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Tackling the elephant in the room – Large-scale salmon farming and the potential for far-field ecosystem effects

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ABSTRACT

Significant expansion in salmon production globally has been partially enabled through the establishment of large-capacity sea-farms in high-energy environments that collectively produce substantial quantities of organic waste with potential to cause regional scale environmental degradation. We analyse results from comprehensive spatial and temporal surveys of water column particulates and seabed environmental indicators for responses to farm production, and residual effects. Results confirmed that while the particles can and do reach a relatively wide area, benthic effects do not necessarily follow suit. There was limited evidence of longer-term environmental degradation at some near-field locations and spatially removed deeper sites. We concluded that evidence for regional biological effects was negligible, suggesting: i) modern waste tracing techniques are more sensitive than traditional effects indicators, and ii) waste fluxes in the far-field were being assimilated without causing environmental perturbation. Monitoring at potential accumulation points, especially for sites with complex bathymetry and hydrodynamics is advised.

1. Introduction

In response to the expanding human population and increasing demands for fish-based protein, global aquaculture production has been growing at a rate of approximately 6 % annually (FAO, 2018) and placing increasing pressure on environmental resources. In the last 20 years, the vast majority of this expansion has been met by culturing species that require feed inputs (FAO, 2018), which are in-turn associated with significant waste outputs (Bannister et al., 2016; Cromey and Black, 2005; Wang et al., 2013). Sea-cage salmon farming is an important and highly lucrative sector of this industry, and in 2021, Norway alone produced ~1.6 million tons of salmon with an estimated value of NOK 70 billion (Fiskeridirektoratet, 2021, approximately €6B). While land-based systems are becoming increasingly popular (Bjørndal and Tusvik, 2019; León-Muñoz et al., 2023), invariably, the simplest and most cost-effective way to increase production is to install more sea-based farms and to increase outputs from existing ones. Invariably, this involves exploiting the virtues of dispersive and offshore sites as they are generally perceived to have greater assimilative capacity for waste (Keeley et al., 2019) and therefore fish production. Ultimately however, the assimilative capacity of the surrounding ecosystem is finite

(e.g., Valdemarsen et al., 2012), and it is critical that such expansion is undertaken with full awareness of the effects, and ideally, within pre-defined limits based on environmental and societal tolerances.

Farming in dispersive locations is not without risk and has potential environmental threats stemming from significantly increased farm sizes and total feed use. Not least of which being that more waste is produced and a generally broader effects footprint results (Keeley et al., 2019), which has the potential to challenge compliance in the far-field (i.e., at the outer limit of effects - beyond the primary waste deposition area). Even at small capacity sites, strong currents can create elevated organic loading 1 km from the farms (Sarà et al., 2006). Scope for effects beyond the immediate vicinity of the farm is supported by a recent study which estimated that approximately only 30 % of the particulate waste that was produced at a high-capacity dispersive site was accounted for by local benthic process; the remainder being available for deposition in the far-field (Keeley et al., 2019). Greater particle transportation range means increased scope for overlapping effects between farm localities, which has implications for minimum space between installations and environmental monitoring designs. Overlapping of footprints may compound effects in the far-field, and increase the potential for influencing adjacent habitats and potentially important commercial

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resources (e.g., intertidal clam beds, Robinson *et al.*, 2005). Moreover, the natural physical attributes of well flushed sites means that they are more likely to have hard and mixed-bottom habitats in the vicinity, including complex and relatively diverse reef structures (Dunlop *et al.*, 2021; Keeley *et al.*, 2020). Dispersive environments commonly also support important wild fisheries; for example, in the Frøya region of Norway, where this study was based, the multiple high production farms are situated amidst valuable wild-catch fisheries for scallops, crab, cod and flatfish. Recent studies suggests that fish-farm-derived waste can be incorporated into their body tissues at least 1 km from the discharge source (White *et al.*, 2017; Woodcock *et al.*, 2018). There is, therefore, a pressing need to better understand the potential for far-field ecological effects from dilute but persistently elevated sedimentation, and for increased scope for interactions with the wider ecosystem.

Benthic effects in the immediate vicinity of traditional sea-based fish farms ('near-field', ca. 0–600 m away) can be severe but are also reasonably well understood (Brooks and Mahnken, 2003a, 2003b; Buschmann *et al.*, 2006; MPI, 2013). In shallow and/or non-dispersive (weak current) environments the majority of the waste, principally in the form of fish faeces and variable quantities of feed pellets, accumulates on the seabed immediately beneath and near to the cages (Bannister *et al.*, 2016; Brooks *et al.*, 2002; Keeley *et al.*, 2013b). Such severe effects are typically limited to an area not much larger than the vicinity of the farm, decrease logarithmically with distance, and natural conditions are evident a relatively short distance away (e.g., 25 m – 300 m, Borja *et al.*, 2009; Brown *et al.*, 1987; Kalantzi and Karakassis, 2006). By contrast, the benthic footprint in a dispersive environment is less acute, often with minimal organic accumulation due to frequent resuspension and exaggerated horizontal transportation of the organic waste (Keeley *et al.*, 2013a; Keeley *et al.*, 2019; Sarà *et al.*, 2006). In effect, stronger hydrodynamics spread the waste more widely and at a lower intensity that is more readily assimilated by the environment, which facilitates increased production (Keeley *et al.*, 2019). Less acute and severe effects mean that the beneath-farm environmental compliance standards are less likely to be exceeded. Strong currents enhance oxygen delivery to the fish and support the use of larger cages (Oldham *et al.*, 2018), which means that total fish production can be considerably higher than in more sheltered, non-dispersive locations. Greater dispersion and dilution also mean that the scope for water column eutrophication (and contamination) from the dissolved waste component tends to be negligible (Jansen *et al.*, 2018; Jansen *et al.*, 2016). As such, farming can be conducted at greater intensity both in terms of fish within cages and farming unit densities.

The few studies that have demonstrated the potential for farm influence at or beyond ca. 600 m directly down current from a farm, cite water depth (Bannister *et al.*, 2016; Kutti *et al.*, 2007) and strong hydrodynamics (Keeley *et al.*, 2019; Sarà *et al.*, 2006) as being the main mechanisms. Previous attempts to look more broadly in the far-field have generally avoided the challenges associated with measuring effects per se and instead resorted to numerical models to predict the potential, with minimal validation (McIver *et al.*, 2018; Sowles and Churchill, 2004; Symonds, 2011). The resuspension scenarios that have been produced for dynamic sites to date do indicate different and often atypical footprints (Broch *et al.*, 2017; Carvajalino-Fernández *et al.*, 2020b; Keeley *et al.*, 2013b). Notably, some confirm the potential for complex distribution patterns with particles accumulating in naturally depositional areas or in nearby deep spots where gravity ultimately prevails (Broch *et al.*, 2017). Significant challenges arise when it comes to determining what constitutes an 'effect' at distant locations due to the subtle nature of the changes in relation to natural spatial and temporal variability. As such, this question cannot be addressed without substantial sampling effort in space, time, a complementary suite of indicators and replication, which quickly becomes cost-prohibitive. The challenge of definitively identifying effects is compounded by the existence of numerous environmental indicators, some of which are more closely linked to ecological effects per se, and which vary greatly in

terms of their sensitivity and perceived reliability (Cranford *et al.*, 2020; Hargrave, 2010; Keeley *et al.*, 2012) and it can be difficult to determine where to place the emphasis. Moreover, low-level effects from organic waste can be interpreted as mild fertilization (Pearson and Rosenberg, 1978) with minor enhancement of some species and limited detrimental effects, which may not be viewed adversely.

Thus arises the controversial question of whether dilution is the solution in terms of waste discharges; or more specifically, at what point does contamination become pollution? (Chapman, 2007). The underlying concern is that subtle changes may be going unnoticed, and although minor in magnitude, the spatial extent over which it is occurring could be very large and amount to broadscale environmental alteration or degeneration, thereby contributing to a 'sliding background'. Here, we examine large spatially and temporally comprehensive datasets including multiple indicator variables for suspended particulates, benthic tracers and benthic effects. The samples come from a carefully positioned array of monitoring stations in the near-, far-, and very-far-field before during and after a synchronized production cycle involving multiple high-capacity salmon farms in a large salmon producing region in mid-Norway. The results are hereby compiled to test for a response to production and for residual effect, both in terms of waste influence and ecological impact.

2. Methods

2.1. Site description

The study was conducted within the Frøya archipelago in mid-Norway (Lat: 63.7° N, Fig. 1) amidst large clusters of low-lying rocky islands and 'skerries' with moderate to high wind and wave exposure. During the study period (spanning 2015 and 2016), the cluster of islands where the study was focused (ca. from Innerhøln north) contained approximately 13 functioning high-capacity salmon farm localities (several with more than one farm license). From a fish farming perspective, the Frøya area is relatively shallow (< 100 m depth) and highly dispersive (regularly current speeds >10 cm s⁻¹) due its proximity to the Norwegian Coastal Current which passes just outside the archipelago and the episodic storm-driven currents and long-period wave orbitals. The seabed around the farms mostly comprised mixed substrates, with a complex bathymetry due to the many rock-reef structures separated by areas with soft sediments (Keeley *et al.*, 2020). Fish production in the study area was conducted under single-year-class management (one cohort is followed through to harvest) and roughly synchronized between farms. During the study cycle, production peaked in March–April 2016 at ~50,000 tons·month⁻¹ (Fig. 2) and the adult fish were harvested out (and therefore feed use diminished) between July and October. The amount of feed used over that period varied between farms with a maximum of ~70,000 tons for one locality (over 2 years) and a total combined feed use of ~500,000 tons.

2.2. Spatial and temporal design

With the intention of being able to detect minor changes in areas beyond the immediate vicinity of the farm (but potentially subject to farm influences), the study was divided up into two general area groups: Far-field and Reference. The far-field group comprised 25 potentially impacted stations that were situated between 0 m and 2000 m from at least one high-capacity farm; hereafter termed 'FF' stations (Fig. 1). The positioning of these stations was determined with respect to proximity to farm in combination with some topography and substrate requirements; namely: 'deep-spots' (or depressions) where waste was more likely to accumulate, and where the substrate was able to be physically sampled with a conventional grab (i.e., mud and sands). This was often challenging due to the prevalence of hard and mixed substrates, such as gravel, broken rock and bedrock. Station depths were selected to: a) be comparable to the very near farm stations (i.e., 32–80 m deep where

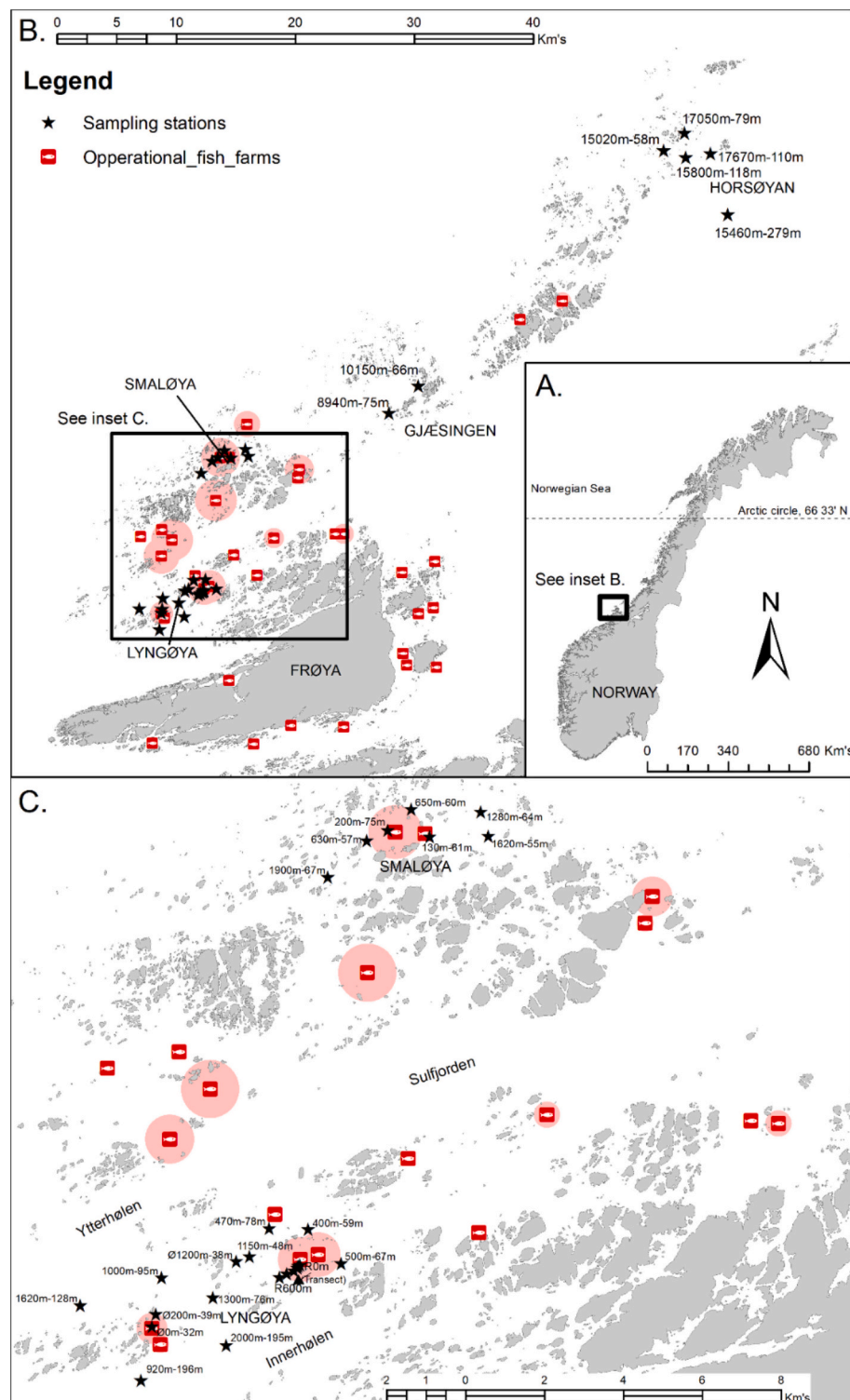


Fig. 1. Site map: A. general location along Norwegian coast, inset B. Frøya archipelago indicating active marine farms (red fish symbol) and sampling stations (black stars) with far-field reference group (stations outside of inset C) and near-field group, and inset C. zoomed in view of near-field sample stations. Light red circles indicate proportional feed use over the study period (2015 and 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impacts would be obvious), and b) include some deeper areas (i.e., 150–200 m) nearby that may represent the ultimate settling point (fate) for particles. FF stations were positioned in two subclusters: one contained 7 stations around two farms at the outer reaches of the South-West part of the archipelago (near Smaløya; Stations (Distance–Depth): 1900 m–67 m, 630 m–57 m, 200 m–75 m, 650 m–60 m,

130 m–61 m, 1280 m–64 m, 1620 m–55 m; Fig. 1C), and the other contained 15 stations around Lyngøya (between Innerhølen and Ytterhølen, Fig. 1). Of which, twelve stations were widely distributed around the area (Stations: 1620 m–128 m, 1000 m–95 m, 1200 m–38 m, 470 m–78 m, 1150 m–48 m, 400 m–59 m, 500 m–67 m, 1300 m–76 m, 200 m–39 m, 0 m–32 m, 920 m–196 m, 2000 m–195 m), and three were

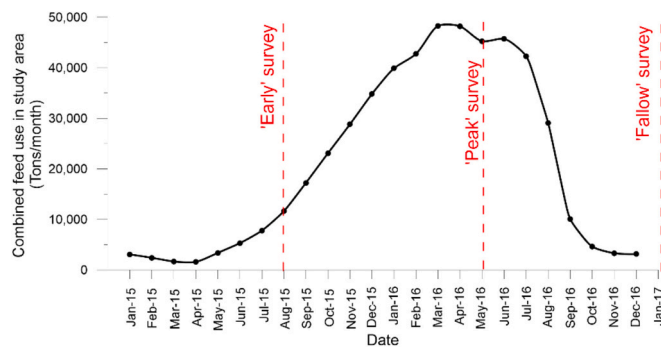


Fig. 2. Month combined feed use (tons) for the wider study area over the survey period (2015 and 2016).

along a transect radiating away from a single farm (denoted with 'R' preface): R0 m–50 m, R100 m–43 m and R600 m–34 m. Note that the first number in the station names represents distance to nearest farm, and the second number, site depth (both in meters).

The reference group (hereafter collectively termed '**Refs**') contained 7 stations that were between 8.9 and 17.6 km away from the nearest farm and were therefore almost certainly removed from the influence of farm waste (Fig. 1B). These Ref stations comprised one sub-group of five stations (Stations: 15020 m–58 m, 17,050 m–79 m, 17,670 m–110 m, 15,800 m–118 m, 15,460 m–279 m) situated within a cluster of islands in the Horsøyen area at the northern extent of the Frøya archipelago and a second subgroup of 2 stations situated within the Gjøvingen archipelago (10,150 m–66 m, 8940 m–75 m; Fig. 1B). Efforts were made to identify Ref stations that were comparable to the FF stations both in terms of depth and substrate.

Three repeat surveys were conducted: early in the production cycle (hereafter termed survey '**Early**'), late in the production cycle during peak feed use (hereafter survey '**Peak**'), and 3–7 months after the fish were harvested out (varied between farms, hereafter survey '**Fallow**') (Fig. 2). On each sampling event measurements were made of depositional flux rates (gravimetrically and with tracers; hereafter termed '**Suspended particulate**' waste indicators), multiple benthic environmental characteristics (including sediment geochemistry, tracers and macrofauna), hereafter termed '**Benthic**' waste indicators. The suspended particulate parameters were considered indicative of the prevalence and confirmation of the presence and spatial distribution of waste prior to settling. The benthic parameters were considered in two categories: i) 'benthic tracers', using relatively sensitive chemical tracers to confirm the presence of farm wastes, and ii) 'benthic effects', based on established ecological (macrofauna) changes and sediment organic content.

2.3. Indicators of suspended particulate waste

Deposition of suspended particulate matter was measured by deploying sediment traps at each station for a period of between 8 and 14 days immediately prior to conducting the benthic sampling. Each mooring supported a frame holding duplicate sediment traps (inner diameter 10 cm, aspect ratio 6, distance between cylinders 90 cm) mid-water, approximately 15 m above the bottom (mAB). Before deployment, all collecting cylinders were filled with clean seawater taken from the deployment site and 500 ml salt-water (45 ‰) with approximately 4 % buffered formalin added at the bottom of the cylinders as a preservative. After retrieval, the sediment traps were left to settle for 6–12 h before the top 70–80 % of the water was carefully decanted off and the remaining sample (<2 l) transferred to a sample container and retained for subsequent analysis.

In the laboratory, the volume of the sample was recorded before the contents were homogenized (by vigorous shaking) and a representative 1 l sub-sample was taken. The 1 l subsample was then further sub-

sampled with a 50 ml Bird-pipette after homogenizing the contents again by shaking. Three 50 ml sub-samples from each collection cylinder were filtered through precombusted and weighed filters (47 mm Whatman GF/F). Two filters were used for analysis of total particulate matter (TPM) and particulate organic matter (POM) after rinsing with 50 ml of ammonium formate to remove salts and preservative. The third filter for stable isotope ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) analysis was rinsed with 50 ml of filtered seawater. Conspicuous organisms (e.g. copepods) were removed from the filters by eye using a pair of forceps. TPM dry weight was determined gravimetrically after the material was dried at 105 °C for 24 h. POM on the filters was determined as the weight loss after ignition at 450 °C for 6 h. Stable isotope analysis was conducted on 7 mm diameter circles stamped out of dried filters using a stainless-steel core punch rinsed with 70 % ethanol between samples. The filter sub-samples were packed into tin capsules with sample weight dependent on farm production cycle and distance from the farm. For peak production, farm locations required one 7 mm subsample, while reference locations required two-three 7 mm subsamples.

All samples were analyzed by the University of California, Davis, Stable Isotope Facility for C and N, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ using a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire UK). Samples were run against reference materials (Bovine liver: $\delta^{13}\text{C}$ = 21.69, $\delta^{15}\text{N}$ = 7.72, Glutamic Acid $\delta^{13}\text{C}$ = 16.65, %C = 40.81, $\delta^{15}\text{N}$ = –6.8, %N = 9.52, Enriched alanine $\delta^{15}\text{N}$ = 41.13).

2.4. Benthic waste indicators

2.4.1. Benthic effects (macrofauna and organic content)

Triplicate sediment samples were collected from each station using a large, heavily weighted 0.1 m² van-Veen grab, which ensured adequate penetration into the varied sediment types. Each successful grab was sub-sampled for sediment organic content and macrofauna community composition. Macrofauna was subsampled using a 10 cm diameter, 10–15 cm deep core, which was carefully removed without losing the interstitial waters and a large bung was inserted into the bottom. Sediment cores were sieved through a 1 mm mesh and the material retained on the mesh was preserved with buffered 4 % formalin. Full taxonomy was conducted on the contents, whereby all fauna were picked out, counted and identified to the lowest possible taxonomic level. The resulting species count data were used to generate a suite of macrofauna based metrics and biotic indices. Macrofaunal assemblage metrics: S (number of taxa) and N (total abundance), Margalef species richness (d) and Shannon-Weiner diversity index (H') were calculated using the DIVERSE function in PRIMER v6 and the AMBI (AZTI Marine Biotic Index) was calculated using the BBI (v0.3.0) function in R. Sediment organic and inorganic carbon content (LOI450 and LOI950, respectively) was determined gravimetrically from a separate subsample within the same grab by drying the sediment at 40 °C for 48 h followed by combustion at 450° for 2 h.

2.4.2. Chemical tracers in sediments

The fatty acid content of sediments obtained from the same grab as the macrofauna sample were evaluated following the methods of Woodcock et al. (2019). The terrestrial biomarkers selected were 18:1n-9, 18:2n-6, 18:3n-3, and the sum of those three fatty acids (Sum_3TF) because they are proven indicators of fish farm waste (White et al., 2017; Woodcock et al., 2017) and known to be present in the fish diets being used at the study farms. Sediments were also analyzed for carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) stable isotope composition. Carbonate was removed from dried sediment samples using a modification of the method described by Komada et al. (2008), whereby 0.1 g of sediment was weighed out into a glass vial and 5 drops of HCl was added. Samples were allowed to effervesce for 5 min at room temperature and were thereafter placed in a drying oven at 50 °C overnight. This process was repeated until effervescence was no longer observed in the majority of samples. For 0.1 g of sediment, approximately 10 acidification cycles

and a total of 2.5 ml HCl was required to remove carbonates. Samples were then stored in the oven to keep dry before 40–50 mg of each sample was weighed out into tin capsules. All samples were sent to the University of California, Davis, Stable Isotope Facility for C and N, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ for analysis.

2.5. Statistical indicators of waste influence

The way in which each of the FF stations changed between surveys in comparison to the Ref stations was summarized using four statistics to indicate the response to the production cycle and 2 statistics to indicate possible residual effects (Table 1). Firstly, the mean value of each FF station in the (first) early survey ('FF_{Early}') was calculated to indicate the start point and scale of the numeric and whether it was a positive or negative number, to aid interpretation. Next, the absolute change between Early and Peak, and then Peak and Fallow surveys (in native units) were calculated for each FF station (denoted: 'FF_{AbChg_{e-p}}', 'FF_{AbChg_{p-f}}', respectively), which indicates both the direction and magnitude of change in native units. To compliment this, the 'Change from Parallel' (CFP) was calculated to give an indication of whether the difference between the FF station and Ref stations increased or decreased, and in which direction, both between the Early and Peak surveys and the Peak and Fallow surveys (denoted: 'CFP_{e-p}', 'CFP_{p-f}', respectively). The degree of change is expressed as a fraction of the final (Fallow) value at the FF station. A value of zero indicates a parallel response (no influence), >0 indicates FF increased relative to Ref over period, and < 0 (i.e., a negative fraction) indicates FF decreased relative to Ref over the given period. The index also indicates how big the deviation was relative to the start point for the FF station, e.g., +0.30 = 30 % increase relative to Ref. The fourth indicator for the response to the production cycle ('Sta × Sur') was the significance of the interaction between distance categories (factor Dist_cat), which separated FF from Ref stations, and Survey, where Dist_Cat was the grouping factor for FF and Ref stations (using aov() in R). Sta × Sur therefore indicated the level of significance in the event that an individual FF station responded differently through time (i.e., due to production cycle) as compared to the Ref stations (treated as a group). 'Station' was included in the model to account for between station variability (within Refs).

The residual effect analysis was conducted in two parts: firstly, an aov test was conducted to assess the significant of the difference between

Table 1

Description of statistics used to indicate significant and direction of changes in response to production cycle and signs of residual effects. Subscripts 'e-p' = Early to Peak survey periods, 'p-f' = Peak to Fallow survey periods.

Response to production cycle		
FF _{Early}	Mean value at first survey (Early)	= Station mean at FF _{Early}
FF _{AbChg_{e-p}}	Absolute change in value at FF station between Early and Peak (e-p) and Peak and Fallow (p-f)	= FF _{Peak} - FF _{Early} = FF _{Peak} - FF _{Fallow}
CFP _{e-p}	Change from parallel expressed as a fraction of the value at the FF station at Fallow survey.	= (FF _{Peak} - Ref _{Peak}) - (FF _{Early} - Ref _{Early}) / FF _{Fallow} = (FF _{Fallow} - Ref _{Fallow}) - (FF _{Peak} - Ref _{Peak}) / FF _{Fallow}
Sta × Sur	P-value for Station:Survey interaction term in model	= factor Dist_Cat:Survey P value (model: aov(FF [StationX] ~ Dist_Cat + Survey + Dist_Cat:Survey + Station))
Residual effects		
SigDiff _{E/F}	P-value indicating significance of difference between Early and Fallow surveys for the given FF station	= factor Survey P value (model: aov(FF[StationX] ~ Survey _{E,F}))
E/F_Dir	Direction of change between Early and Fallow, expressed as fraction Fallow of Early	= mean(FF _{Fallow}) / mean(FF _{Early})

the Early and Fallow period at each FF station based on the P value for that factor (Table 1). Secondly, the direction of the difference (whether Fallow value was larger or smaller than Early value) was indicated by a simple ratio between the FF_{Fallow} and FF_{Early} station means. Where >1 means Fallow values were higher than Early values and conversely for <1, e.g., a value of 1.25 = Fallow 25 % elevated relative to Refs.

These values were then compiled in a table and assigned colour scales and arrows based on cell value (in Microsoft Excel) to highlight trends and directions. The directions of the colour scales and arrows were adapted for each individual environmental variable based on established knowledge about which direction (i.e., an increase or a decrease) is indicative of a farm effect or influence (Supplementary data Table S1-S24). For example, decreased macrofauna diversity (Shannon index, H') typically indicates a deterioration in ecological quality and possible farm affect. Whereas, decreased sediment organic content (LOI450) indicates an improvement in environmental quality in the context benthic enrichment from fish farms.

The statistics generated for each station (Supplementary data Table S1-S24) were then assessed with respect to the criteria specified in

Table 2

Summary of criteria used to allocate scores to give an overall assessment of what the statistics indicate about whether a given station was influenced by the production cycle, conducted for each station and each indicator variable. 'Deterioration' = FF_{AbChg_{e-p}} or CFP_{e-p} in a direction consistent with farm impact of influence. Conversely FF_{AbChg_{p-f}} or CFP_{p-f} for 'Improvement'.

Examples of criteria for scores	Score	Inference about farm influence	
Sta × Sur P < 0.01 + any 'Deterioration' and 'Improvement', or Sta × Sur P < 0.1 + strong 'Deterioration' then strong 'Improvement'	3	Almost certainly	Enrichment effect from farm production
Sta × Sur P 0.01–0.1 + weak 'Deterioration' and 'Improvement', or Sta × Sur P > 0.1 + strong Deterioration then strong Improvement	2	Probably	
Sta × Sur P > 0.1 + 'Deterioration' then 'Improvement' indicated, one of which may be close to zero, or No Sta × Sur test but weak 'Deterioration' then weak 'Improvement' (at least 1 CFP >0.1), or either e-p or p-f missing but either e-p indicators strong 'Deterioration' or p-f indicates strong 'Improvement'	1	Possibly	
Sta × Sur P > 0.15, or Sta × Sur P < 0.1 but change (e-p, p-f) in same direction	0	None	Neutral
Sta × Sur P 0.01–0.01 + weak 'Improvement' then 'Deterioration', one of which may be close to zero, or No Sta × Sur test but strong 'Improvement' then strong 'Deterioration' (at least 1 CFP >0.1), or either e-p or p-f missing but either e-p indicators strong 'Deterioration' or p-f indicates strong 'Improvement'	-1	Possibly	Counter-effect
Sta × Sur P > 0.1 + 'Improvement' then 'Deterioration' indicated, one of which may be close to zero, or Sta × Sur P > 0.1 + strong Improvement then strong Deterioration	-2	Probably	
P < 0.05 + 'Improvement' then 'Deterioration' P < 0.1 + strong 'Improvement' then strong 'Deterioration'	-3	Almost certainly	

Table 2 and Table 3 which provides a framework for evaluating the FF AbChg statistics in conjunction with CFP and the Sta $\times$ Sur interaction to score the station from +3, being an almost certain farm affect, to -3, being an almost certain opposite effect to what would be expected from farm related influence/enrichment. The midpoint, 0, indicates a parallel response with respect to FF versus Refs and therefore, no apparent deviation from natural. This was conducted individually for each Station and for each environmental parameter. Table 3 provides the criteria for determining whether the Fallow survey samples were more or less consistent with a farm affect, i.e., looking for signs of residual effects before and after the production cycle plus 3–6 months recovery. A score of +2 indicates that the Fallow station was significantly and substantively more influenced (or impacted) than in the Early survey. A score of -2 indicates the opposed while 0 is neutral/unchanged. This test utilized a simple aov P value ($\text{SigDiff}_{E/F}$) and the index which indicates direction of change (F/E_{Dir}). This assessment procedure was repeated for all 22 stations for each of the eight suspended particulate waste indicating variables, six benthic tracer variables, and 9 benthic effects variables. In total, 572 individual assessments were made (each involving 8 descriptive statistics) for both Response to production and Residual effect (Supplementary material S1-S26). The production response and the residual effects scores were then summed for each station with each of the three groups of environmental variables (i.e., suspended particulate tracers, benthic tracers, benthic effects) to provide a multi-indicator, weight-of-evidence-based assessment of effects. These overall scores are then summarized in ordered, colour-coded tables, and selected results also displayed in colour-coded graduated circles that reflect the in ArcGIS to visualize the results in relation to spatial proximity to the farms.

2.6. Waste dispersal model simulation

We used the Regional Ocean Modelling System (ROMS, Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005) with a 3-level one-way nesting structure to model ocean currents in the study area. The outermost nesting level was the NorKyst800 system (Albretsen et al., 2011), which has a horizontal resolution of 800 m and covers the entire Norwegian coastline. The intermediate level has a horizontal resolution of 160 m and covers an area of 250 km $\times$ 200 km, centered around the study area. The innermost region covers the area shown in Fig. 1C with a horizontal resolution of 32 m. All nesting models have 35 terrain-following vertical levels. The simulation period spanned the production cycle during which the three surveys were conducted: i.e., 2015-02-01 to 2016-08-12. Details about the model and the nesting method are described by Carvajalino-Fernández et al. (2020b), which used a similar nesting structure with 2 nesting levels.

The particle transport model Ladim (LADIM, Ådlandsvik and Sundby, 1994, <https://github.com/bjornaa/ladim>) was used to model fecal dispersal from each location. Sinking, resuspension and burial was implemented as a Ladim plugin (<https://github.com/pnsaevik/ladi>

Table 3

Summary of criteria used to assign each station a score that reflects whether the sample from the Fallow survey was more or less impacted/influenced toward farm type effects than in the Early survey, for each variable.

Description	Criteria	Score
Effect of influence at Fallow significantly and substantively greater than at Early	P-Val < 0.05 & Index >2 (doubling), or P < 0.001	2
Effect / influence at fallow greater than at Early	P-Val < 0.1 & Index >1	1
Early and post-fallow comparable / N.S.	Non-significant, change $\approx$ 0	0
Early survey more influenced / affected than Fallow	P-Val < 0.1 & Index <1	-1
Early survey significantly and substantively more influenced / affected than at Fallow	P-Val < 0.05 & Index <0.5, or P-Val < 0.001	-2

m_plugins, version 1.2.1). Particle sinking velocity was sampled from the distribution of Bannister et al. (2016). In the simulation, one computational particle represented 1 kg of particulate organic matter (POM). This is similar to the modelling approach used by Carvajalino-Fernández et al. (2020b).

Size and position of individual farm cages were taken from aerial photographs (Bing Aerial). Cages were visible on the images for all locations except the outermost one, where cages were placed manually based on a crude knowledge of the farm layout. Feeding data from individual farms were used as model input, with peak production occurring around March 2016 (proprietary data). Fecal output was assumed to be 20 % of the feed usage, in accordance with Cubillo et al. (2016). Excess feed was not included in the simulation.

Experimental data from literature does not give size-dependent values for the critical shear stress required for fecal particle resuspension (Cromey et al., 2002, Law et al., 2016, Carvajalino-Fernández et al., 2020a, 2020b). We chose therefore to model this relationship using the Rouse number instead:

$$P = \frac{w}{\kappa} \cdot \sqrt{\frac{\rho}{\tau}},$$

where w is the sinking velocity, $\kappa = 0.41$ is the von Karman constant, τ is the shear stress and ρ is the fluid density. When $P > 1$, the sinking effect is stronger than the turbulent upward mixing and the particle will be pinned against the bottom; horizontal motion during flight will be brief and small (Lynch et al., 2014). In our model, we therefore require that $P < 1$ for fecal particles to be resuspended, giving a critical shear stress of:

$$\tau_c = \frac{\rho w^2}{\kappa^2}.$$

Horizontal movement of suspended particles was determined by the ocean currents as given by the hydrodynamic model. Vertical movement was set equal to the sinking velocity of the individual particle, plus an extra random upwards or downwards movement as determined by the vertical mixing of the hydrodynamic model. A consistent numerical scheme for heterogeneous mixing fields was used to propagate the particles (LaBolle et al., 2000) at each time step.

Model results were expressed on a 2D plot of the region in units of accumulated settled particles (g/m^2) for the modeled period (Fig. 3). The output was interrogated to obtain the predicted settle particles at each of the 22 sampling stations. Log10 transformed station-specific fluxes were then plotted against: distance to farm and the measured benthic responses in terms of both fatty acid tracers and effects and corresponding polynomial coefficients and model fits (residual sum of squares) were displayed.

3. Results

3.1. Examples for orientation to use of statistics

Four examples of the types of responses that occurred in the measured variables coupled with the associated statistics that were calculated to indicate change are provided in Fig. 4 for explanatory purposes.

3.1.1. Example a): Significant increase in N in response to production, no residual effect

Total mean abundance of macrofauna (N), which typically increases with increasing availability of organic carbon, increased by 2361 individuals at station 0 m–32 m between the Early and Peak surveys (FF_AbChg_{e-p}) and the corresponding change from parallel (CFP $_{e-p}$; response relative to Ref stations) was 9.4 times that of N at Fallow (Fig. 4a). The subsequent mean reduction between Peak and Fallow (FF_AbChg_{p-e}) was 2771 individuals and the CFP $_{p-e}$ was -11.1 times that of N at Fallow. The corresponding Sta $\times$ Sur interaction was highly

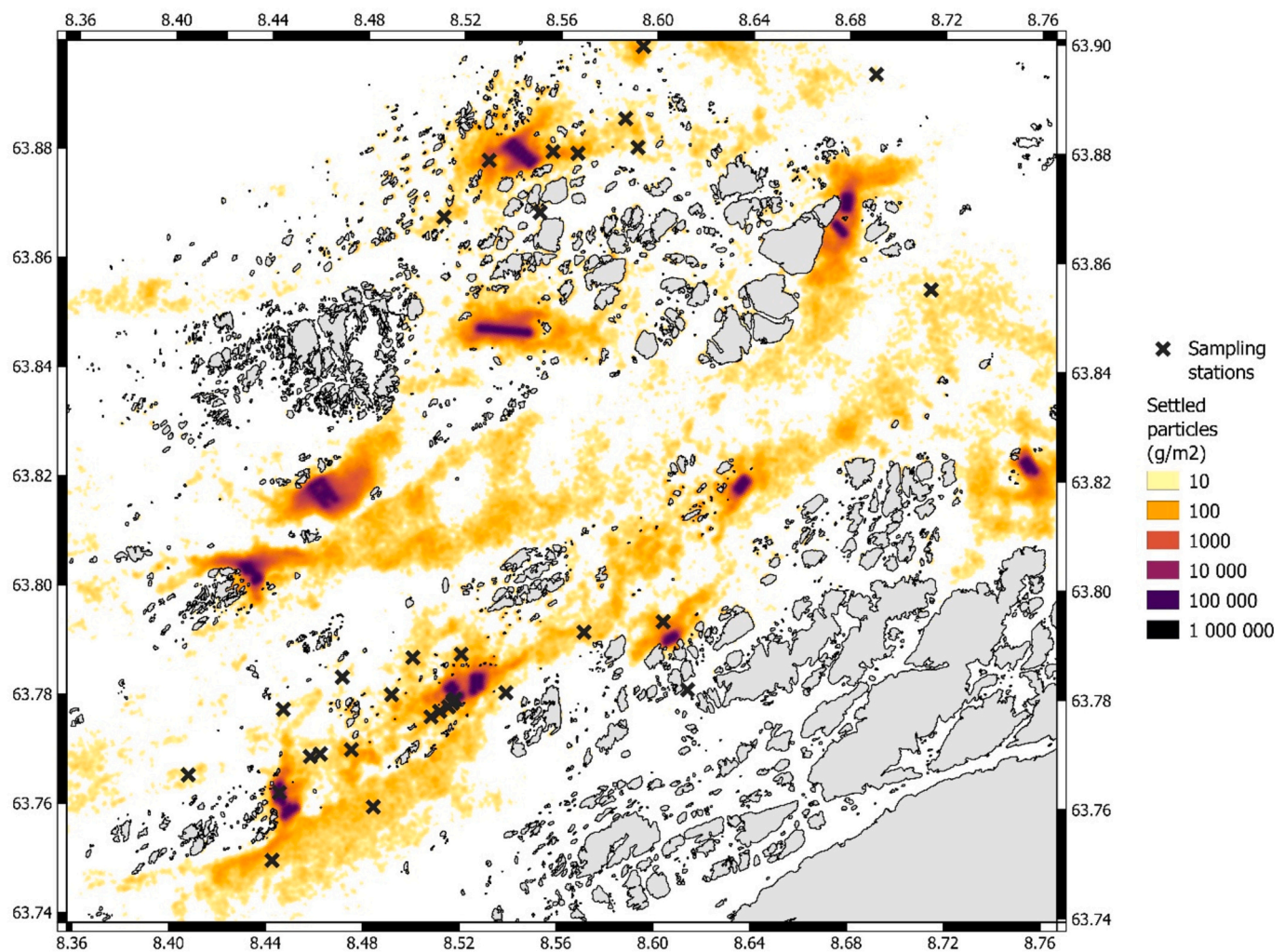


Fig. 3. Modeled prediction of accumulated settled particles (g/m²) in study area for model period. Black crosses indicate FF stations.

significant ($P < 0.0001$). Together the statistics indicated a positive response to the production cycle: Response summary = +3. Average N at the FF station at Fallow was 37 % that of Early but the means were statistically comparable therefore, Residual effect = 0.

3.1.2. Example b): Mildly significant decrease in response to production, no residual effect

At station 130 m–61 m, mean J' (Peilou's evenness index) at the FF and Ref stations was similar at both the Early and Fallow surveys but was reduced at the FF station relative to the Refs at the Peak survey (by 47 % of the FF Fallow J', Fig. 4b). The variability in the FF Peak estimate was high, but the interaction was still considered significant ($P = 0.02$). As a reduction in J' is consistent with increased organic enrichment, the Response summary = +3. Average J' at the FF station at Fallow was 83 % that of Early and the means were statistically comparable therefore, Residual effect = 0.

3.1.3. Example c): Impacted at early, value remained relatively constant, but generally improved

Station 0 m–32 m, benthic AMBI at FF decreased slightly (i.e., improvement in benthic quality) from Early to Peak (-0.1 , $CFP_{p-f} = -0.13$) and from Peak to Fallow (-0.3 , $CFP_{p-f} = -0.09$) indicating stable conditions with slight recovery from a strongly impacted starting state (Early AMBI = 5.6, Fig. 4c). As the trend was not consistent with a response to the concurrent production cycle, Response summary = 0. AMBI at Fallow was 92 % that of Early and the change was not

significant, hence Residual effect = 0.

3.1.4. Example d): Very minor response to production no residual effect

The MAMBI value at the FF station R630 m–57 m showed very little change between surveys and had a non-significant Sta × Sur interaction term (Fig. 4d). However, the Ref station mean reduced slightly (indicating a slightly more impacted state) at Peak and this was not mirrored by the FF station (remained relatively less impacted), hence Response summary = -1. As the Early and Fallow values were comparable, Residual effect = 0.

The same exercise was undertaken for each of the 650 assessments (full summary of statistics provided in Supplementary material S1–26). The summary statistics for one variable, suspended particulate matter (g m⁻² d⁻¹), is provided in Table 4. In this instance, most stations in close proximity to the farms (ca. <400 m) increased in mass between Early and Peak and then decreased again to near-background at Fallow. Significant production responses were observed at most FF stations <1000 m away (the most distant of which being at 920 m–196 m). Residual effect (in this context, TPM levels elevated at Fallow relative to Peak) were apparent at most of the stations along the farm transect (denoted by the 'R' prefix).

3.2. Integrated assessment: Suspended particulates

3.2.1. Response to production cycle

Fluxes of suspended particulates in water column showed a clear

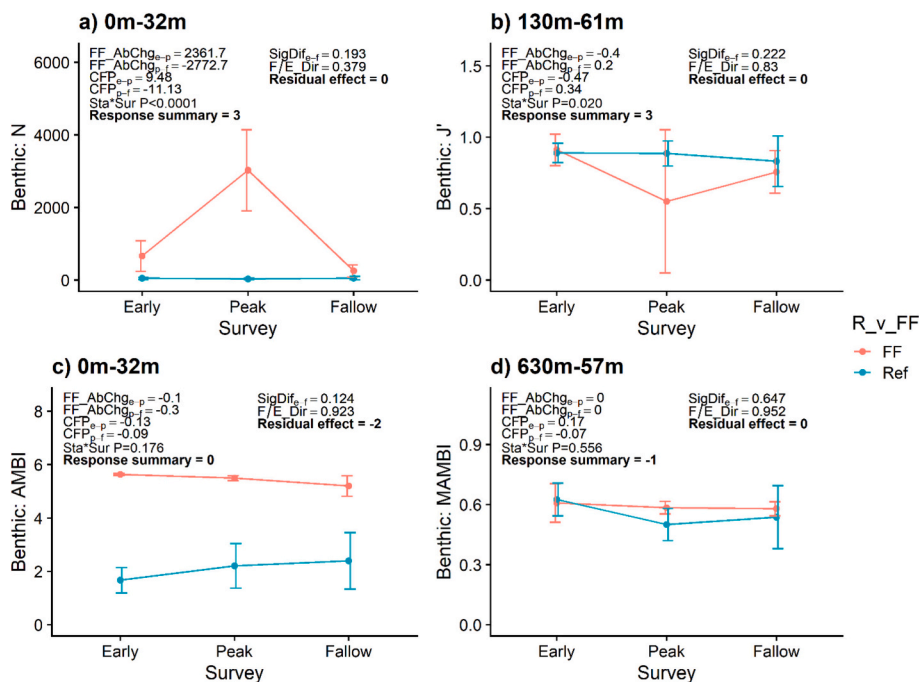


Fig. 4. Examples of relative change plots for index calculations: **Top left:** Station 0 m–32 m, benthic N (total abundance); **Top right:** Station 130 m–61 m, benthic J; **Bottom left:** Station 0 m–32 m, benthic AMBI; **Bottom right:** Station R630 m–57 m benthic MAMBI.

Table 4

Summary of statistics providing an overall assessment of: a) response to production cycle ('Summary response'), and b) Residual effects ('Summary residual'), calculated for each station for the (example) variable: Total particulate matter (TPM, $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) of seston. See Table 1 for a description of each of the statistics. Results for each and all of the suspended particulate variables are provided in Supplementary Information Table S1 – S24. Significance: '****' = $P < 0.001$, '***' = $P < 0.01$, '**' = $P < 0.05$, '.' = $P < 0.15$.

A. Total particulate matter (TPM)											
Station	Response to production			Residual effect?			Summary			Summary	
	FF_Early	FF_AbChg_e-p	FF_AbChg_p-f	Sta x Sur	P-Val	Sig.?	FF_Early	FF_AbChg_e-p	FF_AbChg_p-f	Summary Response	Summary residual
R0m-50m	5.31	35.96	-38.91	0.000	***		15.58	-16.75	3	0.036 *	0.44 -2
0m-32m	5.78	12.54	-15.24	0.007	**		4.30	-5.12	3	0.159	0.53 0
R200m-35m	5.53	1.57	-4.58	0.000	***		0.91	-2.03	3	0.047 *	0.46 -2
130m-61m	2.42	2.58	-1.31	0.000	***		0.89	-0.50	3	0.151	1.53 0
200m-39m	7.22	-2.07	-2.83	0.000	***		-0.58	-1.45	0	0.099 .	0.32 -1
200m-75m	4.46	0.42	-0.66	0.174			0.27	-0.28	1	0.858	0.95 0
400m-59m	2.77	-0.17	1.25	0.226			0.14	0.18	0	0.376	1.39 0
470m-78m	4.83	-2.95	1.91	0.006	**		-0.59	0.36	-3	0.158	0.79 0
500m-67m	2.95	NA	NA	NA	NA		NA	NA	NA	0.001 **	1.51 1
R600m-34m	2.82	-0.15	-1.01	0.065	.		0.35	-0.94	3	0.122	0.59 0
630m-57m	3.90	1.32	-1.29	0.005	**		0.52	-0.47	3	0.958	1.01 0
650m-60m	4.67	-0.36	0.19	0.811			0.08	-0.08	1	0.750	0.96 0
920m-196m	5.95	0.62	5.64	0.000	***		0.11	0.42	2	0.001 ***	2.05 2
1000m-95m	4.51	-1.91	1.26	0.231			-0.31	0.19	-1	0.525	0.85 0
1150m-48m	4.46	-2.42	0.88	0.041	*		-0.58	0.11	-2	0.194	0.65 0
1200m-38m	4.20	-0.15	-0.85				0.18	-0.43	1	0.109	0.76 0
1280m-64m	3.72	-0.51	1.48	0.220			0.05	0.20	0	0.389	1.26 0
1300m-76m	3.69	1.99	-2.27				0.80	-0.82	1	0.431	0.92 0
1620m-55m	3.03	0.40	-0.15				0.34	-0.21	1	0.706	1.08 0
1620m-128m	4.89	NA	NA	NA	NA		NA	NA	NA	0.755	0.89 0
1900m-67m	3.31	-0.63	0.02	0.696			0.04	-0.19	1	0.116	0.82 0
2000m-195m	6.74	NA	NA	NA	NA		NA	NA	NA	0.004 **	1.82 NA

response to production at all FF stations within 400 m of a farm, and the strength of the response increased predictably (from 'very likely' to almost 'certainly') with reducing distance to farm (Fig. 5A & Fig. 6A). This trend was particularly evident in terrestrial fatty acids (18,1n-9, 18,2n-6, 18,3n-3) and the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures, which were consistently influenced out to 600 m + (Supplementary material

Tables S21–24). Seston quantity and composition (TPM & POM) were similarly influenced, but not to the same spatial extent from farms (Supplementary material Tables S19–20). Several stations further afield (out to 1300 m away) were also 'probably' influenced, especially 500 m–67 m and 1280 m–64 m which were situated in adjacent water bodies and not directly down-current from any farm (Fig. 6A). Notably, station

Depth (m)	Dist2Farm (m)	FF Station	WATER COLUMN		SEABED			
			A. Suspended particulates		B. Benthic tracers		C. Benthic effects	
			Response	Residual	Response	Residual	Response	Residual
50	0	R0m-50m	0.762	-0.214	0.467	-0.400	-0.074	-0.111
32	0	0m-32m	0.476	-0.214	0.533	-0.200	0.000	0.278
43	100	R100m-43m	0.714	-0.357	0.533	-0.300	0.083	-0.222
61	130	130m-61m	0.267	0.000	0.400	0.000	0.185	0.000
39	200	200m-39m	0.429	0.000	0.133	0.100	0.148	-0.056
75	200	200m-75m	0.400	0.143	0.222	NA	NA	NA
59	400	400m-59m	0.333	0.214	0.267	0.000	0.000	0.000
78	470	470m-78m	-0.048	0.143	-0.133	-0.100	0.037	0.000
67	500	500m-67m	0.333	0.286	-0.133	-0.100	-0.037	0.000
34	600	R600m-34m	0.714	0.143	-0.133	0.200	0.444	0.389
57	630	630m-57m	0.250	0.125	0.400	-0.300	-0.259	0.056
60	650	650m-60m	0.067	-0.143	-0.067	-0.500	0.037	0.000
196	920	920m-196m	0.238	0.214	0.467	0.000	-0.167	-0.056
95	1000	1000m-95m	0.238	0.071	0.200	0.000	0.259	-0.056
48	1150	1150m-48m	0.095	0.143	0.000	0.100	-0.259	0.000
38	1200	1200m-38m	0.222	0.167	0.111	0.000	NA	NA
64	1280	1280m-64m	0.400	0.143	0.133	-0.100	-0.222	0.056
76	1300	1300m-76m	0.143	0.143	0.000	NA	NA	NA
55	1620	1620m-55m	0.000	0.071	0.133	-0.200	0.037	0.000
128	1620	1620m-128m	-0.111	0.357	0.067	0.000	-0.222	0.056
67	1900	1900m-67m	0.333	0.214	0.000	0.000	0.074	-0.056
195	2000	2000m-195m	-0.222	0.500	0.000	-0.200	-0.111	0.056

Key to response to production cycle		Key to residual effects	
-1.00	Certain opposite affect	-1.00	Significant and substantive improvement
-0.66	Very likely	-0.66	Very likely
-0.33	Probably	-0.33	Probably
0.00	Neutral - followed background	0.00	Unchanged
0.33	Probably	0.33	Probably
0.66	Very likely	0.66	Very likely
1.00	Certain farm effect / influence	1.00	Significant and substantive residual impact

Fig. 5. Collective assessment of **response to production cycle** and **residual effects** for **a) water column suspended particulates** (biodeposition mass, and tracers) **b) benthic tracers** (terrestrial fatty acids 18:1n-9, 18:2n-6, 18:3n-3, and δ C13 and δ N15 isotopes), and **c) benthic effects** (sediment organic content, macrofauna metrics and indices) colour-coded according to likelihood. Values are the average of the response to production scores (for all relevant variables) normalised on to a scale form 0–1, whereby 0 indicates neutral or parallel response to background Reference values and 1 indicates clear, certain response during peak production, with positive values (shaded red) indicating a direction consistent with organic enrichment or presence of farm waste, and negative values (shaded green) indicating opposite effect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1900 m–67 m, which was situated in a deep relatively exposed nearby channel, was also ‘probably’ influenced.

3.2.2. Residual effects

The characteristics of the suspended particulate matter were generally ‘unchanged’ or ‘probably’ changed between the Early and Fallow surveys, which straddled the regional production cycle (Fig. 5A and Fig. 6B). Most of the more distant FF stations, beyond ca. 200 m away ‘probably’ had greater farm waste content in the final Fallow survey than in the Early survey. This was particularly apparent at the deeper reference sites. Stations close to the farms (0–200 m away), especially near to Farm-R, ‘probably’ had less farm-derived suspended particulate waste at Fallow compared to Early.

3.3. Integrated assessment: Benthic tracers

3.3.1. Response to production cycle

The cumulative summary of benthic tracers indicated a clear response to production in the range of ‘probable’ to ‘very likely’ for all FF stations within 200 m of a farm (Fig. 5B, Fig. 7A). Significant interactions consistent with farm influence were particularly evident in all three fatty acids in the sediments, while δ 13C and δ 15N also increased then decreased in response to production, but changes relative to the Reference sites was generally non-significant (Supplementary material Tables S1–6). Indicators of farm waste in accordance with the

production cycle (in the ‘probable’ to ‘very likely’ range) were also observed further away, most notably at stations 400 m–59 m, 630 m–57 m and 920 m–196 m. There was also weak evidence of increased prevalence of farm waste at 4 stations between 1000 m and 1620 m away from any active farms (Fig. 5B, Fig. 7A). Weak opposite responses, where tracers were lower at peak production, were observed at R600 m–34 m, 470 m–78 m, and 500 m–67 m.

3.3.2. Residual effects

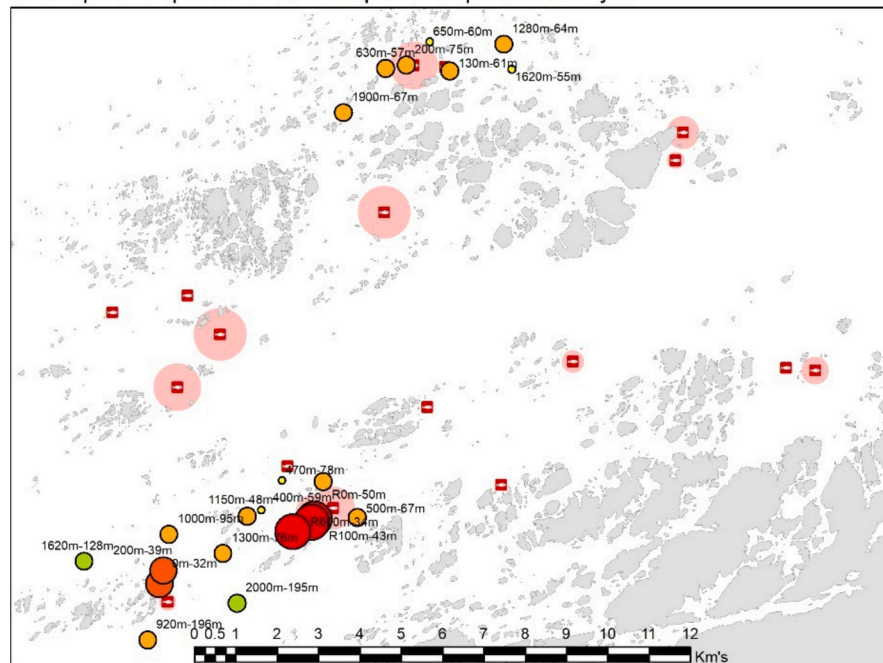
At most FF stations prevalence of the sediment tracers was either the same or slightly reduced at point of Fallow (relative to Early); the exceptions being two stations close to Farm-R (R0 m–50 m and R100 m–43 m) and two stations 630–650 m away from any farms, which exhibited probable to very likely improvement (i.e., less waste present at Fallow than Early). Only R600 m–34 m indicated a probable increase in tracers at the Fallow survey, relative to the Early survey (Fig. 5B).

3.4. Integrated assessment: Benthic effects

3.4.1. Response to production cycle

Responses to the production cycle were generally less evident in the benthic effects indicators due to a lot of non-significant results as well as some conflicting responses between variables (Supplementary material Tables S8–15). Collective positive responses, consistent with farm effects, were evident at R600 m–34 m (Probable – Very likely), 130 m–61

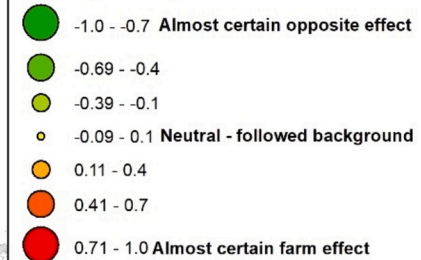
A. Suspended particulates - Response to production cycle



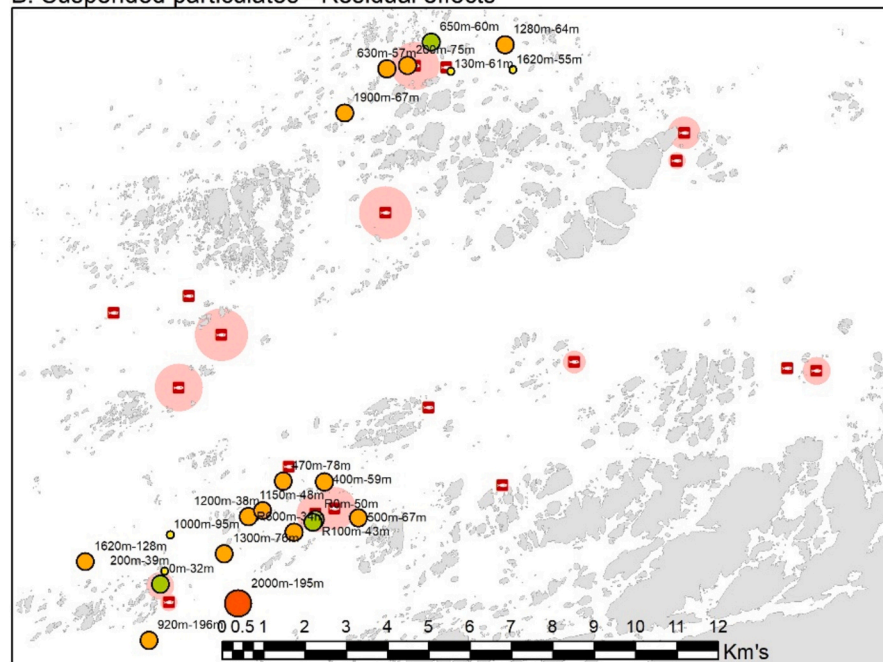
Legend

Operational fish farms

Certainty & magnitude



B. Suspended particulates - Residual effects



Legend

Operational fish farms

Significance and size

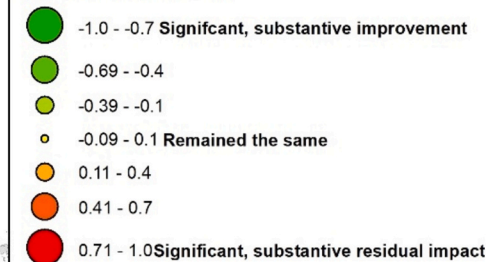


Fig. 6. Results from suspended particulates in the water column (mid-water). Site map of Frøya archipelago indicating active marine farms (red fish symbol, with relatively level of production in study period indicated by pink circles – no pink circle = no production in period) and sampling stations colour coded and proportionally scaled to indicate mean, multi-indicator-based normalized assessment of: A) certainty and magnitude of response to production cycle and B) size and significance of residual effects of. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

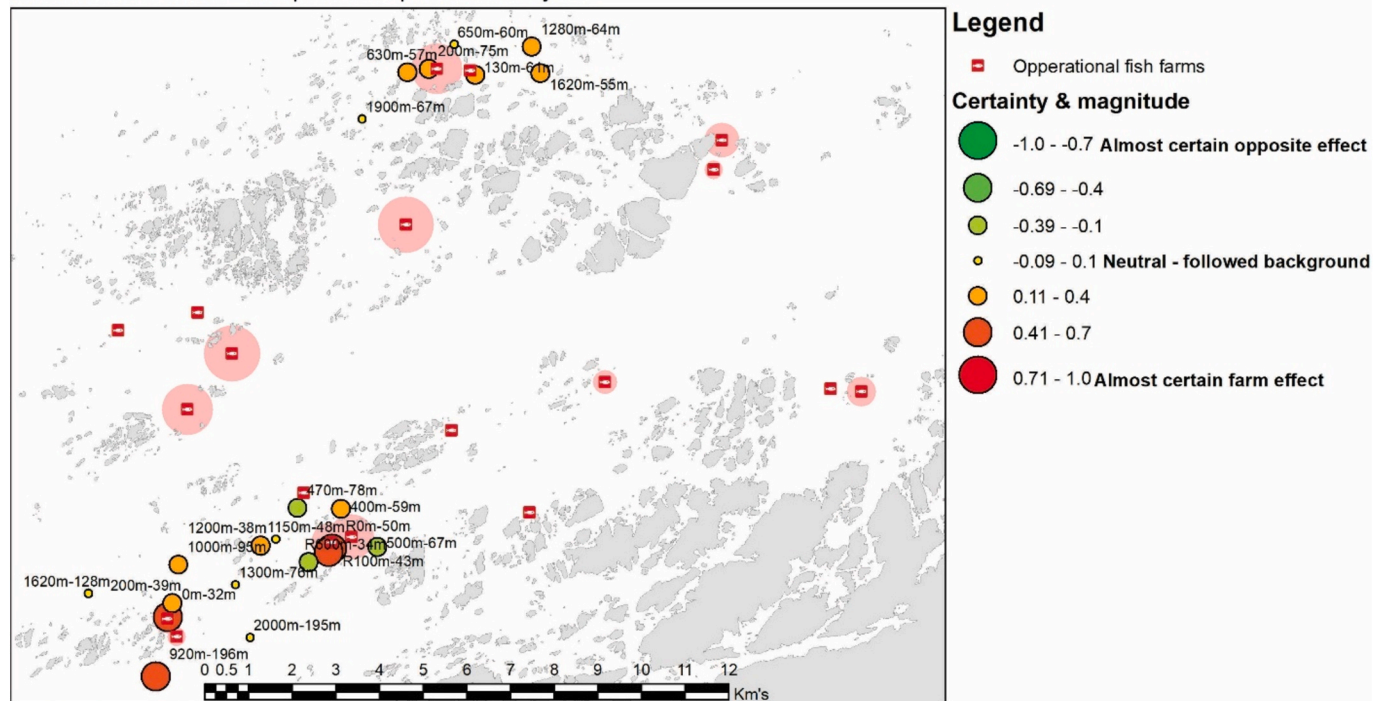
m, 200 m–38 m and 1000 m–95 m (Neutral – Probable, Fig. 5C, Fig. 7B). It was notable that significant interactions consistent with farm effects were not observed for other FF stations within 200 m of a farm (where a response would be expected), especially R0 m–50 m and 0 m–34 m. In most of these cases, the benthic indicators were already strongly impacted at Early (refer e.g. Fig. 4a,c), and while the Sur-Sta interaction was often significant, this was due to consecutive improvements in the indicator at FF (relative to Ref), which was not deemed to be consistent with a response to production, and as such were allocated a ‘neutral’ (0) response.

Some of the FF stations indicated an opposite effect in response to the production cycle. Generally speaking, the cases of weak opposite effects (in the range of neutral to probable) were observed further away from the farms at 630 m–57 m, 1150 m–48 m, 1280 m–64 m and 1629 m–128 m.

3.4.2. Residual effects

Evidence for residual benthic effects was negligible with Sig.Diff and E/F Dir indicating no change (between Early and Fallow, Fig. 5c) for the majority of the FF stations. However, FF station R100 m–43 m exhibited

A. Benthic Tracers - Response to production cycle



B. Benthic effects - Response

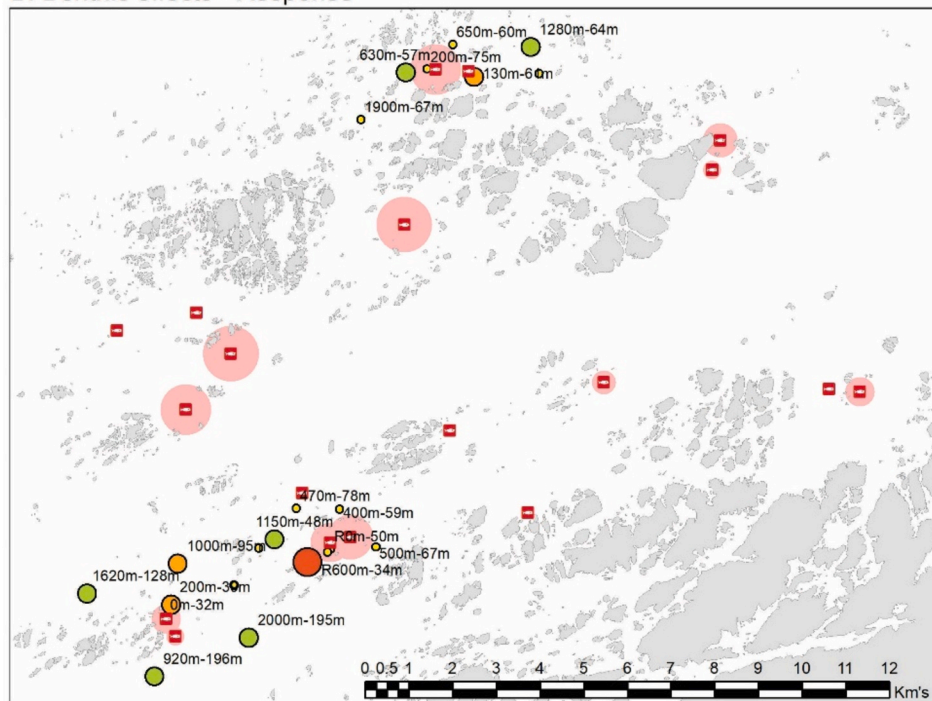


Fig. 7. Certainty and magnitude of response to production cycle from: **A) fish-waste tracers in sediments, and B) sum of indicators of benthic enrichment effects.** Site map of Frøya archipelago indicating active marine farms (red fish symbol, with relatively level of production in study period indicated by pink circles – no pink circle = no production in period) and sampling stations colour coded and proportionally scaled to indicate mean, multi-indicator-based normalized assessment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

probable improvement between Early and Fallow (collective assessment = 0.22, respectively). Conversely, probable to very likely residual benthic effects consistent with organic enrichment existed for station R600 m–34 m, down-current from Farm-R, and for 0 m–32 m.

3.5. Linear relationships with modelling outputs

The amount of predicted settled particles ($\log_{10}$, g/m^2) was highest for the two stations closest to the farms (i.e., 0 m), but reduced rapidly with distance (Fig. 8A). Trends with respect to distance were difficult to distinguish beyond ca 200 m, however all the highest predicted settled particles tended to occur within 700 m of the farm (Fig. 8A). The fit of

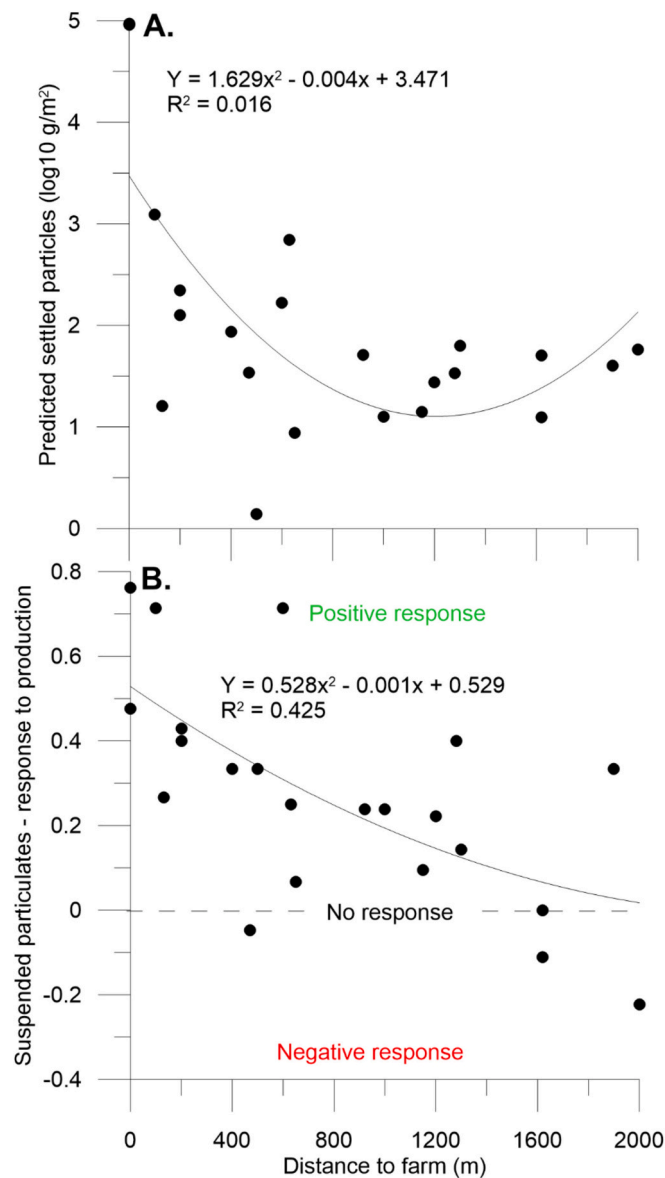


Fig. 8. Distance from farm (in a straight line, m) plotted against: a) predicted (modeled) accumulated settled particles ($\log_{10} \text{ g/m}^2$) for the FF stations, and b) response to production observed in suspended particulates in mid-water (integrated response from all variables, scale: 1 (almost certain enrichment response) to -1 (almost certain opposite response), and 0 = no response).

the polynomial model was poor ($R^2 = 0.016$). In comparison, the trend with respect to distance from the farm for the observed response to production in suspended particulates in the water column (mid-water) was more apparent (Fig. 5C). The strongest positive responses to production were observed closest to the farm and the trend decreased relatively linearly ($R^2 = 0.425$) with increasing distance away.

The benthic response to production evidenced from prevalence of terrestrial fatty acid tracers in sediments increased relatively consistently in accordance with quantity of ($\log_{10}$ transformed) predicted settled particles (Fig. 9A), meaning that sites that were predicted to receive the highest amount of farm waste also generally showed a stronger positive response to the production cycle ($R^2 = 0.513$). By contrast, there was no clear trend evident with respect to the response observed in benthic effects (Fig. 9B), being variable around 0 for the range of predicted settled particles.

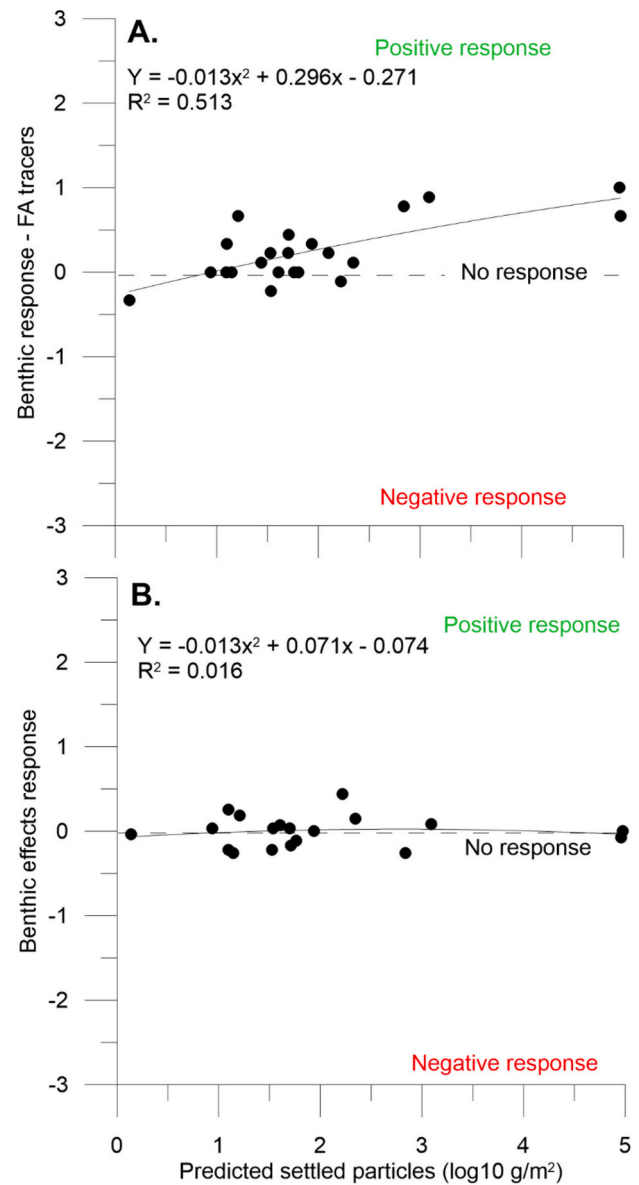


Fig. 9. Regressions of predicted (modeled) accumulated settled particles ($\log_{10} \text{ g/m}^2$) for the FF stations against benthic response to production cycles evidenced by: A) terrestrial fatty acid tracers, and b) chemical and biological effects.

4. Discussion

4.1. Broad-scale responses to production cycle

The approximately synchronized production cycles of numerous large capacity farms in the Frøya region of mid-Norway provided a unique opportunity to test for low-level effects in the wider receiving environment. Far-field effects were detected; however, the patterns were spatially and temporary complex, with a notable disparity between the spatial range of farm-derived particles and any related benthic effects. The results thereby highlighted an important distinction between the 'field of influence' and ecological effect per se.

The comprehensive array of sample stations deliberately spanned the conventionally understood effects 'footprint' zone, usually $<0.2\text{--}0.3 \text{ km}$ away from a functioning farm (Borja et al., 2009; Brooks and Mahnken, 2003a; Giles, 2008), as well as the previously observed extreme outer limit of influence of approximately 1 km (Bannister et al., 2016; Keeley et al., 2019; Sarà et al., 2006). In addition to the near-field (farm scale,

0–0.5 km away) and far-field (regional 0.5–2 km, beyond the immediate farm footprint) clusters, the sampling array included two important reference clusters in the very far-field (>8 km, 'Ref') clearly removed from any farm influence and could therefore be used to reliably reflect natural conditions and associated temporal variability. This was particularly important for the purpose of this study, which was to test for minor changes at the outer extent of influence. All stations were necessarily located on soft sediments (often amidst patches of rock and mixed substrate) and often in 'deep-spots' where dissipating currents and the persistent force of gravity dictates that particles will eventually settle; thereby comprising potential accumulation points. Another unique feature of this study was that many of the potentially influenced FF stations were in 'a-typical' positions relative to the farm installations i.e., not on linear down-current transects that are usually employed to elucidate gradient effects. Instead, the stations were often positioned behind rock clusters or main channels, around bends, or perpendicular to the flow of the main body of water. The results were appropriately varied, especially beyond >200 m away, where the responses were not a clear function of distance and instead included a mixture of clear farm effects, but also neutral and opposite effects. Much of which can presumably be explained by the bathymetry and hydrodynamics and the length and complexity of the actual pathway that a particle must take to reach the station; as opposed to the direct path between two points that was used in the analysis.

Samples obtained from the sediment traps in-particular showed a disproportional increase in depositional flux rate at most stations between Early to Peak production surveys, and the associated terrestrial fatty acids and isotopes signatures indicated that they were at least partially derived from fish feed sources (Woodcock et al., 2017). While this was the anticipated response for stations <400 m away, it was notable that clear positive responses were also observed at a station 1280 m from any farm (1280 m–64 m) in a semi-exposed northern area of the archipelago bordering the open sea (Fig. 6a). Similarly, a station 1900 m away from the same farm, but in the opposite direction (1900 m–67 m), also recorded elevated levels of farm-derived particles relative to the background conditions. In contrast, another station, only 470 m from a farm was statistically indistinguishable from the reference sites.

Observations of a non-linear and variable response with respect to distance-from-farm highlight the need for high resolution depositional modelling, which can adequately accommodate complex bathymetries and hydrodynamics. Results from the model that was applied in this study suggested that: 1) there is still some way to go before the models can adequately resolve such spatial complexities, and 2) the influence of waste in the far-field is probably underestimated by such models, whereby the (water column particles and benthic tracer) responses that were observed in the 200–1200 m range were not well predicted by the model. The latter could be attributed to a number of factors, for example, this study adopted a comprehensive observational approach with novel tracers that are possibly more sensitive than the methods that have been used to validate models to date. Additionally, there are known deficiencies in the way in which particle dynamics are simulated, most pertinent here could be the way in which particles break apart upon entering turbid water. According to Stokes' law, smaller particles sink at much slower rates and resuspend more readily. Current assumptions are that >75 % of the particles (by mass) settle within 500 m of a farm, mainly as a product the size distribution at point of release (Bannister et al., 2016), if subsequent break-up is rapid and extensive, then a much greater proportion will remain in suspension longer, increasing transportation range, i.e., deposited in the far-field zone. In accordance with the findings of Robinson et al. (2005), these fine particles are very likely what was being detected in the more distant locations in this study.

While many clear responses to the production cycle were observed in the suspended particulate matter, and to a lesser extent the benthic tracers, the observed trends did not translate predictably into measurable benthic effects. A weak positive relationship between the

suspended particulate matter and the benthic tracers (Pearson $R^2 = 0.21$) was observed, suggesting some level of benthic-pelagic coupling, but neither shared a meaningful relationship with the benthic effects indicators (Pearson $R^2 < 0.1$). It can therefore be interpreted that while the influence field of the farms was relatively large, once dispersed and diluted, the organic loading was insufficient to appreciably alter the macrofauna communities in the far-field and was therefore presumably within the assimilative capacity of the receiving environment. This finding is consistent with that of Sarà et al. (2006), who also described an apparent disconnect between influence field and the current concept of benthic effects, and raised questions surrounding the concept of 'impact'. In our case, the biological effects were entirely based on macrofauna community composition, which is a well-established and robust ecological indicator (Pearson and Rosenberg, 1978). However, it should be acknowledged that this was assessed from relatively small (triplicate) sub-cores, and it is possible that sparsely distributed or rare species were not well sampled, which may have impacted our ability to detect more subtle changes in diversity.

An unexpected result from the benthic effects data was that several of the stations closest to the farms (i.e., within 100 m) did not meet the statistical criteria for a clear response to the production cycle. However, closer inspection of the Early data indicated that sediments closest to Farms were already strongly impacted at the first (Early) survey. These stations tended to have notably reduced richness and AMBI values in excess of 4 (indicative of 'poor' ecological quality status, Muxika et al., 2005) at survey Early. Consequently, the change between Early and Peak for those benthic variables was negligible, while a general trend of recovery occurred subsequently. Therefore, the CFP_{e-p} (change from parallel) statistic was not consistent with an 'impact' and/or the Sta × Sur interaction was not significant, which confounded the response indicators. Given that this trend was apparent in the benthic effects data and not the suspended particulates or benthic tracers, it suggests that either the composition of the macrofauna community had had been rapidly impacted with the introduction of young fish approximately 3 months prior to survey Early, and/or the seabed was carrying some residual impacts from previous production cycles, as both sites had been in use for many years. Interestingly, total macrofauna abundance (N) did show a strong production response at 0 m–23 m, the assimilative biomass in the sediments can still be responsive despite suppressed diversity (Keeley et al., 2019). Long recovery trajectories coupled with rapid and pronounced impact responses upon farm reintroduction have also been observed at low current sites (Keeley et al., 2015). As such, these findings reiterate that recovery and re-impact trajectories in the benthic environment occur on a different time scales and don't necessarily couple tightly with rates of depositional flux.

4.2. Residual degenerative effects

This study provided only limited evidence of longer-term degenerative trends, which was assessed here through tests for residual effects in accordance with the production cycle. The suspended particulates captured at stations situated close to, and in the immediate down-current direction from, the farms were unchanged or slightly improved (less farm related waste) at Fallow relative to Early. Stations that 'improved' were predominantly within 200 m of Farm-R, where effects from the early production were most pronounced. Whereas, when the Fallow survey was conducted, the production and any associated discharge had ceased at least 3 months prior, after the fish were harvested out. Nonetheless, stations R600 m–34 m and 0 m–32 m did show clear signs of residual benthic effects, despite being strongly impacted at time Early, which is evidence of an undesirable degenerative trend in the near-field.

Although the evidence for residual benthic effects was negligible, some of the more distant regional stations also showed signs of lingering influences of particulates in the water column, which was an interesting result given where they were situated. This occurred at the most distant

and deep stations (2000 m–195 m, 1620 m–128 m and 920 m–196 m), situated in the main channels adjacent to two of the main study farm areas. A delayed response in the outer, and deeper stations could be indicative of a progressive spreading of the waste over time due to resuspension processes, which can re-entrain the particles into the water column when current speeds exceed the critical erosion threshold (Adams et al., 2020; Carvajalino-Fernández et al., 2020a, 2020b). The study region is known to be subjected to periodic storm events, with moderately large, long-period waves that have deep penetrating wave orbitals as well as wind-induced currents, which on one occasion clearly visibly changed the condition of the sediments beneath one farm in a matter of days (Author Pers. Obsv.). It is interesting that the same spatial pattern was not evident in the benthic tracers, which showed minimal signs of residual farm effect aside from the reduced prevalence of tracers close to the farms. Such decoupling is likely related to the biological availability and therefore relatively short persistence in the marine environment of terrestrial fatty acids (Woodcock et al., 2019).

Lastly, on average, the Ref stations indicated a minor deterioration (toward increased organic enrichment) at the mid (Peak) survey that was consistent across benthic fauna richness and diversity indicators. This was partly responsible for the interactions that suggested a negative response to production at some of the FF stations for benthic fauna. On the surface this can be interpreted as a farm effect at the reference sites, which would confound the study design. However, it is extremely unlikely that any meaningful quantity of organic particles from a fish farm were transported >8 km, including across open water masses, and because none of the tracers showed any sign of being elevated at the reference stations, the general changes that occurred there was attributed to natural variability, or more specifically, seasonality. The Peak survey occurred in May, which coincides roughly with the spring algal bloom period, and presumably an increased natural depositional flux of dead phytoplankton cells.

5. Conclusion

The data presented here have been compiled, analyzed, integrated and synthesized to provide a robust multi-indicator assessment of both the response to production and residual effects arising from farm-derived organic particulates on multiple spatial scales. Elevated concentrations of waste particles were detected in the water column in response to the production cycle consistently out to approximately 1.3 km and a similar corresponding trend was evident in the fatty acid and isotope tracers in the sediments. However, the presence of waste generally did not translate into benthic ecological effects in the far-field, with a weak and varied response beyond 600 m. The overall conclusion being that despite synchronized discharge of large quantities of waste within a single geographical region, it was sufficiently dispersed and diluted such that it was able to be effectively assimilated by the receiving environment without notably modifying the composition of the benthic community. So, although a relatively wide area was ‘influenced’ by the waste, the discharge did not result in meaningful pollution in the ecological context. It is recommended that for the purposes of depositional footprint modelling it is useful to consider both concepts: i. e., the range of influence, and the range of effects.

Potential accumulation and degenerative trends were evident at some far-field locations, especially at the deeper stations adjacent to the farms, but the majority of the stations beyond 600 m showed little or no signs of persisting effects. The potential for accumulative effects does appear to be a site-specific issue determined by relatively fine-scale bathymetry and hydrodynamics. It is therefore prudent to evaluate new farming localities carefully with this in mind, and to undertake routine long-term monitoring in locations that have the physical propensity to accumulate particles. Waste dispersion modelling is useful for gauging the distribution of waste plumes, but there is still much room for improvement for use around complex bathymetries and in how particle dynamics are simulated. Collectively however, the results suggest that

relatively large-scale sea-cage farming can occur without impacting the broader benthic environment when conducted in physically dynamic and dispersive environments.

CRedit authorship contribution statement

Nigel KEELEY: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Pål SÆVIK:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Skye WOODCOCK:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Raymond BANNISTER:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nigel Keeley reports financial support was provided by Norges Forskningsrad. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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