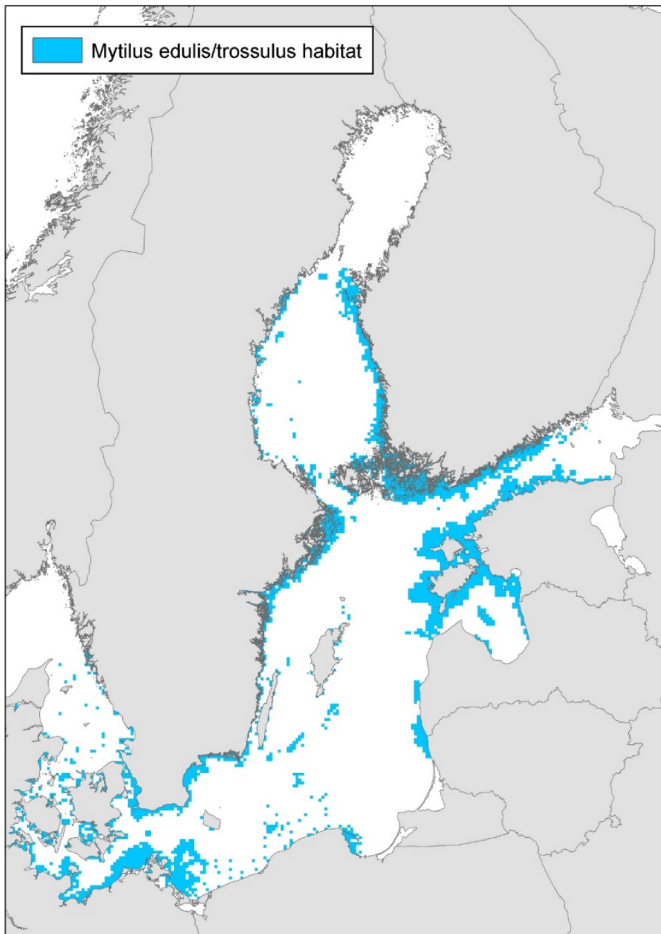


Figure 1