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Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay in Southwestern New Brunswick

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ABSTRACT

Chang, B.D., Page, F.H., Losier, R.J., Greenberg, D.A., Chaffey, J.D., and McCurdy, E.P. 2005. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay in southwestern New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2599: iii + 55 p.

Infectious salmon anemia (ISA) was first detected in salmon farms along the mainland shore of southwestern New Brunswick in 1996-98 and in farms in the adjacent western Deer Island area in late 1998. Farms in both areas have been reinfected in subsequent years and there has been speculation that the virus may have been transmitted through the water between the mainland and Deer Island farms. In an effort to help estimate the potential for water exchange of the ISA virus between farms in these areas, we used a 3-dimensional tidal water circulation and particle transport model. Water exchange scenarios based on the movement of particles during one tidal excursion, as predicted by the model, are compared to those estimated by a simple method assuming a 5-km radius circular zone of water exchange around each farm. We also examined the effectiveness of removing certain farms in order to create a separation zone between mainland and Deer Island salmon farms.

RÉSUMÉ

Chang, B.D., Page, F.H., Losier, R.J., Greenberg, D.A., Chaffey, J.D., and McCurdy, E.P. 2005. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay in southwestern New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2599: iii + 55 p.

L’anémie infectieuse du saumon (AIS) a été décelée pour la première fois dans des fermes de salmoniculture situées dans le Sud-Ouest du Nouveau-Brunswick, sur le rivage de la partie continentale de la province, entre 1996 et 1998, ainsi que dans des fermes situées à proximité du secteur, sur la côte ouest de l’île Deer, à la fin de 1998. Les fermes aquacoles de ces deux secteurs ont été touchées de nouveau depuis ce temps, et on a émis l’hypothèse voulant que le virus ait été transmis par l’eau, à partir des fermes de la partie continentale vers celles de l’île Deer. Afin d’estimer le potentiel de transport du virus de l’AIS par voie d’eau entre les fermes de ces secteurs, nous avons élaboré un modèle tridimensionnel de la circulation des eaux de marée et du transport des particules. Nous avons ensuite comparé les scénarios d’échange d’eau reposant sur le déplacement des particules durant une marée, tels que prédits par le modèle, aux scénarios estimés à l’aide d’une méthode simple, en présumant de l’existence d’une zone d’échange d’eau autour de chaque ferme d’un rayon de 5 km. Nous avons également examiné s’il serait efficace de retirer certaines fermes afin de créer une zone tampon entre les installations salmonicoles de la terre ferme et celles de l’île Deer.

INTRODUCTION

BACKGROUND

Infectious salmon anemia (ISA) first appeared among salmon farms in southwestern New Brunswick (SWNB) in the summer of 1996 and has been present every year since, resulting in considerable economic loss (McGeachy and Moore 2003). As part of the management strategy for this disease, the salmon farming region of SWNB was partitioned into Bay Management Areas (BMAs) (NBDAFA 2000). The intent of BMAs is to improve cooperation and communication among farm operators, in order to assist in fish health and environmental management. All farms within the same BMA are encouraged to synchronize the placement and harvesting of fish. The boundaries of the BMAs (Fig. 1) were based on fish health, economic, and oceanographic considerations (Halse 2002). Initially, oceanographic considerations were a relatively minor factor in defining BMAs, due in part to a lack of oceanographic knowledge.

Farms in Bliss Harbour (BMA 9) and Lime Kiln Bay (BMA 10) were first infected with ISA in 1996. Subsequently, farms in Back Bay (BMA 8) were first infected in 1997, farms in Letete Passage (BMA 7) in 1998, and farms in western Deer Island (BMAs 2-4) in late 1998 to early 1999 (McGeachy and Moore 2003). Following the initial outbreaks, farms in BMAs 8, 9, and 10 were all synchronized as odd year-class farms (smolt entry in the spring of odd years), while those in the western Deer Island area were all synchronized as even year-class farms. Despite fallowing and synchronization of smolt entry in these areas, subsequent year-classes in mainland areas (BMAs 7-10) and Deer Island (BMAs 2-4) have been infected with ISA. One possible reason suggested for the reinfections is that farms in BMAs 2 and 7 served as pathways for disease transmission between the odd year-class mainland farming areas and the even year-class Deer Island farms.

The main objectives of this project were to examine the validity of the existing BMA boundaries and the effectiveness, from the perspective of reducing disease transmission via water exchange, of creating a separation zone through the removal of farms in BMAs 2 and/or 7. We studied this using a 3-dimensional tidal circulation and particle transport model. The model results were compared to a simpler approach using a circular zone of influence around each farm. The methodology used in this study has previously been used to examine fish health and oceanography issues at salmon farms in the southern Grand Manan Island area of SWNB (Page and Chang 2002; Page et al. 2004, 2005).

CAUSES OF THE SPREAD OF ISA AMONG SALMON FARMS

Previous studies have suggested that, at the larger scale (in the order of tens of kilometres or more), the spread of ISA is likely related to vectors such as boat traffic and the transport of fish among farms. However, at the smaller tidal excursion scale, physical transport of the ISA virus (from infected fish and discharged fish wastes) in the sea is a possible mechanism for disease spread (Murray et al. 2002). Such passive transport would be in the order of several kilometres or less, limited by the tidal exchange around farms (JGIWG 2000; Murray 2003). The pattern of occurrence of ISA in SWNB (McGeachy and Moore 2003; McClure et al. 2004) suggests that both large scale vectors (such as movement of boats, fish, personnel, and equipment among farms) and smaller scale passive transport in seawater among adjacent farms may have occurred.

FISH HEALTH MANAGEMENT ZONES IN OTHER SALMON FARMING AREAS

Hydrographically defined control and surveillance zones or management areas have been implemented in other salmon farming areas as a way to reduce the spread of ISA among salmon farms (Stewart 1998). The Norwegian Animal Health Authority's (2002) "Contingency plan for the control of infectious salmon anaemia in Norway" includes the establishment of Control Zones around ISA-infected farms. The Control Zone is a circular area with a radius of at least one tidal excursion (where known), but not less than 5 km, centred on the infected farm. Conditions applied to all farms within the Control Zone include: increased fish health surveillance; a prohibition of fish movement into or out of the zone; restrictions on the transport of fish through the zone; and a requirement for fallowing and disinfection of all farms prior to restocking. In addition, there is a larger Surveillance Zone which includes all farms whose Control Zones overlap with the Control Zone of the infected farm (a 10- to 20-km radius area around the infected farm).

Similar Control Zones have been used in the Scottish salmon farming industry (JGIWG 2000). A circle with a radius equal to one tidal excursion is drawn around the centre of each farm. In the absence of on-site water current data or computer modelling studies, the tidal excursions were estimated from existing maps of maximum tidal current speeds during spring tides in Scottish coastal waters. When a farm becomes infected, there is a requirement for simultaneous fallowing and increased fish health surveillance at all farms within its Control Zone. A larger Surveillance Zone (or Management Area) consists of all salmon farms having overlapping tidal excursion areas, although in a few cases slight overlaps in tidal excursions are allowed between adjacent zones.

METHODS

The site boundaries for fish farms in the study area were provided by NBDAFA and were entered into a Geographic Information System (MapInfo Professional® 7.0). There were a total of 33 finfish farms within the study area: BMAs 2, 3-east, 6, 7, 8, 9, and 10 (Fig. 1). Simple estimates of the zone of influence or water exchange around each farm were made by drawing a 5-km radius circle centred on the farm site, then deleting any land areas which fell within this circle, as well as any water areas which were separated from the farm site by land. If it was known that the fish cages were not located at the middle of a site, the circle was centred over the approximate location of the fish cage cluster. These circular areas were drawn using the MapInfo buffer tool, and are henceforth referred to as buffer zones.

More precise estimates of the tidal excursions around farms were made through the use of a 3-dimensional particle tracking model (Greenberg et al. 2005) that was customized to our geographic domain of interest. The geographic domain of the model includes the entire Bay of Fundy and Gulf of Maine. The model estimates the tidal currents by dividing the geographic area into triangles (called finite elements) and by numerically solving the equations of motion at each x,y,z,t grid point within the model domain. When the model is run, a depth profile of the current is calculated at each corner of every triangle every 2.07 s. The circulation model is fully non-linear, has 21 sigma depth levels (reduced in water shallower than 10 m), and has variable horizontal resolution (minimum approximately 50 m). This feature of the finite-element model makes it well suited for covering the wide domain of influence with the required detail in the area of interest needed to resolve local characteristics. The spatial resolution of the model is relatively coarse in the middle of the Gulf of Maine and quite fine in the salmon farming areas of SWNB. The model also has the capability of simulating wetting and drying of intertidal areas. Although the generic model code has the capability of including boundary forcing, internal water density and surface winds as current driving forces, the customized model for the SWNB area has only been run using boundary forcing by the principal diurnal lunar tide, the M_2 tide.

Using the model, pseudo-drogues or numerical particles were released from a starting grid located approximately at the centre of each farm or, where known, at the location of the cage cluster (Fig. 1). For most farms, particles were released simultaneously from 36 points in a 200 × 200 m square grid (40 m between adjacent grid points). In some of the smaller farms, a few of the particle release points were located slightly outside the site boundaries, and for farm MF-045, the particle release grid was broken into three clusters to accommodate the irregular shape of this farm site. Slightly fewer than 36 particle release points were used at some farms where, because of the proximity to the shore, some of the release points would have been located over land and were therefore eliminated. The particles were released and maintained at 1 m below the sea surface. Each particle was tracked and its position output every 20 min for one tidal cycle (12.42 h). Some particle tracks were shorter than one tidal cycle, because the tracks terminated when they hit the shore. For each farm site, particles were released from every grid point at hourly intervals over a 12-h period (for a total of 432 particle releases from most farms) in order to represent conditions over one entire tidal cycle.

In order to estimate the areal extent of one model-derived tidal excursion area, the marine surface area in the vicinity of each farm was divided into a grid of 100 × 100 m square cells. A farm's tidal excursion area was then estimated as the total of all cells through which passed at least one of the particle tracks from that farm. As a measure of the relative intensity of particle distribution, we calculated the number of particle tracks which passed through each 100 × 100 m cell.

To measure the influence (due to water circulation) each farm had on other farms, we determined which farm sites (receiving farms) were overlapped (at least partially) by each originating farm's water exchange area (as estimated by a 5-km radius buffer zone and by a model-derived tidal excursion area). To measure the influence (due to water circulation) that other farms had on each farm, we determined which water exchange areas (from originating farms) overlapped (at least partially) each receiving farm site. We also determined which farms had overlapping water exchange areas (estimated using 5-km radius buffer zones and model-derived tidal excursion areas).

We compared the interactions among farms using two measures of overlap. The simplest was the presence or absence of overlaps of each water exchange area with farm sites and with water exchange areas. We also used a quantitative measure to estimate the intensity of these overlaps when using the model-derived tidal excursion areas. We determined the number of particle tracks (of the total 432 released from most originating farms) which overlapped farm sites and farm tidal excursion areas. For both measures, we compared the similarity among farms by performing cluster analyses with Bray-Curtis similarity coefficients using PRIMER 5 software (Clarke and Warwick 1994).

RESULTS

ESTIMATION OF POTENTIAL INTERACTIONS AMONG FARMS USING 5-KM RADIUS CIRCULAR BUFFER ZONES

Figure 2 shows the 5-km radius buffer zones of all farms in the study area. The figure suggests considerable water exchange among farms throughout the study area. Figures 3-8 show the buffer zones for all farms in each BMA. The areas of the buffer zones ranged from 27.1-64.5 km^2 (Table 1).

The presence or absence of overlaps of buffer zones with farm sites is shown in Table 2. In almost all instances, where one farm's buffer zone overlapped a second farm's site, the second farm's buffer zone overlapped the first farm's site. This is because all buffer zones were based on 5-km radius circles. There were only six instances (1%) out of the total 655 overlaps of buffer zones with farm sites where one farm's buffer zone overlapped a second farm's site, but the second farm's buffer zone did not overlap the first farm's site. These occurred as a result of two aspects of the way that buffer zones were calculated. Firstly, buffer zones were based on 5-km circles drawn around a point located approximately at the center of each farm site; as a result, there were some cases where the center points of two farms were slightly greater than 5 km apart, but part of the site boundaries of one farm (e.g. a larger farm) extended to within 5 km of the second farm, while the site boundaries of the second farm (e.g. a smaller farm) did not extend to within 5 km of the first farm. Secondly, we excluded from the buffer zone any areas which were isolated from the originating site by land; as a result, due to differences in topography around different farms, there were some instances where two farms were within 5 km of each other, but one farm was not within the other farm's buffer zone because it was in an isolated bay that was excluded from that buffer zone.

Each buffer zone overlapped an average of 19.8 farm sites within the study area (including the originating farm site; see Fig. 9, Table 6). Farms in BMAs 8, 9, and 10 and farm MF-038 in BMA 7 had the highest numbers of overlaps, ranging from 21-26. Each buffer zone overlapped an average of 30.5 buffer zones (of farms in the study area, including the originating farm's buffer zone; see Fig. 10, Tables 3 and 7). Note that there were a few overlaps with sites (and their buffer zones) located outside of the study area, in BMAs 1a, 1b, 3-west, and 4 (see Fig. 2-4); these overlaps were not included in our analyses.

The cluster analysis based on the presence or absence of overlaps between buffer zones and farm sites indicated considerable similarity among farms (Fig. 11). No farms were completely separate from all other farms (at 0% similarity). At a similarity level of 14%, there were two clusters: all farms in BMAs 2, 3-east, and 6, plus the two farms in the northern part of BMA 7 (MF-039 and

MF-040) in one cluster and the other 24 farms in the other cluster. The cluster analysis based on the presence or absence of overlaps among buffer zones indicated very high similarity among all farms in the study area (Fig. 12). There were no completely separate clusters at 0-79% similarity.

DESCRIPTIONS OF MODEL-DERIVED TIDAL EXCURSION AREAS

Figure 13 shows the model-derived tidal excursion areas (all hourly releases from each farm combined) of all farms in the study area. The figure shows no breaks in the overlaps among tidal excursion areas in these BMAs. Figs. 14-19 show the tidal excursion areas of all farms in each BMA. Figures 20-25 show the tidal excursion areas for each individual farm, including the relative density of particle tracks present in 100 × 100 m grid cells. The tidal excursion areas were much smaller than the 5-km buffer zones, ranging from 0.4-18.7 km^2 (Table 1), and were not circular in shape.

Tidal excursions of farms in BMA 2 (Fig. 20)

Farm MF-255 had a large tidal excursion area (8.8 km^2) which extended mostly north, then east around Macs Island and along the southern shore of Letete Passage. This tidal excursion area did not overlap any farm sites in BMA 7, but did overlap with the tidal excursion areas of farms in BMA 7. Farm MF-256 had a smaller tidal excursion area (2.9 km^2) which extended mostly east, then south, touching farm site MF-042 and continuing along the eastern shore of Deer Island, reaching farm site MF-215.

Tidal excursions of farms in BMAs 3-east and 6 (Fig. 21)

Farms MF-042, MF-044 and MF-046 had small tidal excursion areas (0.4-1.1 km^2) which did not overlap other farm sites. Farm MF-045 had a quite large tidal excursion area (5.1 km^2) which extended mostly north, touching farm sites MF-042 and MF-255. Farm MF-215 also had a large tidal excursion area (7.4 km^2) which was similar in shape to that of farm MF-045; the tidal excursion area touched farm site MF-042 and passed through farm site MF-255, then continued around the northern and eastern shores of Macs Island.

Tidal excursions of farms in BMA 7 (Fig. 22)

All three farms in BMA 7 had relatively large tidal excursion areas (8.2-13.7 km^2) which extended along the mainland shore of Letete Passage, reaching the mouths of Back Bay and Bliss Harbour. The tidal excursion area of farm MF-038 extended northwest along the mainland shore of Letete Passage, touching farm site MF-039 and approaching very close to farm site MF-040, and also extended southeast, then north, just touching farm site MF-276 (in BMA 8) and approaching close to farm site MF-027 (in BMA 9). The tidal excursion area of farm MF-039 was similar to that of MF-038, except that it passed through farm site MF-040 (to the northwest), but did not touch farm sites MF-038 or MF-276. The tidal excursion of farm MF-040 extended mainly southeast from the farm, passing through farm sites MF-039 and MF-038 and just touched farm site MF-276 (in BMA 8). The tidal excursion areas of all three farms in BMA 7 overlapped with the tidal excursion areas of the other farms in BMA 7 and with those of some farms in BMA 8. The tidal excursion area of farm MF-039 also overlapped with the tidal excursion area of one farm in BMA 9 (MF-032), while the tidal excursion area of farm MF-038 overlapped with the tidal excursion areas of some farms in BMAs 9 and 10.

Tidal excursions of farms in BMA 8 (Fig. 23)

The tidal excursion areas of farms MF-033, MF-034, MF-035 and MF-036 were relatively small (1.1-1.8 km^2), extending southwest and northeast of the release sites, but confined within BMA 8. The tidal excursion areas of farms MF-095 and MF-159 (located near the head of Back Bay) were also small (1.0-1.4 km^2), mostly confined within a narrow channel to the north and south of the release sites, but also extending slightly into the head of Lime Kiln Bay (BMA 10). Farm MF-037 had a slightly larger tidal excursion area (2.2 km^2) which extended into Letete Passage, overlapping farm site MF-038 (in BMA 7) and with the tidal excursion areas of all three farms in BMA 7, and also extending to the south. Farm MF-276 had a large tidal excursion area (18.7 km^2) which extended north into Back Bay, touching farms MF-036 and MF-037, and also east into BMAs 9 and 10, where it overlapped farm site MF-032 and came within 15 m of farm site MF-024. The tidal excursion area of farm MF-276 also overlapped with the tidal excursion areas of several farms in BMAs 7-10.

Tidal excursions of farms in BMA 9 (Fig. 24)

The tidal excursion areas of all farms in BMA 9 were small, ranging from 0.7-3.4 km^2. The tidal excursion areas of farms MF-030 and MF-032 were confined within BMA 9, overlapping only farm sites in the same BMA, while the tidal excursion areas of the other sites in BMA 9 extended north into BMA 10 and overlapped farm sites in BMAs 9 and 10. The tidal excursion areas of all farms in BMA 9 overlapped with the tidal excursion areas of farms in BMA 9 and 10 and the tidal excursion areas of four farms also overlapped with the tidal excursion areas of farms in BMAs 7 and 8.

Tidal excursions of farms in BMA 10

Farms MF-014, MF-016 and MF-024 had relatively large tidal excursion areas (4.0-6.8 km^2) which extended north, as well as south, then east along the mainland shore. Farms MF-017 and MF-018 had small tidal excursion areas (1.2-1.8 km^2) which were confined within BMA 10. The tidal excursion area of farm MF-020 was also small (0.7 km^2) and confined mostly within BMA 10, but also extended into the northern part of BMA 8, approaching close to farm site MF-095. The tidal excursion areas of these farms only overlapped farm sites within BMA 10. Farms MF-022 and MF-023 had small tidal excursion areas (1.2-1.4 km^2) which extended into the northern part of BMA 9, overlapping two-three farm sites in that BMA, as well as with several farms in BMA 10. Most of the overlaps with other tidal excursion areas were with those of farms in BMAs 9 and 10, but the tidal excursion areas of farms MF-014, MF-016 and MF-024 also overlapped with the tidal excursion areas of farms MF-038 (BMA 7) and MF-276 (BMA 8), while that of MF-020 overlapped with the tidal excursion areas of farms MF-095 and MF-159 (BMA 8).

ESTIMATION OF POTENTIAL INTERACTIONS AMONG FARMS USING MODEL-DERIVED TIDAL EXCURSION AREAS

The presence or absence of overlaps of tidal excursion areas with farm sites for the 33 farms in the study area is shown in Table 4. There were 104 overlaps of tidal excursion areas with farm sites (excluding the 33 overlaps of tidal excursion areas with their originating farm sites), of which there were 37 instances (36%) where one farm's tidal excursion area overlapped a second farm's site, but the second farm's tidal excursion area did not overlap the first farm's site.

Each tidal excursion area overlapped an average of 4.2 farm sites (including the originating site; see Fig. 26, Table 8). Most of the overlaps were with farms within the same BMA, although the tidal excursion area of at least one farm in each BMA overlapped farm sites in another BMA.

Each farm site was overlapped by an average of 4.2 tidal excursion areas (including the receiving farm's tidal excursion area; see Fig. 27, Table 8). Most of the overlapping tidal excursion areas were from farms in the same BMA as the receiving farm, but at least one farm site in each BMA was overlapped by the tidal excursion area of a farm in another BMA.

As would be expected, there were more overlaps among tidal excursion areas, compared to the numbers of overlaps of tidal excursion areas with farm sites. Most tidal excursion areas overlapped with tidal excursion areas of farms in other BMAs (Table 5). Each tidal excursion area overlapped with an average of 9.0 tidal excursion areas (including each tidal excursion area's overlap with itself; see Fig. 28, Table 9).

The cluster analysis based on the number of farms sites overlapped by each farm's tidal excursion area (Fig. 29) showed that at 0% similarity, farms MF-044 and MF-046 (both in BMA 6) were each completely isolated and there were three other large clusters: one cluster containing the two remaining farms in BMAs 6, plus the one farm in BMA 3-east and the two farms in BMA 2; one cluster of all farms in BMAs 7 and 8; and another cluster of all farms in BMAs 9 and 10. At 5% similarity, the first of these clusters could be separated into two smaller clusters, one consisting of the three farms in BMA 7 plus the two farms at the mouth of Back Bay (farms MF-037 and MF-276 in BMA 8) and the other smaller cluster consisting of all other farms in BMA 8. The cluster analysis based on the number of farm tidal excursion areas overlapping each farm site (Fig. 30) produced a similar clustering pattern to that in Fig. 29.

The cluster analysis based on the presence or absence of overlaps among tidal excursion areas (Fig. 31) showed that only farm MF-046 remained completely separate from all other farms. At 3% similarity, the other farms could be separated into two large clusters: one cluster containing the remaining farms in BMA 6, plus the one farm in BMA 3-east and the two farms in BMA 2; and one large cluster of all farms in BMAs 7-10. This latter large cluster could be separated, at 14% similarity, into two clusters: one cluster containing farms MF-039 and MF-040 from the northern part of BMA 7, plus all farms in BMA 8, excluding MF-276; and one cluster containing all farms in BMAs 9 and 10, plus farm MF-276 (BMA 8) and farm MF-038 (BMA 7).

The cluster analysis based on the intensity of overlap of tidal excursion areas with farm sites (as measured by the number of particle tracks that overlapped farm sites) showed lower similarity than Fig. 29, and larger numbers of separate clusters (Fig. 32): at 0-1% similarity there were 10 separate clusters. The cluster analysis based on the intensity of overlap among tidal excursion areas (as measured by the number of particle tracks that overlapped tidal excursion areas; see Fig. 33) showed much lower similarity than that shown in Fig. 31. At 0% similarity, farms MF-046 and MF-044 were separate from a large cluster containing all other farms. At 4% similarity, the large cluster could be separated into three smaller clusters: the remaining two farms in BMA 6, plus the one farm in BMA 3 east and the two farms in BMA 2; all farms in BMAs 7 and 8; and all farms in BMAs 9 and 10.

SCENARIOS FOR THE CREATION OF A SEPARATION ZONE BETWEEN MAINLAND AND DEER ISLAND FARMS

When circular buffer zones are used to estimate water exchange areas, there appears to be considerable connectivity (via water circulation) between mainland and Deer Island farms. Removal of farms in BMAs 2 and/or 7 would not completely break this connectivity, since there would still be overlaps of buffer zones of farms in BMA 6 with farm sites in BMA 8 and vice versa (Table 2, Fig. 9).

When model-derived tidal excursion areas are used to estimate water exchange areas, there appears to be considerably less connectivity between mainland and Deer Island farms. There are no overlaps of tidal exchange areas of farms in BMAs 7-10 with farm sites in BMAs 2, 3-east and 6 and there are no overlaps of tidal excursion areas of farms in BMAs 2, 3-east and 6 with farm sites in BMAs 7-10 (Table 4, Fig. 26 and 27). There are, however, overlaps of tidal excursion areas of farms in BMA 2, specifically that of farm MF-255, with tidal excursion areas of farms in BMA 7 (Table 5, Fig. 28). Removal of farm MF-255 would create a separation zone between mainland and Deer Island farms (Fig. 34). Removal of farm MF-256 does not appear to provide any additional separation, since the tidal excursion area of this farm does not extend toward the mainland farms (Fig. 20). Removal of farms in BMA 7 by itself would not create a separation zone between mainland and Deer Island farms (Fig. 35), because there would still be a connection (although very small) between the tidal excursion areas of farm MF-037 (BMA 8) and that of MF-255 (BMA 2). Removal of farms in BMA 7 would, however, provide additional separation between mainland and Deer Island farms, if done in conjunction with the removal of farm MF-255.

DISCUSSION

The simple approach using 5-km radius buffer zones to estimate water exchange areas suggests considerable water exchange among finfish farms in the northern Deer Island, Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay areas of SWNB and that all farms in the study area should be in one management zone. The buffer zone approach also suggests that removal of farms in BMAs 2 and/or 7 would not completely break the connectivity between mainland and Deer Island farms, although it would reduce the amount of water exchange.

The model-derived tidal excursion areas are much smaller than the 5-km radius buffer zones and are not circular. Consequently, they suggest much less water exchange among some farms. The overlaps of tidal excursion areas with farm sites indicate that the Deer Island farms are isolated from the mainland farms; however, the overlaps among tidal excursion areas suggest some connectivity between farms in these two areas.

Both approaches indicate considerable water exchange among farms located along the mainland coast. If the speculation that ISA can be spread through the water is correct, then this indicates the need for collaboration in the fish health management of salmon farms throughout this area.

The tidal excursion area approach suggests that removal of farm MF-255 (in BMA 2) would substantially break the water exchange connection between the mainland farms and the Deer Island farms (Fig. 34), while removal of farm MF-256 (in BMA 2) would not provide any further reduction in connectivity between mainland farms and Deer Island farms. Removal of all farms in BMA 7 (Letete Passage) by itself would not completely eliminate overlaps between tidal excursion areas of farms along the mainland shore and those of farms from Deer Island (Fig. 35); however, removal of farms in BMA 7 would enhance the effectiveness of removing farm MF-255, by increasing the separation distance between tidal excursion areas of mainland and Deer Island farms. As an alternative scenario, it has been suggested that switching all or some of the BMA 7 farms to non-salmonid species would have a similar effect (in terms of creating a separation zone between mainland and Deer Island farms) to removing these farms, at least for the management of ISA or other salmonid diseases.

Some changes have been made in an attempt to create a separation zone between mainland and Deer Island farms, largely based on advice we have provided on water circulation in this area. Farm MF-255 has been removed and farm MF-038, at the southern end of BMA 7, is now growing only cod (NBDAFA, pers. comm.). Farms MF-039 and MF-040, in the northern part of BMA 7, will likely continue to grow salmon (NBDAFA pers. comm.).

The tidal excursion areas indicate considerable water exchange among farms in BMAs 9 and 10, suggesting the need to treat these two BMAs as one management zone. This would mean synchronization of smolt entry and fish health management for all farms in these BMAs. The tidal excursion areas also indicate considerable water exchange among farms in BMAs 7 and 8 (although the connectivity is somewhat reduced with the switching of farm MF-038 to cod), suggesting the need to treat these two BMAs as one. Because there is also some water exchange between BMAs 7 and 8 and BMAs 9 and 10, and because of the close proximity of these four BMAs, a conservative approach would be to treat all four of these BMAs as one management zone.

It must be noted that the tidal excursions as predicted by the model are determined completely by the M_2 tide. Although the M_2 component is the major component of the tide in this area, other factors such as wind and spring-neap tides do play a role and when these are included in the model, the particle trajectories and exposure maps will be modified to some degree, probably increasing the sizes of the predicted tidal excursion areas.

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Table 1. Water exchange areas of finfish farms in the Macs Island area, eastern Deer Island, Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay. Water exchange areas were estimated by two methods: 5-km radius circular buffer zones (excluding land and water areas cut off from the originating farm site by land) and model-derived tidal excursion areas. BMA = Bay Management Area.

Farm site	5-km radius buffer zone (km^2)	Tidal excursion area (km^2)
BMA 2 (Macs Island area)		
MF-255	60.7	8.8
MF-256	63.5	2.9
Mean ± SD	62.1 ± 2.0	5.8 ± 4.2
BMAs 3-east & 6 (eastern Deer Island)		
MF-042	60.2	1.0
MF-044	63.2	1.4
MF-045	56.6	5.1
MF-046	51.3	0.4
MF-215	57.8	7.4
Mean ± SD	57.8 ± 4.0	3.1 ± 2.7
BMA 7 (Letete Passage)		
MF-038	51.1	13.7
MF-039	48.9	8.2
MF-040	46.7	8.9
Mean ± SD	48.9 ± 2.2	10.3 ± 3.0
BMA 8 (Back Bay)		
MF-033	35.5	1.5
MF-034	38.1	1.1
MF-035	42.2	1.1
MF-036	44.7	1.8
MF-037	49.1	2.2
MF-095	27.1	1.0
MF-159	31.0	1.4
MF-276	60.8	18.7
Mean ± SD	41.1 ± 10.7	3.6 ± 6.1
BMA 9 (Bliss Harbour)		
MF-025	49.8	1.6
MF-026	53.6	3.4
MF-027	54.3	2.0
MF-028	52.2	0.7
MF-029	58.2	3.0
MF-030	64.5	1.1
MF-032	59.2	1.2
Mean ± SD	56.0 ± 5.0	1.9 ± 1.0
BMA 10 (Lime Kiln Bay)		
MF-014	30.3	4.0
MF-016	34.7	5.4
MF-017	36.3	1.8
MF-018	36.7	1.2
MF-020	35.1	0.7
MF-022	43.1	1.2
MF-023	46.9	1.4
MF-024	41.5	7.1
Mean ± SD	38.1 ± 5.4	2.9 ± 2.4
All farms combined		
Mean ± SD	48.0 ± 10.8	3.7 ± 4.1

Table 2. Overlaps (indicated by shaded squares) of 5-km radius buffer zones with finfish farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10 in SWNB.

Overlaps of originating farm buffer zones with receiving farm sites		Originating farm																																
		BMA 2		BMA 3-east & 6					BMA 7			BMA 8								BMA 9							BMA 10							
Receiving farm		MF-255	MF-256	MF-042	MF-044	MF-045	MF-046	MF-215	MF-038	MF-039	MF-040	MF-033	MF-034	MF-035	MF-036	MF-037	MF-095	MF-159	MF-276	MF-025	MF-026	MF-027	MF-028	MF-029	MF-030	MF-032	MF-014	MF-016	MF-017	MF-018	MF-020	MF-022	MF-023	MF-024
BMA 2	MF-255	■	■	■		■	■	■	■	■	■					■																		
	MF-256	■	■	■		■	■	■		■	■																							
BMAs 3-east, 6	MF-042	■	■	■	■	■	■	■	■	■	■																							
	MF-044			■	■	■	■	■	■										■															
	MF-045	■	■	■	■	■	■	■	■																									
	MF-046		■	■	■	■	■	■																										
	MF-215	■	■	■	■	■	■	■	■																									
BMA 7	MF-038	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■							■	
	MF-039	■	■	■					■	■	■	■	■	■	■	■		■	■															
	MF-040	■	■	■					■	■	■	■	■	■	■	■																		
BMA 8	MF-033								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-034								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-035								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-036								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-037	■							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■	■	■
	MF-095								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-159								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-276				■				■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■	■	■
BMA 9	MF-025								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-026								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-027								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-028								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-029								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-030								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-032								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
BMA 10	MF-014											■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-016											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-017											■	■	■	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-018											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-020								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-022								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-023								■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	MF-024											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 3. Overlaps (indicated by shaded squares) among 5-km radius buffer zones of finfish farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10 in SWNB.

Overlaps of originating farm buffer zones with receiving farm buffer zones			**Originating farm**																																			
			BMA 2		BMA 3-east & 6					BMA 7			BMA 8								BMA 9							BMA 10							
			MF-255	MF-256	MF-042	MF-044	MF-045	MF-046	MF-215	MF-038	MF-039	MF-040	MF-033	MF-034	MF-035	MF-036	MF-037	MF-095	MF-159	MF-276	MF-025	MF-026	MF-027	MF-028	MF-029	MF-030	MF-032	MF-014	MF-016	MF-017	MF-018	MF-020	MF-022	MF-023	MF-024
Receiving farm	BMA 2	MF-255	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■	■	■
		MF-256	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■								
	BMAs 3-east, 6	MF-042	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■	
		MF-044	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■	■	■
		MF-045	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■	
		MF-046	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■		■	■	■	■	■								
		MF-215	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■	
	BMA 7	MF-038	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-039	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-040	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	BMA 8	MF-033	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-034	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-035	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-036	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-037	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-095	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-159	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-276	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	BMA 9	MF-025	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-026	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-027	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-028	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-029	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-030	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-032	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	BMA 10	MF-014								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-016								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-017								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-018	■			■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-020	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-022	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-023	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		MF-024	■			■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 4. Overlaps (indicated by shaded squares) of model-derived tidal excursion areas with finfish farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10 in SWNB.

Overlaps of originating farm tidal excursion areas with receiving farm sites			**Originating farm**																																
			BMA 2		BMA 3-east & 6					BMA 7			BMA 8								BMA 9							BMA 10							
			MF-255	MF-256	MF-042	MF-044	MF-045	MF-046	MF-215	MF-038	MF-039	MF-040	MF-033	MF-034	MF-035	MF-036	MF-037	MF-095	MF-159	MF-276	MF-025	MF-026	MF-027	MF-028	MF-029	MF-030	MF-032	MF-014	MF-016	MF-017	MF-018	MF-020	MF-022	MF-023	MF-024
Receiving farm	BMA 2	MF-255	■				■		■																										
		MF-256		■																															
	BMAs 3-east, 6	MF-042		■	■		■		■																										
		MF-044				■																													
		MF-045					■		■																										
		MF-046						■																											
		MF-215		■			■		■																										
	BMA 7	MF-038								■		■					■																		
		MF-039								■	■	■																							
		MF-040									■	■																							
	BMA 8	MF-033											■	■	■	■		■	■																
		MF-034											■	■	■	■			■																
		MF-035											■	■	■	■			■																
		MF-036											■	■	■	■			■	■															
		MF-037														■	■			■															
		MF-095											■					■	■																
		MF-159											■		■	■		■	■																
		MF-276								■		■								■															
	BMA 9	MF-025																			■		■	■			■						■	■	
		MF-026																			■	■	■		■	■							■	■	
		MF-027																			■	■	■				■							■	
		MF-028																			■			■			■								
		MF-029																				■	■		■	■									
		MF-030																								■									
		MF-032																		■			■				■								
	BMA 10	MF-014																				■			■			■	■	■					■
		MF-016																				■			■			■	■		■				■
		MF-017																				■						■	■	■					■
		MF-018																				■	■		■			■	■		■		■		
		MF-020																														■	■	■	
		MF-022																			■	■			■						■	■	■	■	
		MF-023																			■	■	■	■	■						■	■	■	■	
		MF-024																				■			■			■	■	■					■

Table 5. Overlaps (indicated by shaded squares) among model-derived tidal excursion areas of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10 in SWNB.

Overlaps of originating farm tidal excursion areas with receiving farm tidal excursion areas			**Originating farm**																																
			BMA 2		BMA 3-east & 6					BMA 7			BMA 8								BMA 9							BMA 10							
			MF-255	MF-256	MF-042	MF-044	MF-045	MF-046	MF-215	MF-038	MF-039	MF-040	MF-033	MF-034	MF-035	MF-036	MF-037	MF-095	MF-159	MF-276	MF-025	MF-026	MF-027	MF-028	MF-029	MF-030	MF-032	MF-014	MF-016	MF-017	MF-018	MF-020	MF-022	MF-023	MF-024
Receiving farm	BMA 2	MF-255	■	■			■		■	■	■	■																							
		MF-256	■	■	■		■		■																										
	BMAs 3-east, 6	MF-042		■	■		■		■																										
		MF-044				■	■																												
		MF-045	■	■	■	■	■		■																										
		MF-046						■																											
		MF-215	■	■	■		■		■																										
	BMA 7	MF-038	■							■	■	■					■			■		■	■		■		■	■	■						■
		MF-039	■							■	■	■					■			■							■								
		MF-040	■							■	■	■					■			■															
	BMA 8	MF-033											■	■	■	■		■	■	■															
		MF-034											■	■	■	■	■	■	■	■															
		MF-035											■	■	■	■		■	■	■															
		MF-036											■	■	■	■	■	■	■	■															
		MF-037								■	■	■		■		■	■			■															
		MF-095											■	■	■	■		■	■													■			
		MF-159											■	■	■	■		■	■	■												■			
		MF-276								■	■	■	■	■	■	■	■		■	■		■	■		■	■	■	■	■	■	■				■
	BMA 9	MF-025																			■	■	■	■	■	■	■	■	■		■	■	■	■	
		MF-026								■										■	■	■	■		■	■	■	■	■	■	■		■	■	■
		MF-027								■										■	■	■	■	■	■	■	■	■	■		■		■	■	■
		MF-028																			■		■	■			■						■	■	
		MF-029								■										■	■	■	■		■	■	■	■	■	■	■		■	■	■
		MF-030																		■	■	■	■		■	■	■						■	■	
		MF-032								■	■									■	■	■	■	■	■	■	■						■	■	
	BMA 10	MF-014								■										■	■	■	■		■			■	■	■	■			■	■
		MF-016								■										■	■	■	■		■			■	■	■	■		■	■	■
		MF-017																		■		■			■			■	■	■					■
		MF-018																		■	■	■	■		■			■	■		■		■	■	■
		MF-020																■	■		■											■	■	■	
		MF-022																			■	■	■	■	■	■	■		■		■	■	■	■	
		MF-023																			■	■	■	■	■	■	■	■	■		■	■	■	■	
		MF-024								■										■		■	■		■			■	■	■	■				■

Table 6. Mean numbers of overlaps of 5-km radius buffer zones (from originating farms) with farm sites (receiving farms), by BMA, for farms in the Macs Island area (BMA 2). eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10). The numbers are means (± SD) of all originating farms in each BMA, including the overlap of each buffer zone with its own farm site.

BMA of originating farms	BMA of receiving farms						
	BMA 2 (n=2)	BMAs 3-east, 6 (n=5)	BMA 7 (n=3)	BMA 8 (n=8)	BMA 9 (n=7)	BMA 10 (n=8)	All (n=33)
2	2.0 ± 0.0	3.5 ± 0.7	2.5 ± 0.7	0.5 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	8.5 ± 0.7
3-east & 6	1.6 ± 0.9	5.0 ± 0.0	1.2 ± 1.1	0.2 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	8.0 ± 1.2
7	1.7 ± 0.6	2.0 ± 1.7	3.0 ± 0.0	6.3 ± 1.5	2.3 ± 4.0	1.0 ± 1.7	16.3 ± 8.4
8	0.1 ± 0.4	0.1 ± 0.4	2.5 ± 0.8	8.0 ± 0.0	7.0 ± 0.0	7.5 ± 0.9	25.3 ± 0.9
9	0.0 ± 0.0	0.0 ± 0.0	0.9 ± 0.4	8.0 ± 0.0	7.0 ± 0.0	8.0 ± 0.0	23.9 ± 0.4
10	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.4	7.4 ± 0.9	7.0 ± 0.0	8.0 ± 0.0	22.5 ± 1.1

Table 7. Mean numbers of overlaps among 5-km radius buffer zones, by BMA, for finfish farms in the Macs Island area (BMA 2), eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10). The numbers are means (± SD) of all originating farms in each BMA, including the overlap of each buffer zone with itself.

BMA of originating farms	BMA of receiving farms						
	BMA 2 (n=2)	BMAs 3-east, 6 (n=5)	BMA 7 (n=3)	BMA 8 (n=8)	BMA 9 (n=7)	BMA 10 (n=8)	All (n=33)
2	2.0 ± 0.0	5.0 ± 0.0	3.0 ± 0.0	8.0 ± 0.0	6.0 ± 1.4	2.5 ± 3.5	26.5 ± 5.0
3-east & 6	2.0 ± 0.0	5.0 ± 0.0	3.0 ± 0.0	7.6 ± 0.9	6.8 ± 1.8	2.8 ± 1.8	27.2 ± 3.0
7	2.0 ± 0.0	5.0 ± 0.0	3.0 ± 0.0	8.0 ± 0.0	7.0 ± 0.0	8.0 ± 0.0	33.0 ± 0.0
8	2.0 ± 0.0	4.8 ± 0.5	3.0 ± 0.0	8.0 ± 0.0	7.0 ± 0.0	8.0 ± 0.0	32.8 ± 0.5
9	1.7 ± 0.5	4.9 ± 0.4	3.0 ± 0.0	8.0 ± 0.0	7.0 ± 0.0	8.0 ± 0.0	32.6 ± 0.8
10	0.6 ± 0.5	1.8 ± 1.9	3.0 ± 0.0	8.0 ± 0.0	7.0 ± 0.0	8.0 ± 0.0	28.4 ± 2.3

Table 8. Mean numbers of overlaps between model-derived tidal excursion areas and finfish farm sites, by BMA, for farms in the Macs Island area (BMA 2), eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10). Top: numbers of farm sites (receiving farms) overlapped by each tidal excursion area (from originating farm). Bottom: numbers of tidal excursion areas (from originating farms) overlapping each farm site (receiving farm). The numbers are means (± SD) of all farms in each BMA, including the overlap of each tidal excursion area with its own farm site.

BMA of originating farms	BMA of receiving farms						
	BMA 2 (n=2)	BMAs 3-east, 6 (n=5)	BMA 7 (n=3)	BMA 8 (n=8)	BMA 9 (n=7)	BMA 10 (n=8)	All (n=33)
2	1.0 ± 0.0	1.0 ± 1.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.0 ± 1.4
3-east & 6	0.4 ± 0.5	1.8 ± 1.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.2 ± 1.6
7	0.0 ± 0.0	0.0 ± 0.0	2.3 ± 0.6	0.7 ± 0.6	0.0 ± 0.0	0.0 ± 0.0	3.0 ± 1.0
8	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.4	4.3 ± 1.8	0.1 ± 0.4	0.0 ± 0.0	4.5 ± 1.5
9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	3.3 ± 1.1	2.6 ± 2.8	5.9 ± 2.7
10	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.6 ± 1.2	3.9 ± 0.8	4.5 ± 1.2

BMA of receiving farms	BMA of originating farms						
	BMA 2 (n=2)	BMAs 3-east, 6 (n=5)	BMA 7 (n=3)	BMA 8 (n=8)	BMA 9 (n=7)	BMA 10 (n=8)	All (n=33)
2	1.0 ± 0.0	1.0 ± 1.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.0 ± 1.4
3-east & 6	0.4 ± 0.5	1.8 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.2 ± 1.3
7	0.0 ± 0.0	0.0 ± 0.0	2.3 ± 0.6	0.3 ± 0.6	0.0 ± 0.0	0.0 ± 0.0	2.7 ± 0.6
8	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.7	4.3 ± 1.8	0.0 ± 0.0	0.0 ± 0.0	4.5 ± 1.3
9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.4	3.3 ± 1.4	0.7 ± 1.0	4.1 ± 2.0
10	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.3 ± 1.5	3.9 ± 0.4	6.1 ± 1.7

Table 9. Mean numbers of overlaps among model-derived tidal excursion areas, by BMA, for finfish farms in the Macs Island area (BMA 2), eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10). The numbers are means (± SD) of all originating farms in each BMA, including the overlap of each tidal excursion area with itself.

BMA of originating farms	BMA of receiving farms						
	BMA 2 (n=2)	BMAs 3-east, 6 (n=5)	BMA 7 (n=3)	BMA 8 (n=8)	BMA 9 (n=7)	BMA 10 (n=8)	All (n=33)
2	2.0 ± 0.0	2.5 ± 0.7	1.5 ± 2.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	6.0 ± 1.4
3-east & 6	1.0 ± 1.0	2.6 ± 1.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	3.6 ± 2.1
7	1.0 ± 0.0	0.0 ± 0.0	3.0 ± 0.0	2.0 ± 0.0	1.7 ± 2.1	1.0 ± 1.7	8.7 ± 3.8
8	0.0 ± 0.0	0.0 ± 0.0	0.8 ± 1.4	6.8 ± 1.3	0.6 ± 1.8	0.9 ± 1.7	9.0 ± 4.5
9	0.0 ± 0.0	0.0 ± 0.0	0.7 ± 0.8	0.7 ± 0.5	6.1 ± 1.1	4.6 ± 2.4	12.1 ± 3.5
10	0.0 ± 0.0	0.0 ± 0.0	0.4 ± 0.5	0.9 ± 0.6	4.0 ± 2.1	5.3 ± 1.3	10.5 ± 2.7

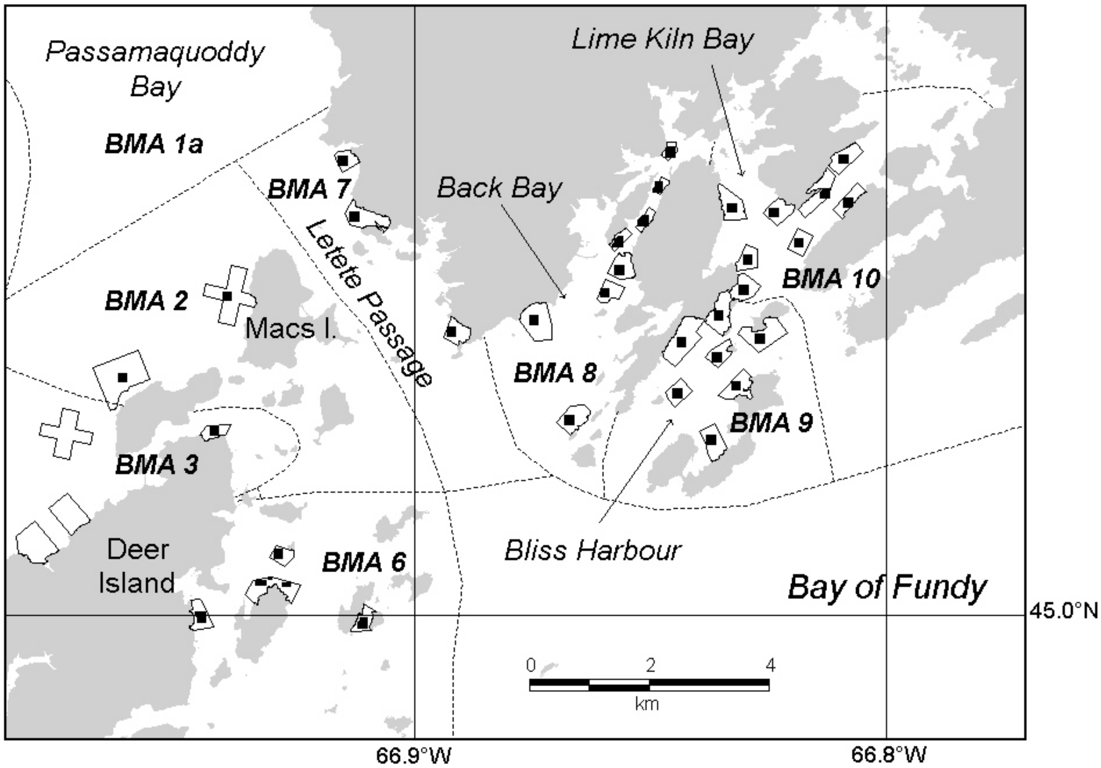


Fig. 1. Map of the northern Deer Island, Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay areas of SWNB, showing BMAs, finfish farms (white polygons) and starting grid locations (small black squares) for model particle releases from farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10.

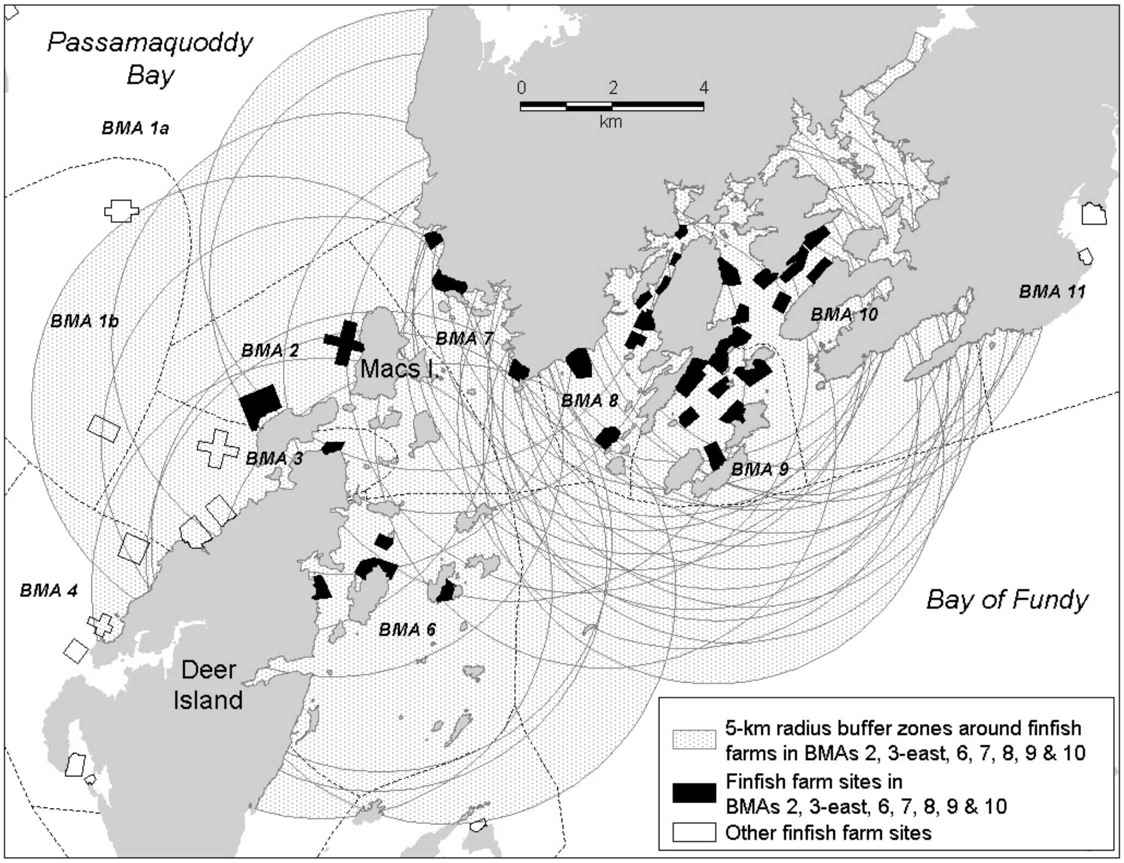


Fig. 2. Map showing 5-km radius buffer zones of all finfish farms in the Macs Island area (BMA 2), eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10).

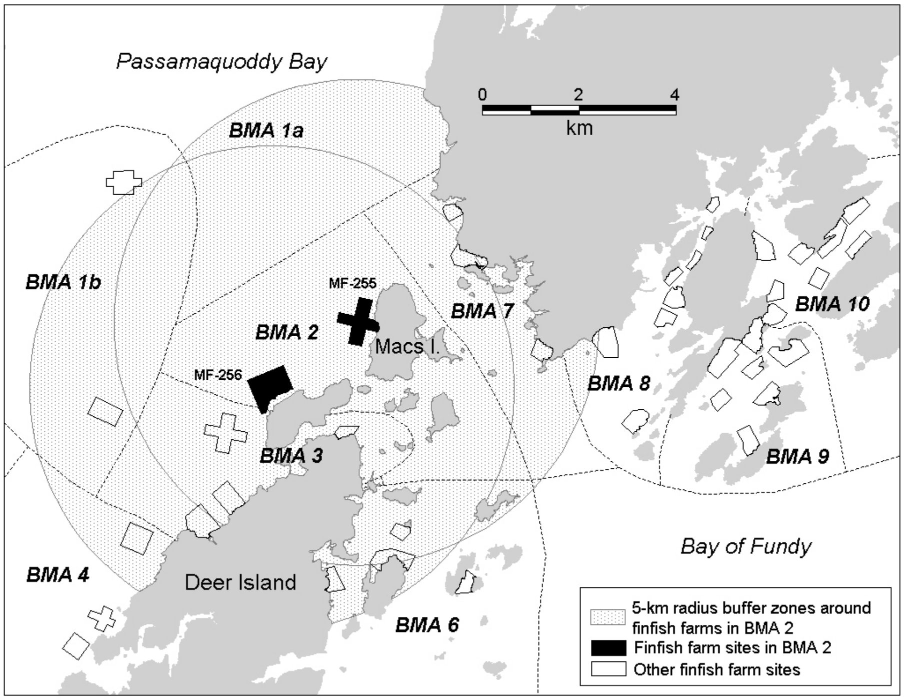


Fig. 3. Map showing 5-km radius buffer zones of finfish farms in BMA 2, Macs Island area.

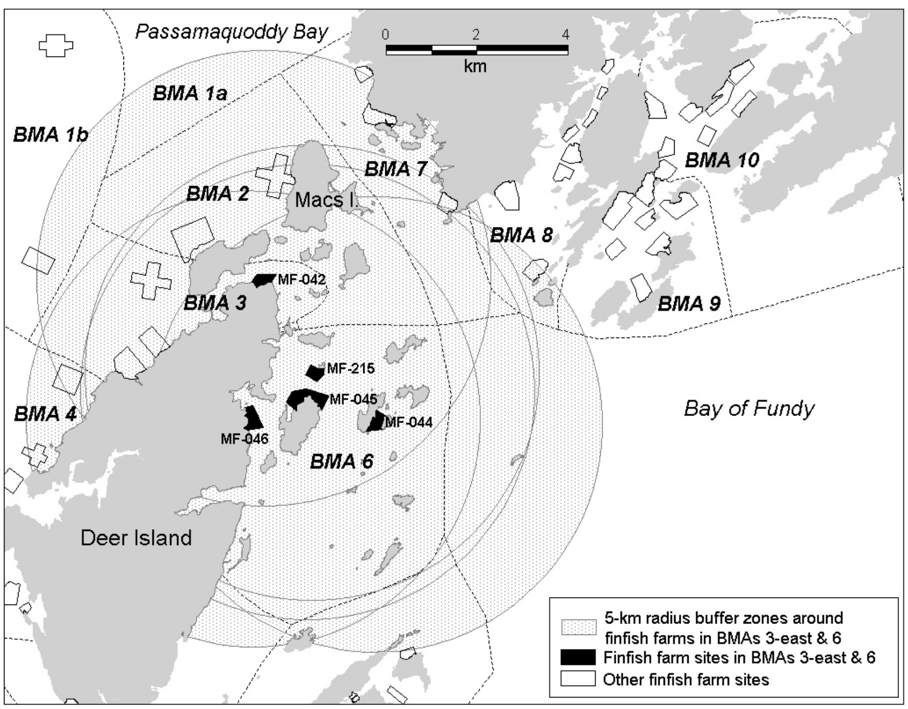


Fig. 4. Map showing 5-km radius buffer zones of finfish farms in BMAs 3-east and 6, eastern Deer Island.

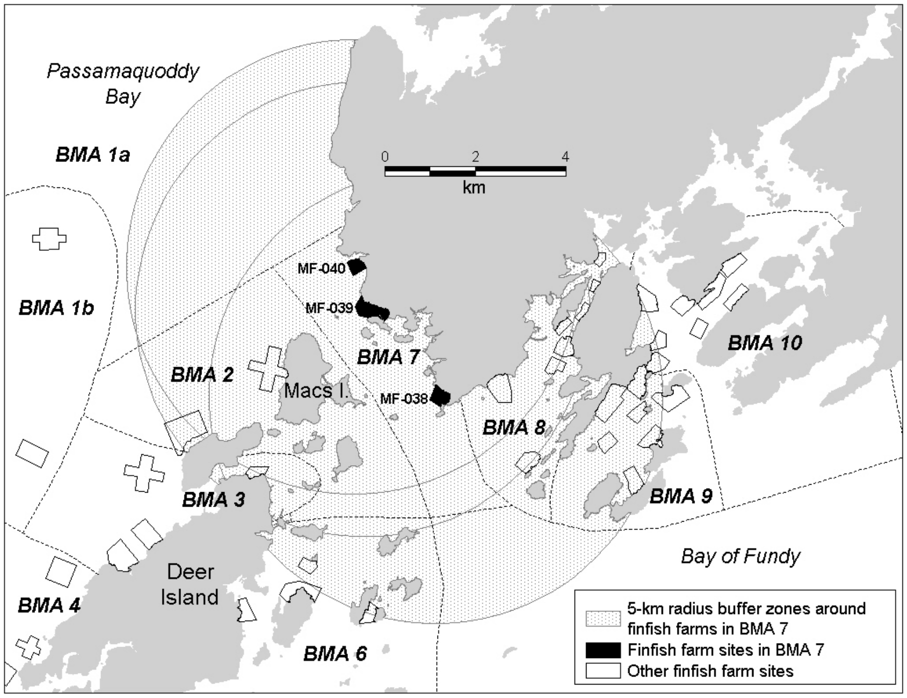


Fig. 5. Map showing 5-km radius buffer zones of finfish farms in BMA 7, Letete Passage.

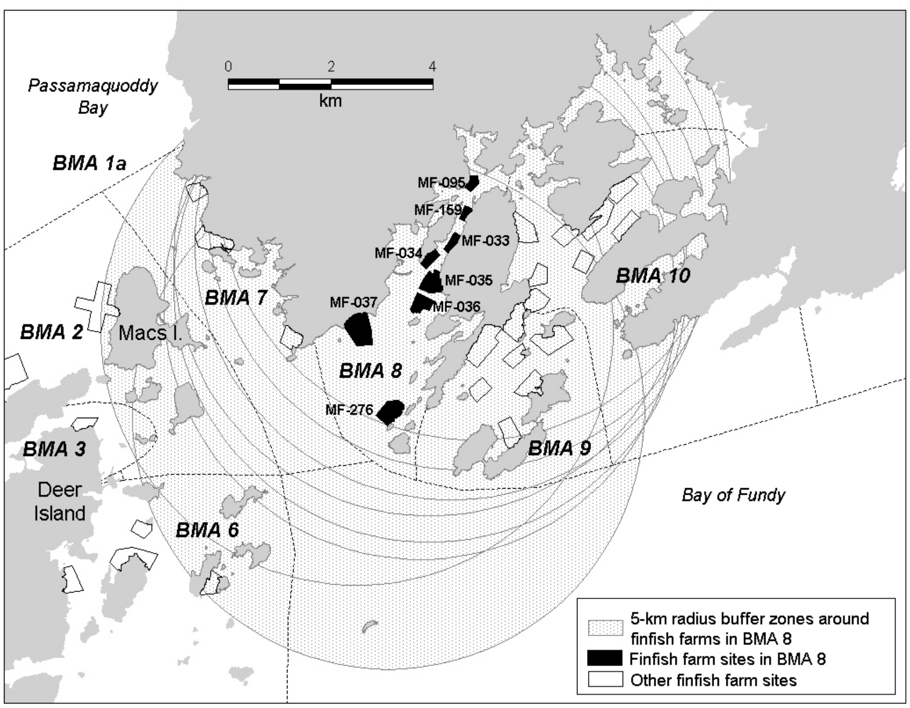


Fig. 6. Map showing 5-km radius buffer zones of finfish farms in BMA 8, Back Bay.

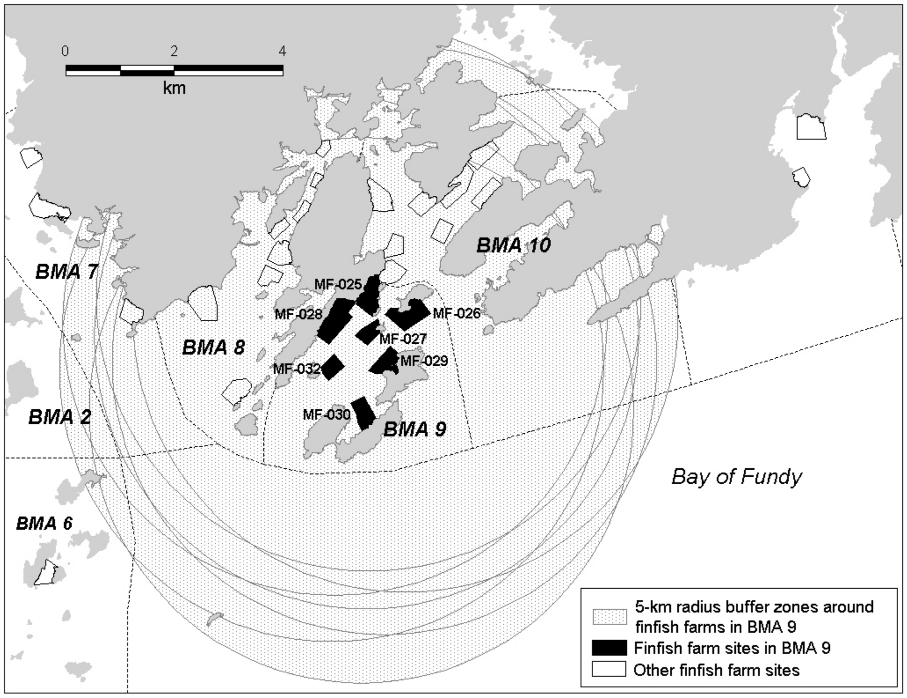


Fig. 7. Map showing 5-km radius buffer zones of finfish farms in BMA 9, Bliss Harbour.

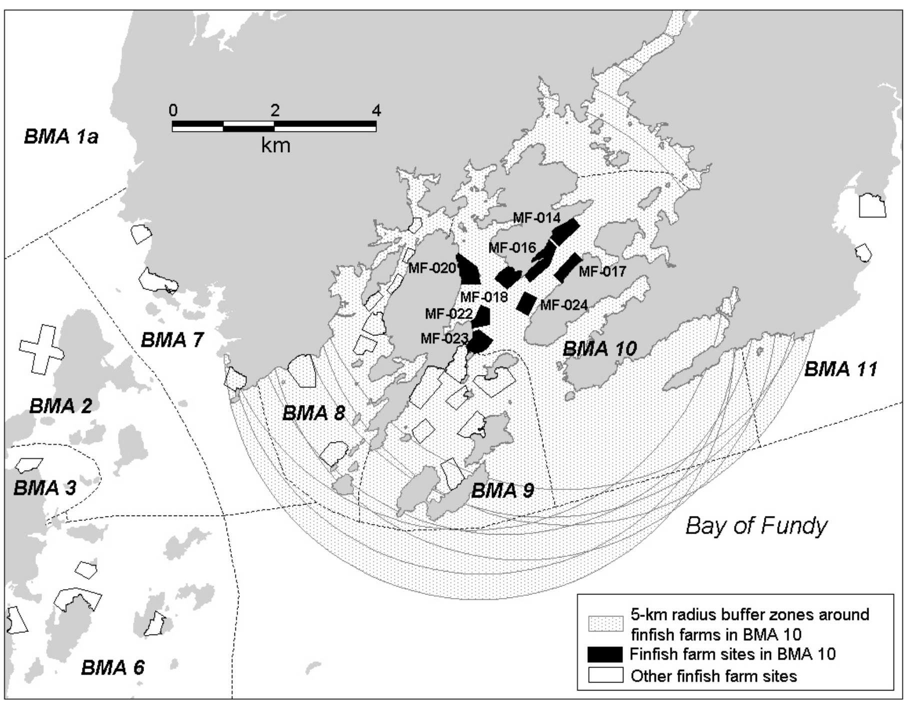


Fig. 8. Map showing 5-km radius buffer zones of finfish farms in BMA 10, Lime Kiln Bay.

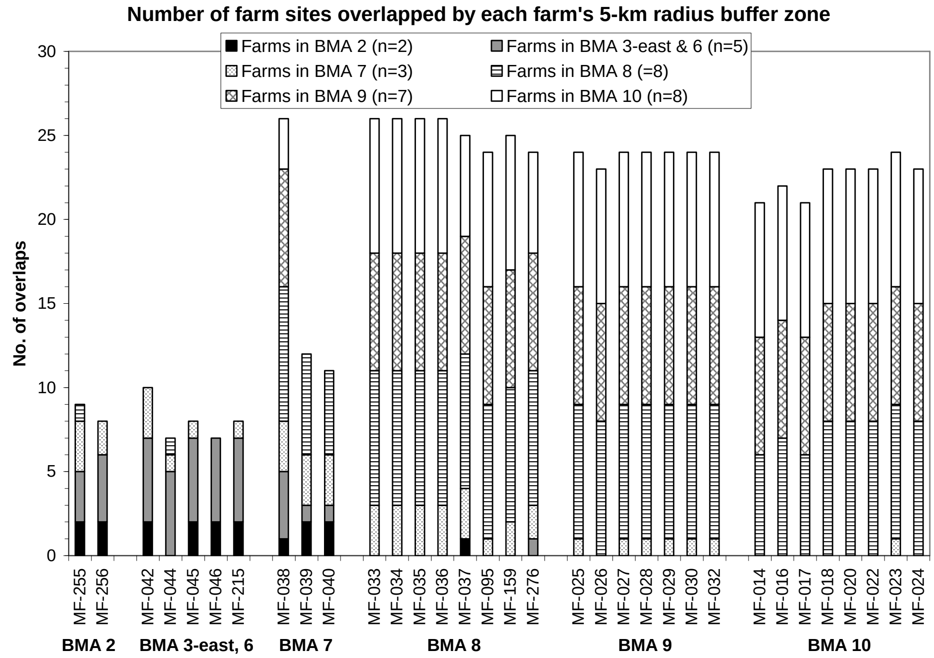


Fig. 9. Number of finfish farm sites overlapped by each farm's 5-km radius buffer zone in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The numbers include overlaps with the originating farm.

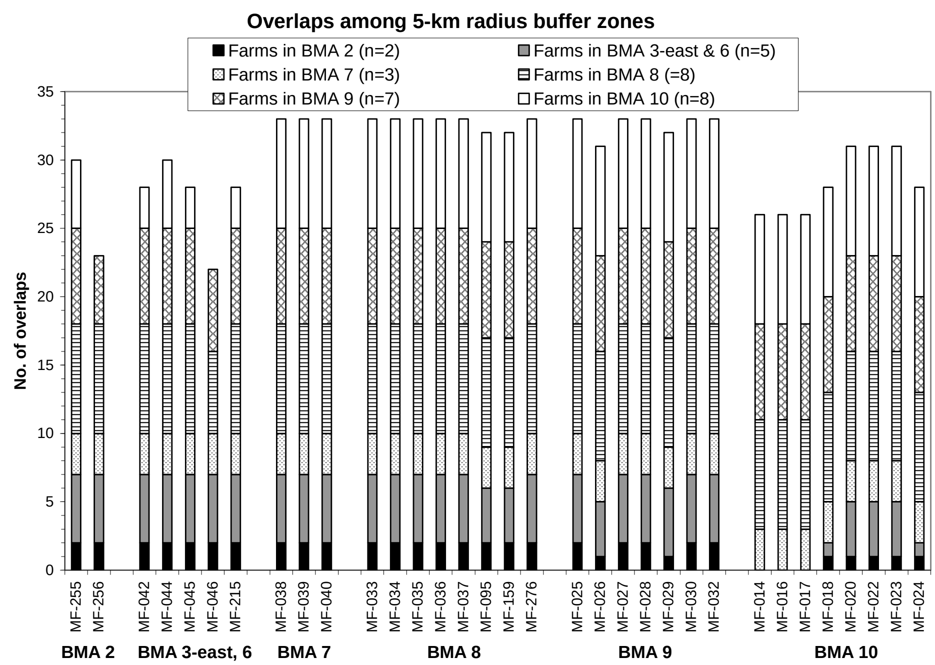
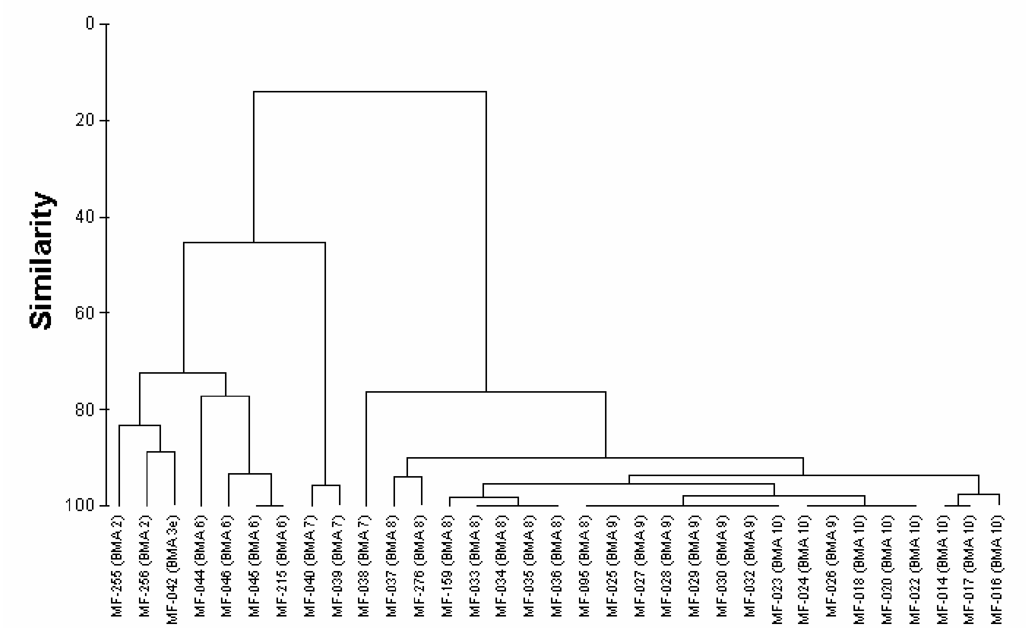
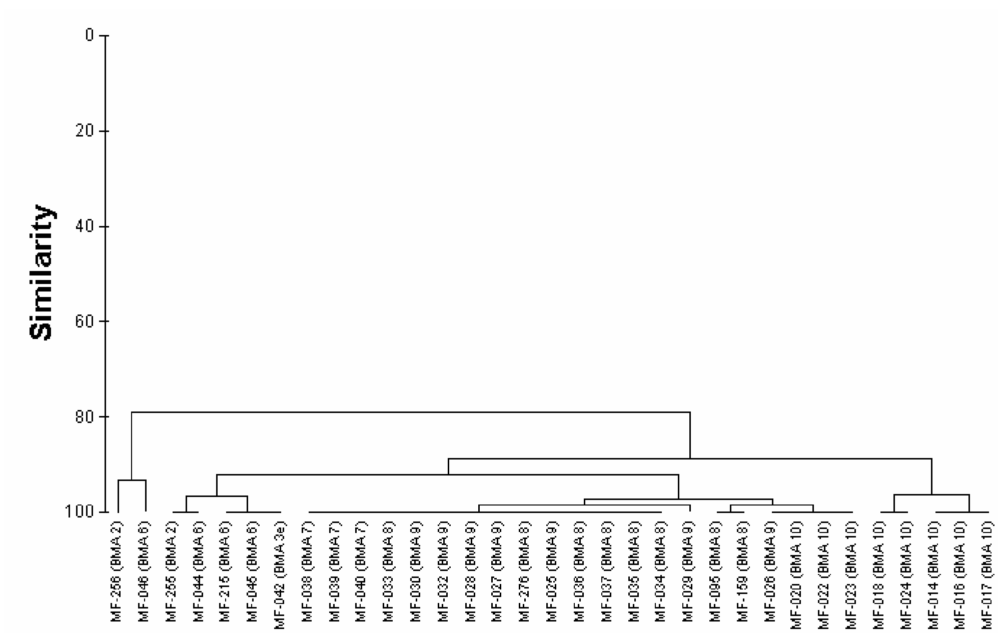


Fig. 10. Number of overlaps among 5-km radius buffer zones of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The numbers include overlaps with the originating farm.



Fig, 11. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps of each farm's 5-km radius buffer zone with finfish farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10.



Fig, 12. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps among 5-km radius buffer zones of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10.

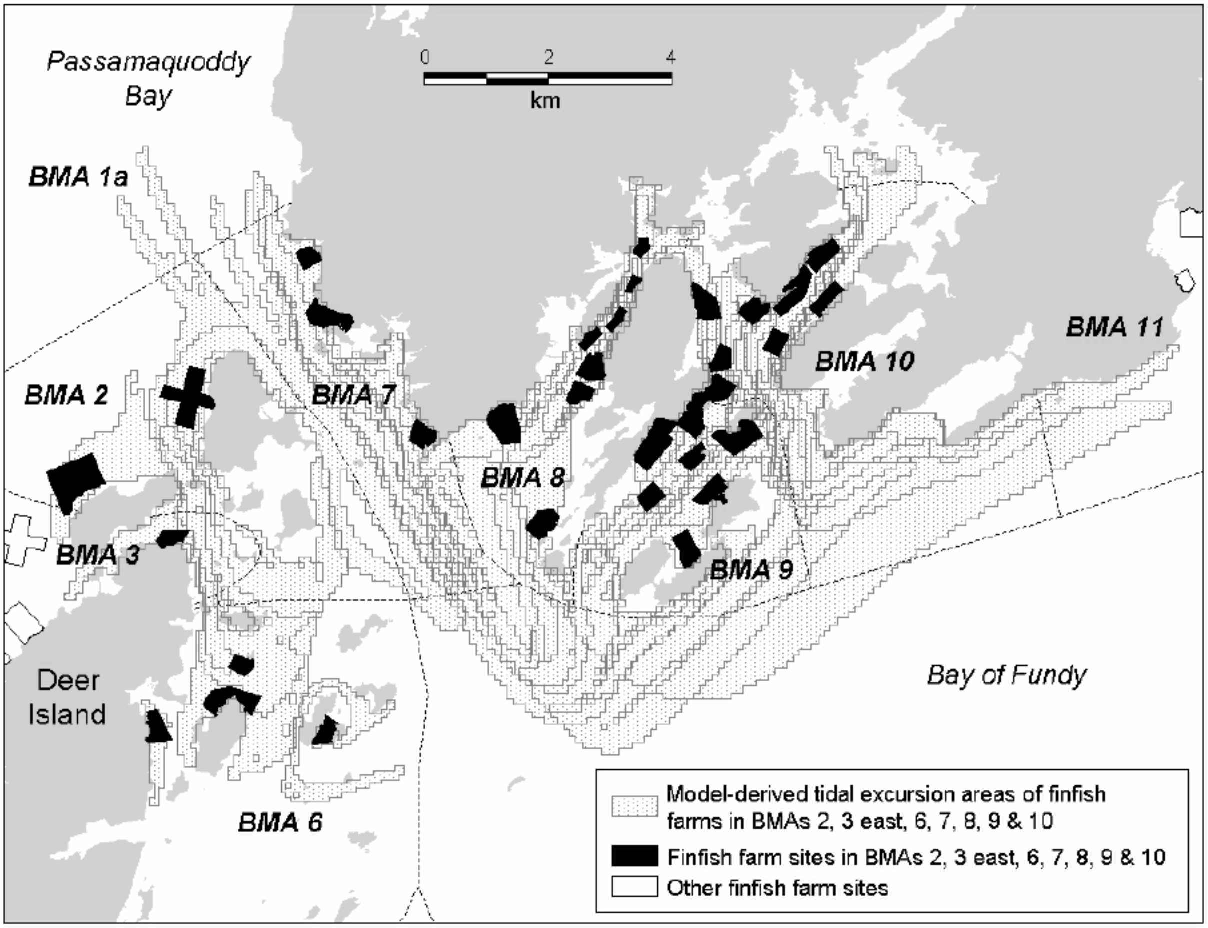


Fig. 13. Map showing model-derived tidal excursion areas of all finfish farms in the Macs Island area (BMA 2), eastern Deer Island (BMAs 3-east and 6), Letete Passage (BMA 7), Back Bay (BMA 8), Bliss Harbour (BMA 9), and Lime Kiln Bay (BMA 10).

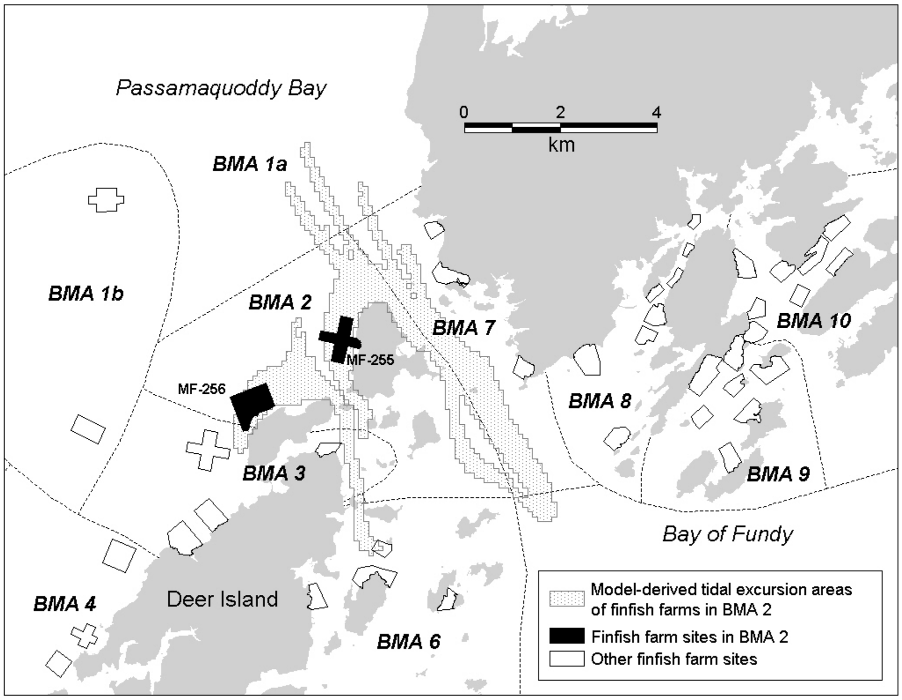


Fig. 14. Model-derived tidal excursion areas of finfish farms in BMA 2, Macs Island area.

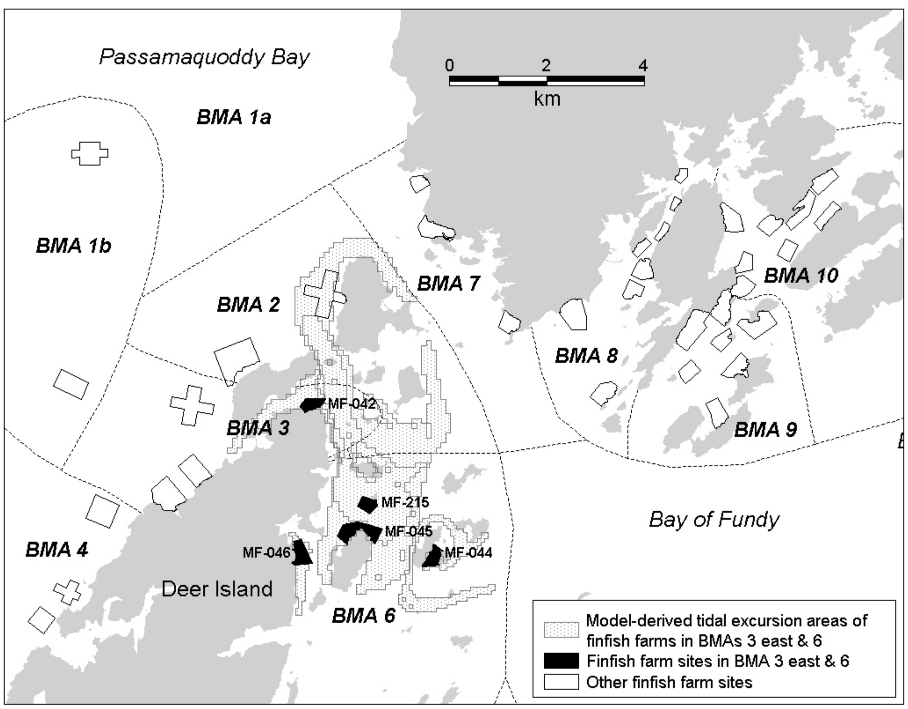


Fig. 15. Model-derived tidal excursion areas of finfish farms in BMAs 3-east and 6, eastern Deer Island.

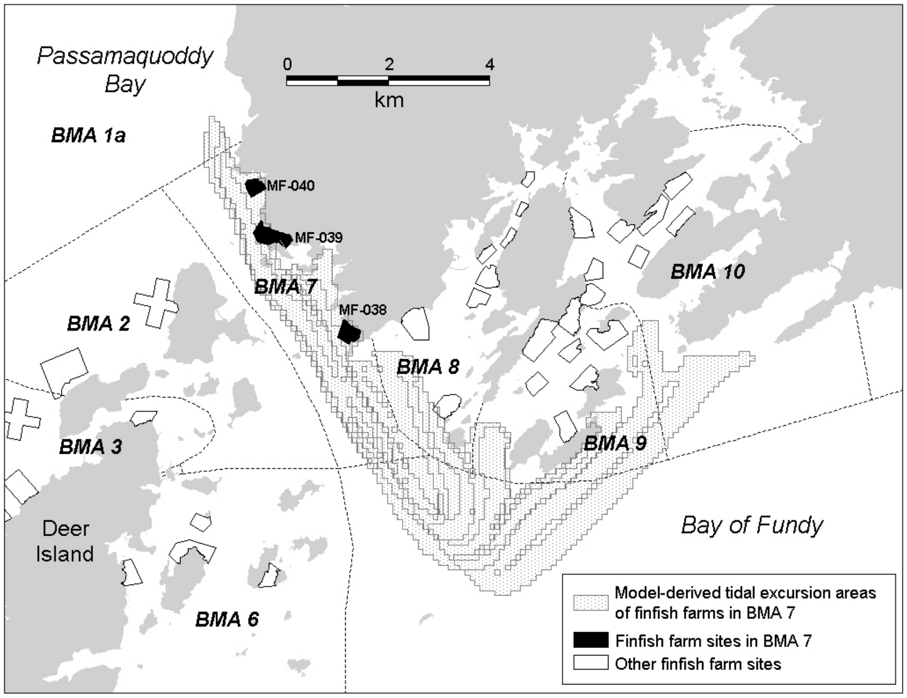


Fig. 16. Model-derived tidal excursion areas of finfish farms in BMA 7, Letete Passage.

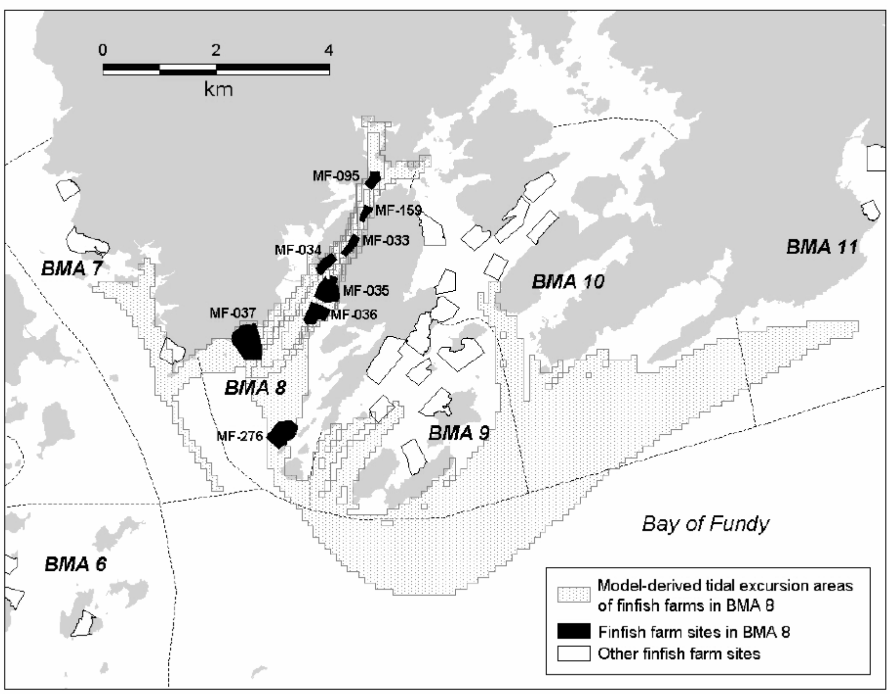


Fig. 17. Model-derived tidal excursion areas of finfish farms in BMA 8, Back Bay.

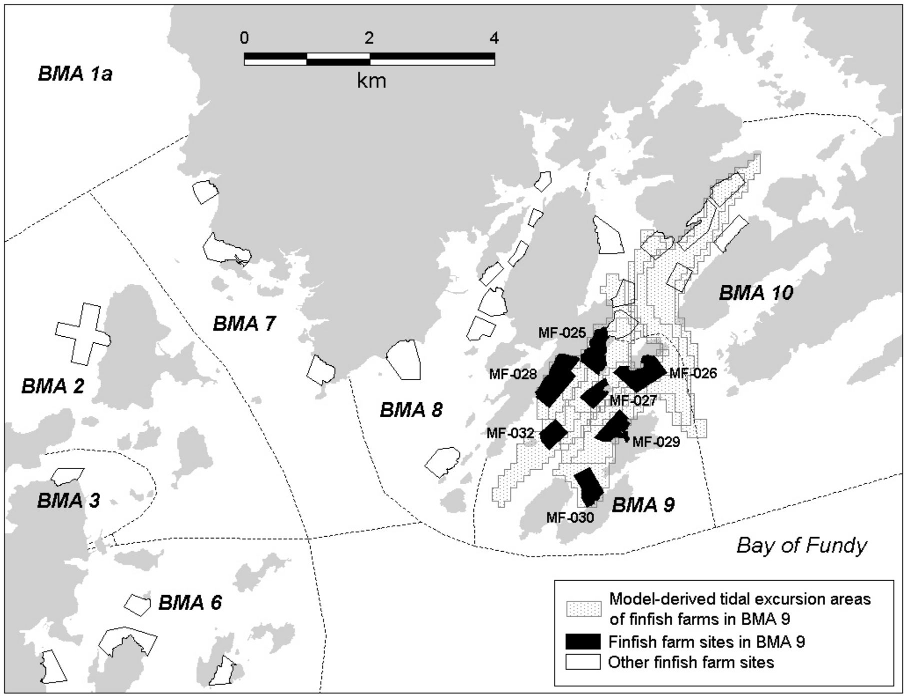


Fig. 18. Model-derived tidal excursion areas of finfish farms in BMA 9, Bliss Harbour.

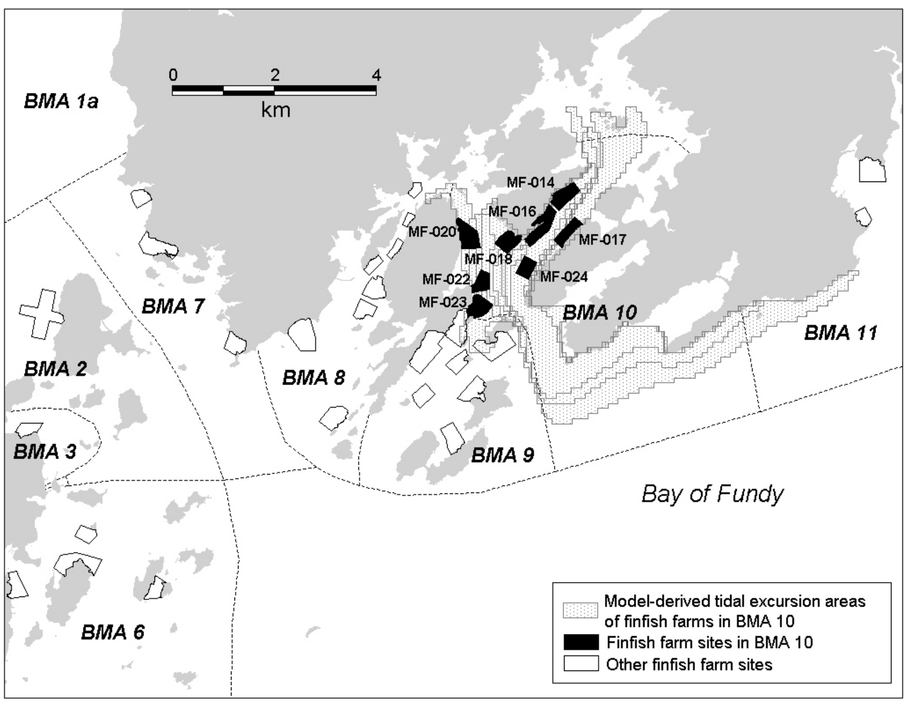


Fig. 19. Model-derived tidal excursion areas of finfish farms in BMA 10, Lime Kiln Bay.

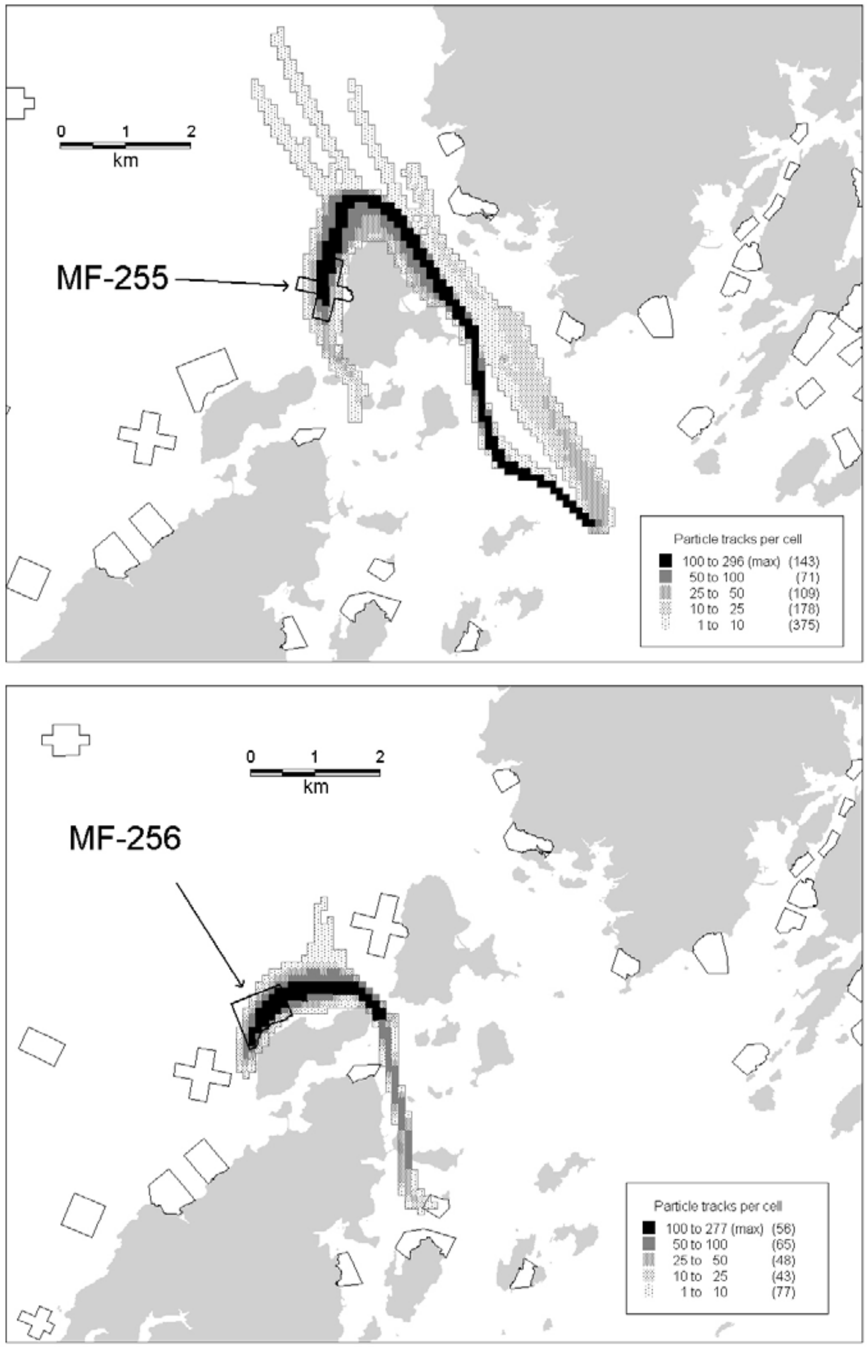


Fig. 20. Model-derived tidal excursion areas of each finfish farm in BMA 2, Macs Island area. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.

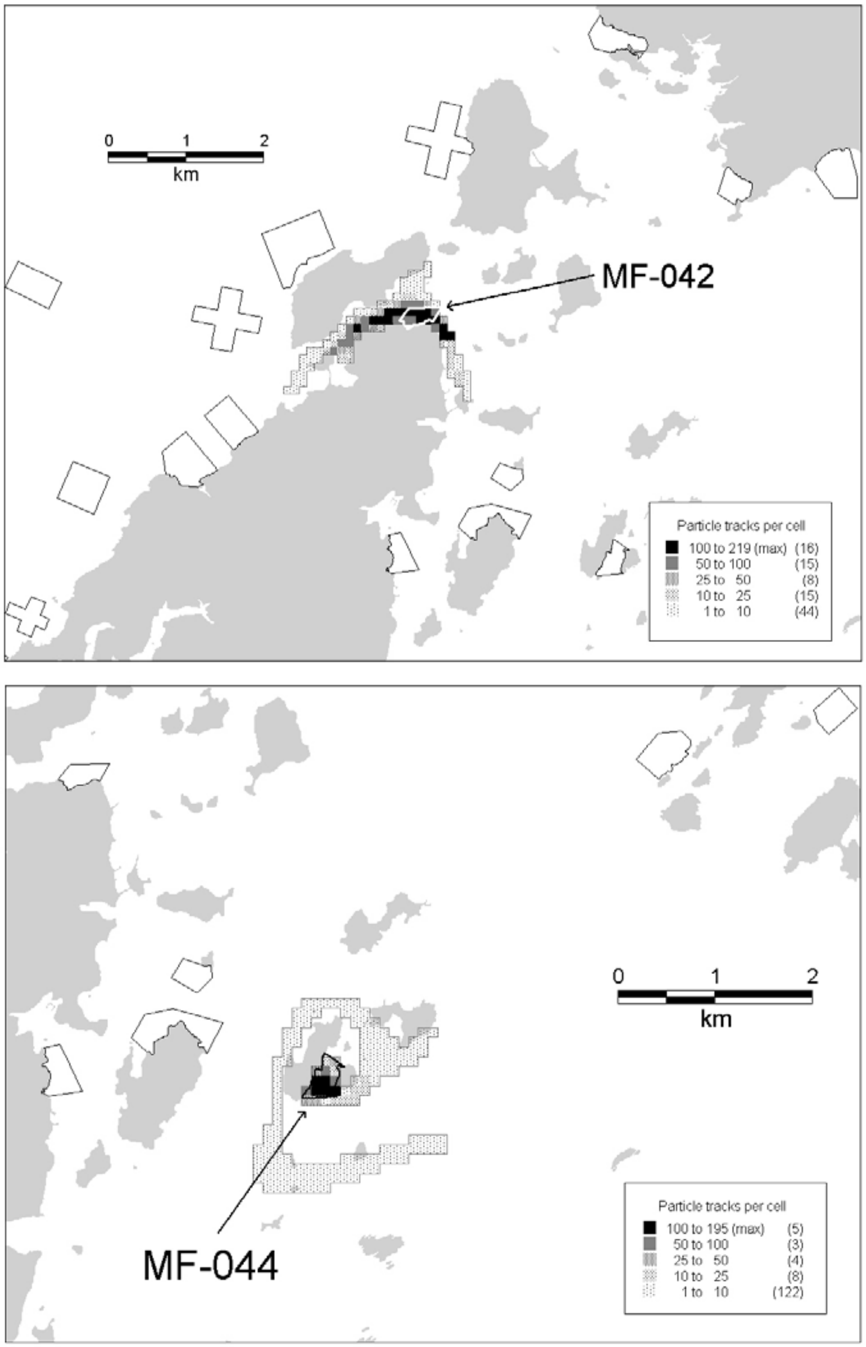
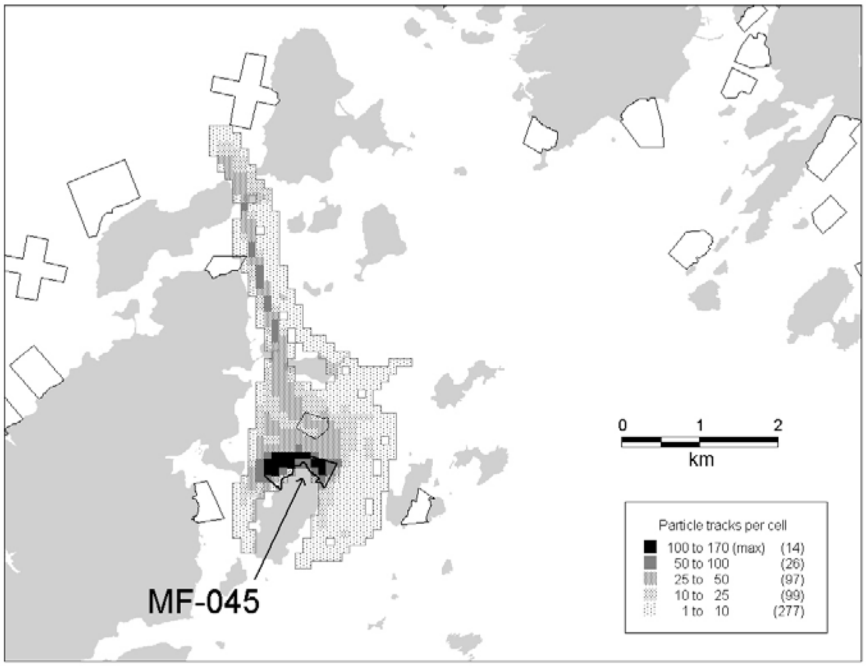


Fig. 21. Model-derived tidal excursion areas of each finfish farm in BMAs 3-east and 6, eastern Deer Island. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm (slightly fewer in some cases) at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.



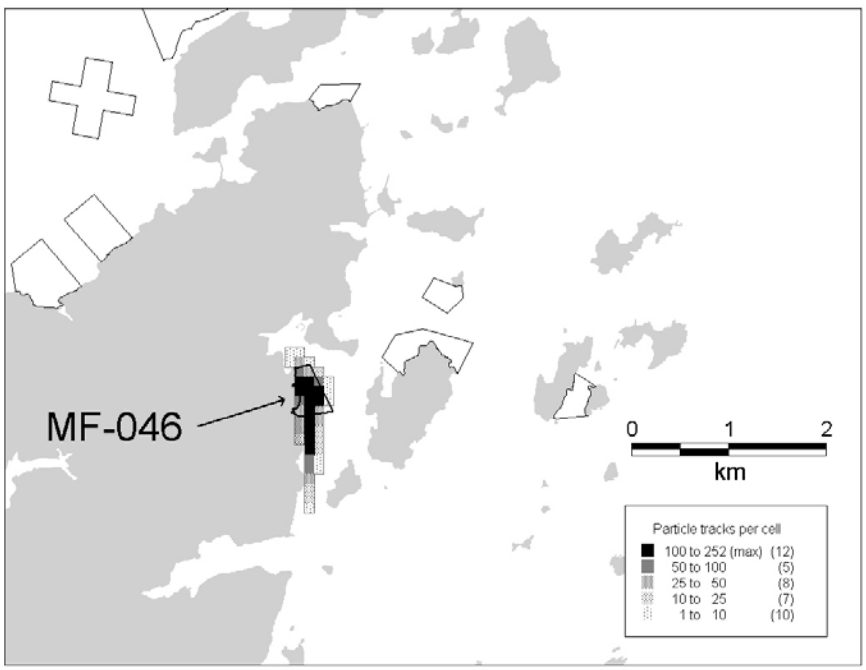


Fig. 21 continued.

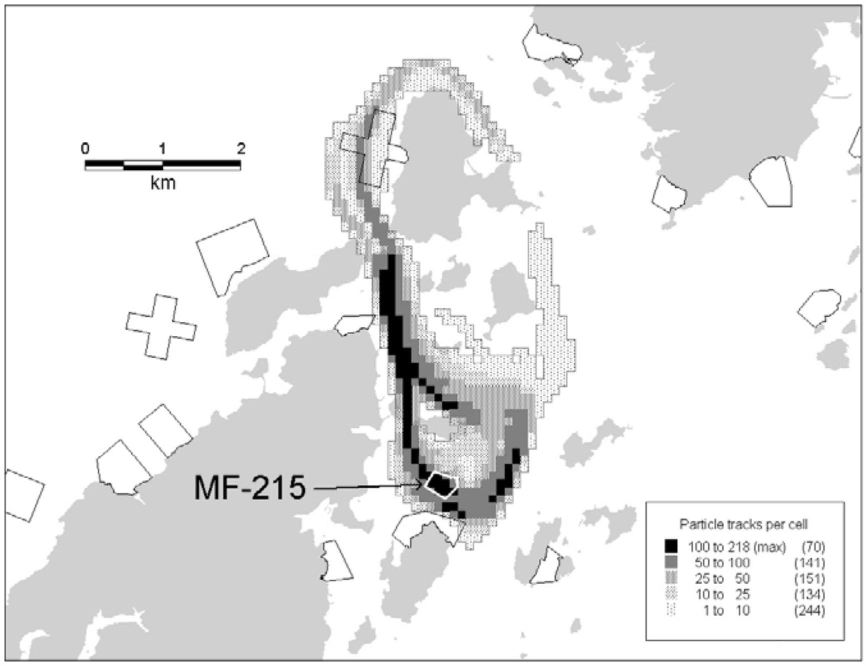


Fig. 21 concluded.

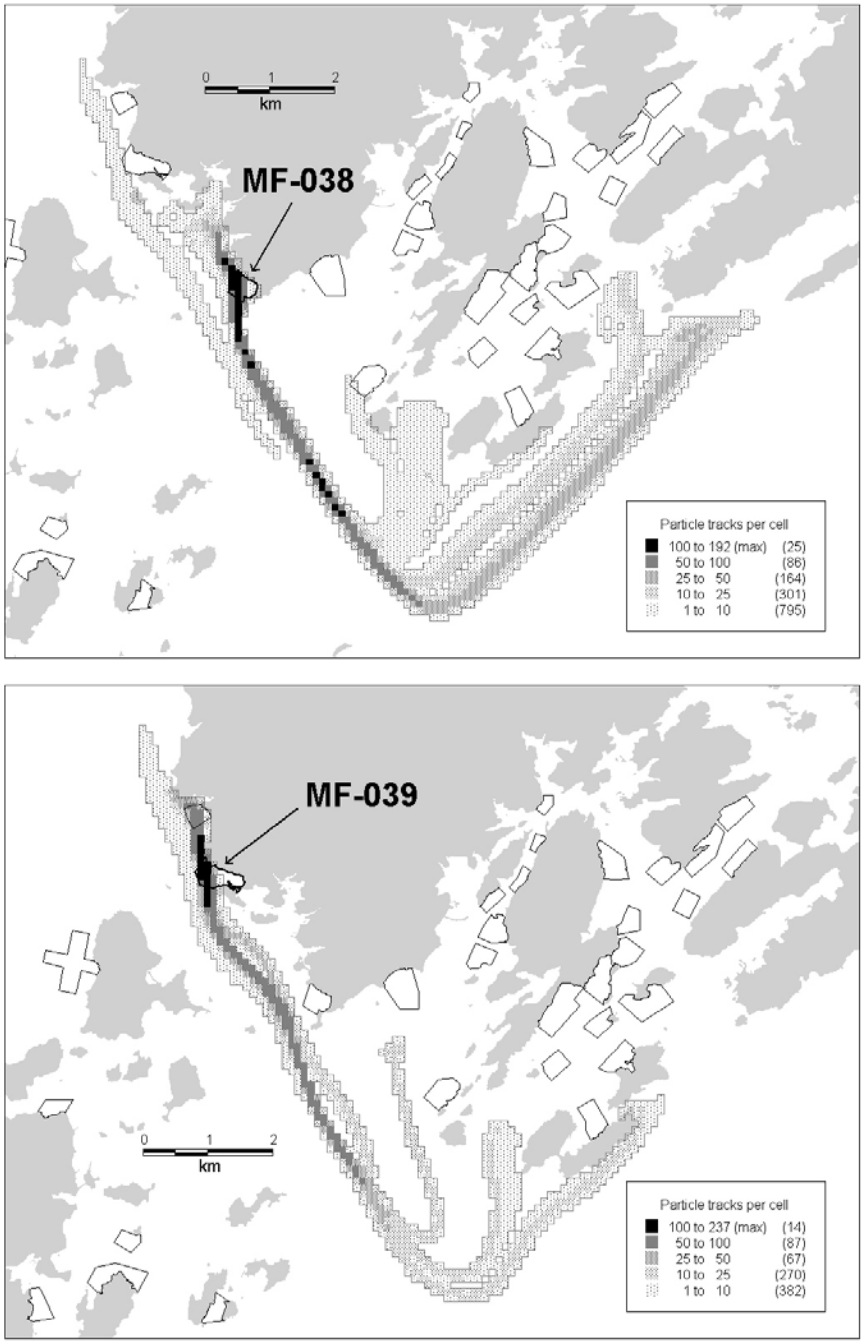


Fig. 22. Model-derived tidal excursion areas of each finfish farm in BMA 7, Letete Passage. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.

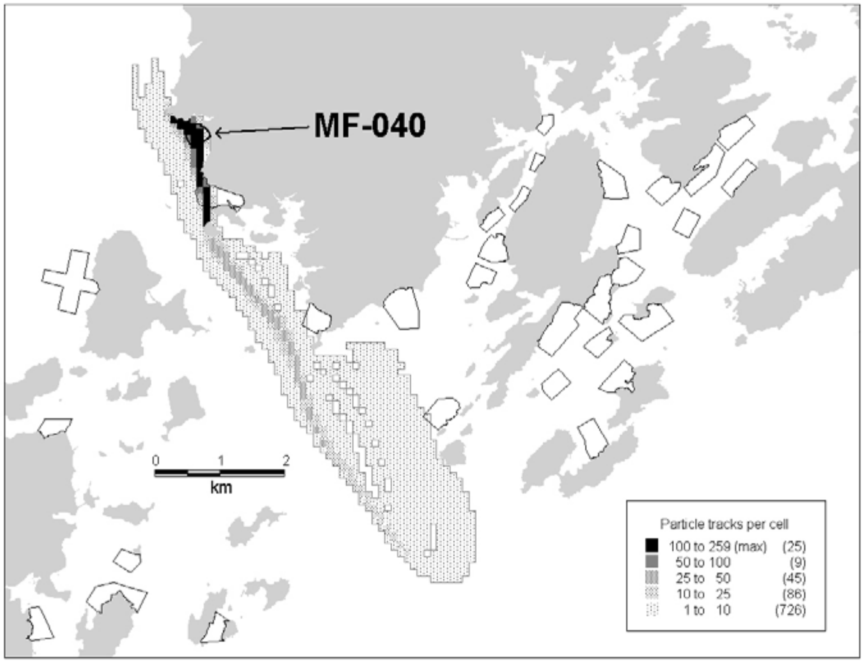


Fig. 22 concluded.

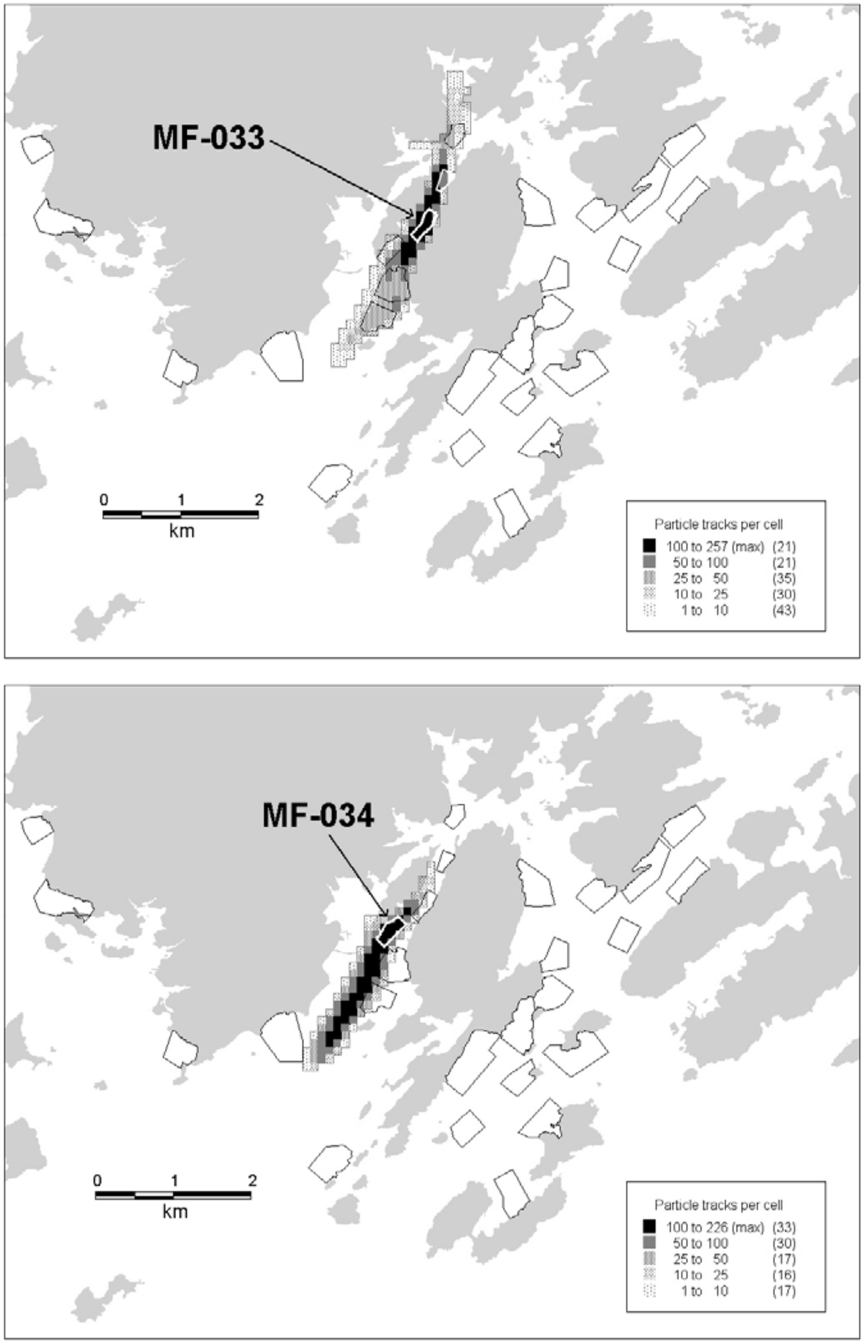


Fig. 23. Model-derived tidal excursion areas of each finfish farm in BMA 8, Back Bay. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm (slightly fewer in some cases) at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.

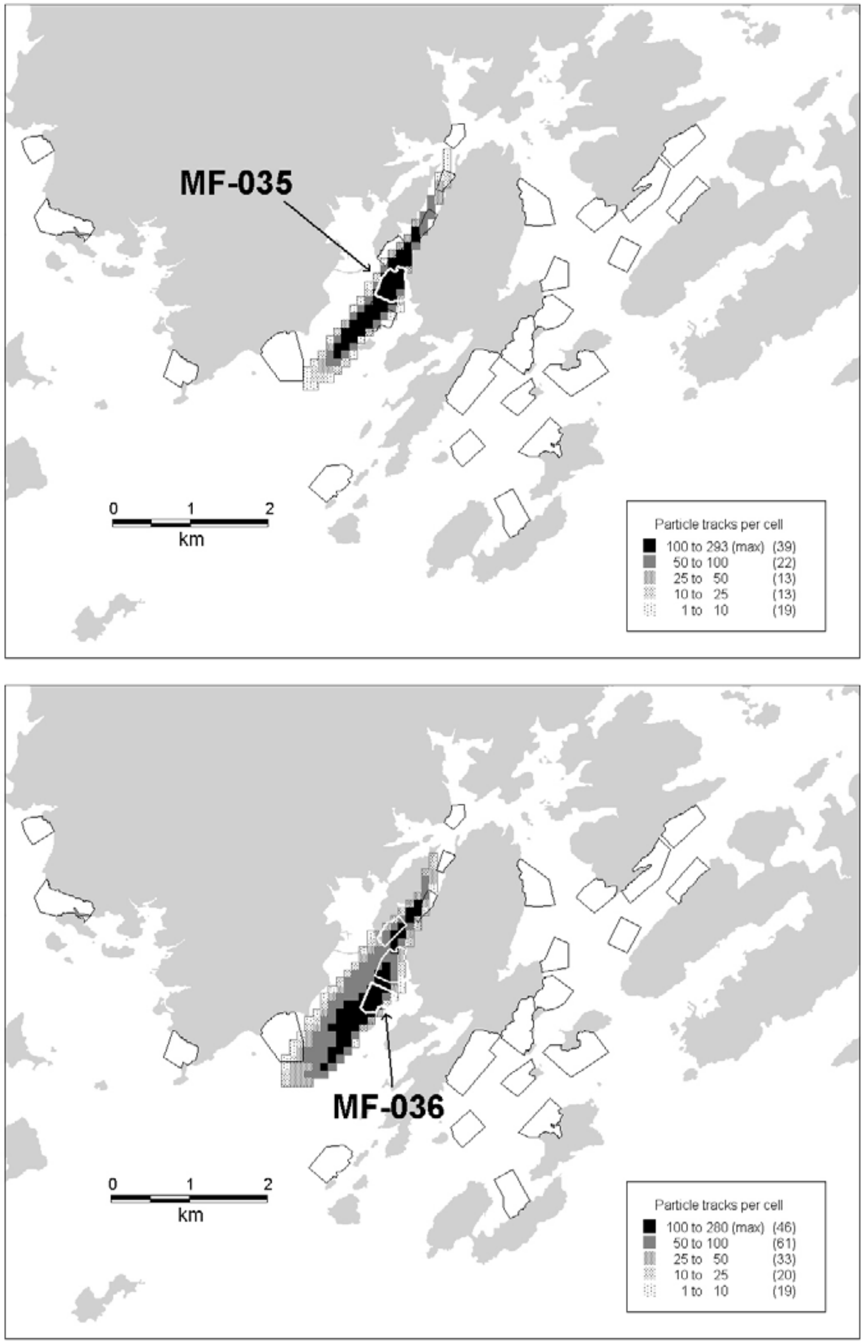
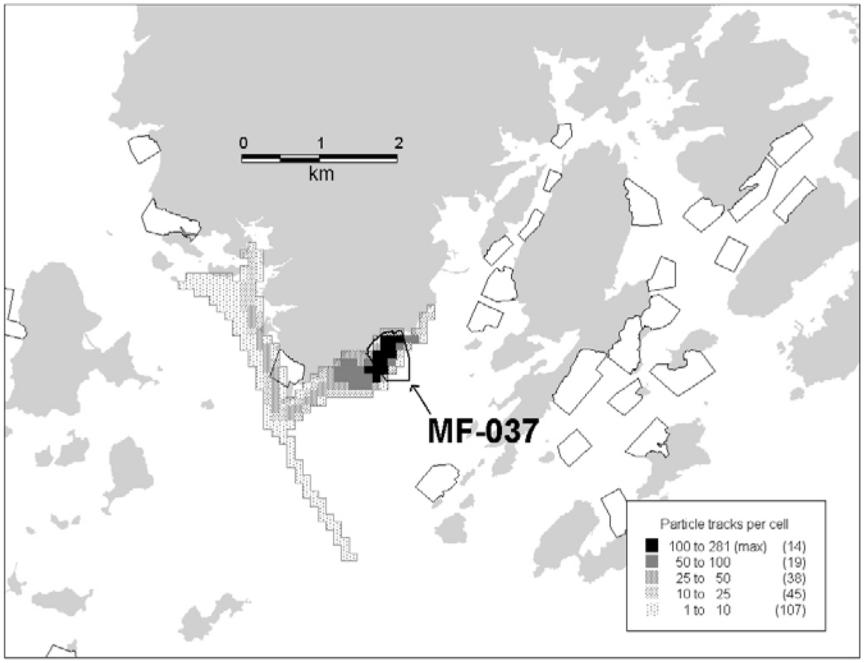


Fig. 23 continued.



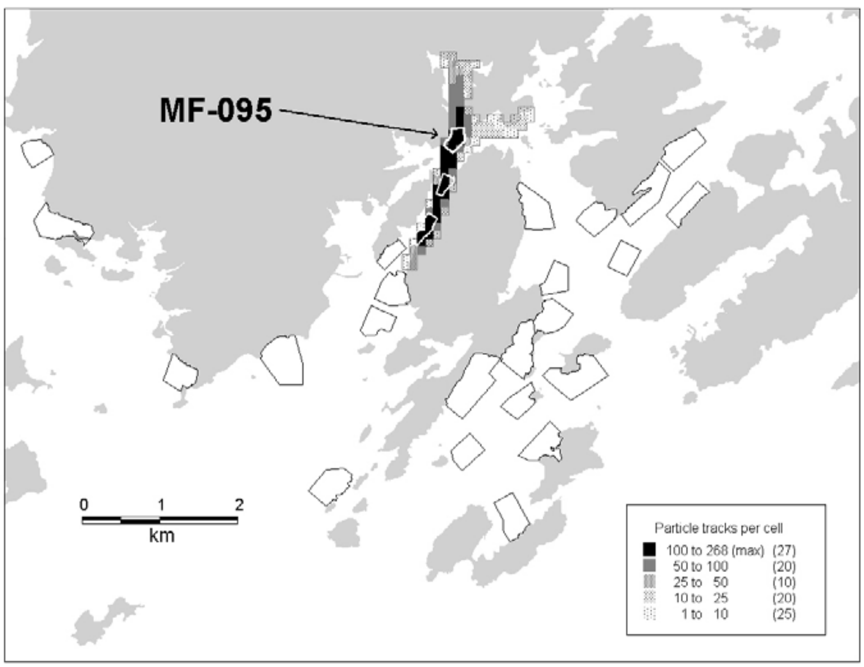


Fig. 23 continued.

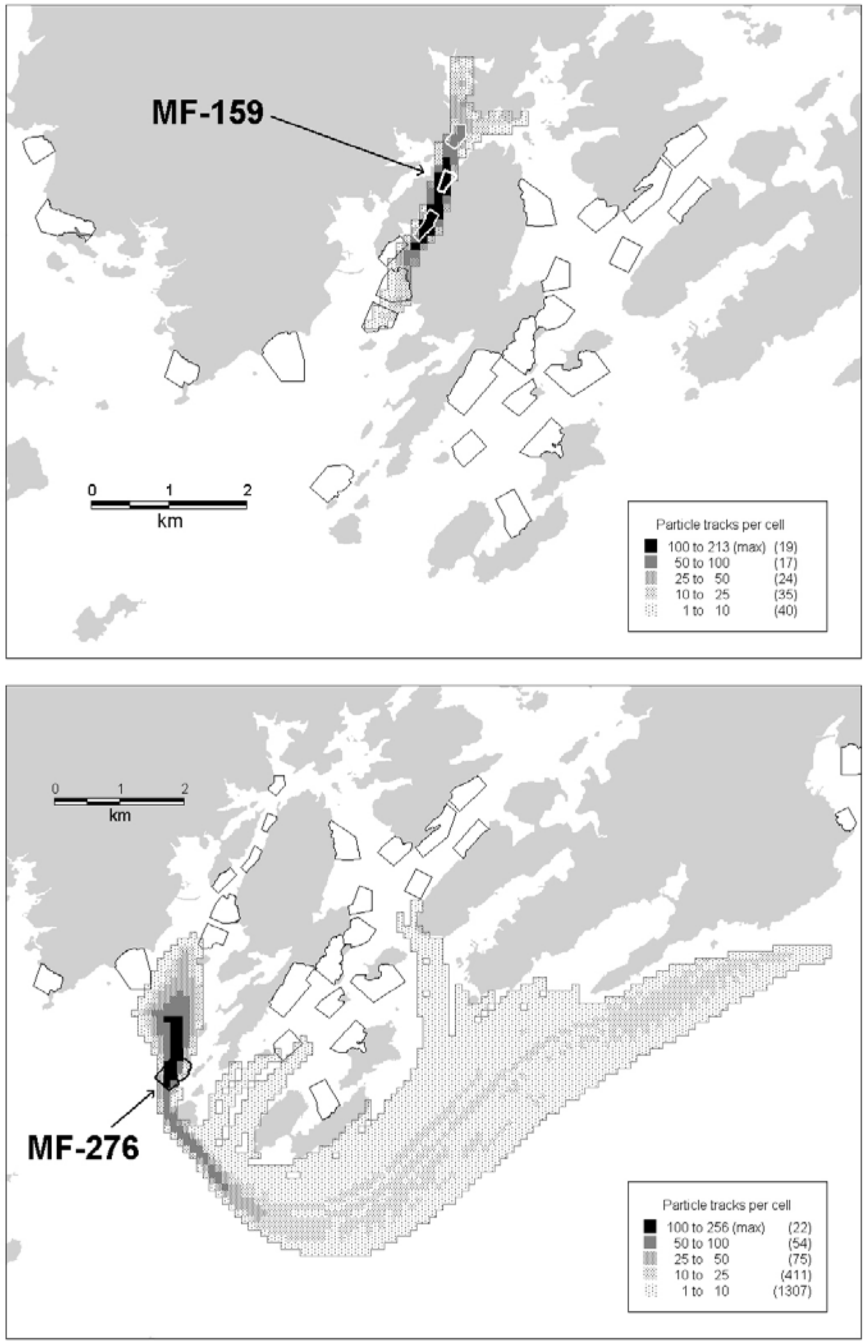
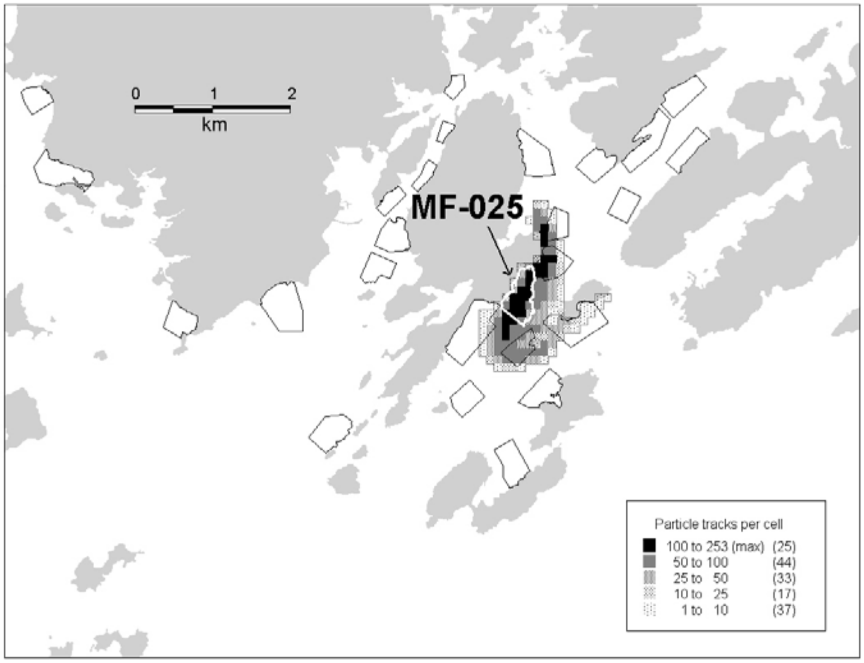


Fig. 23 concluded.



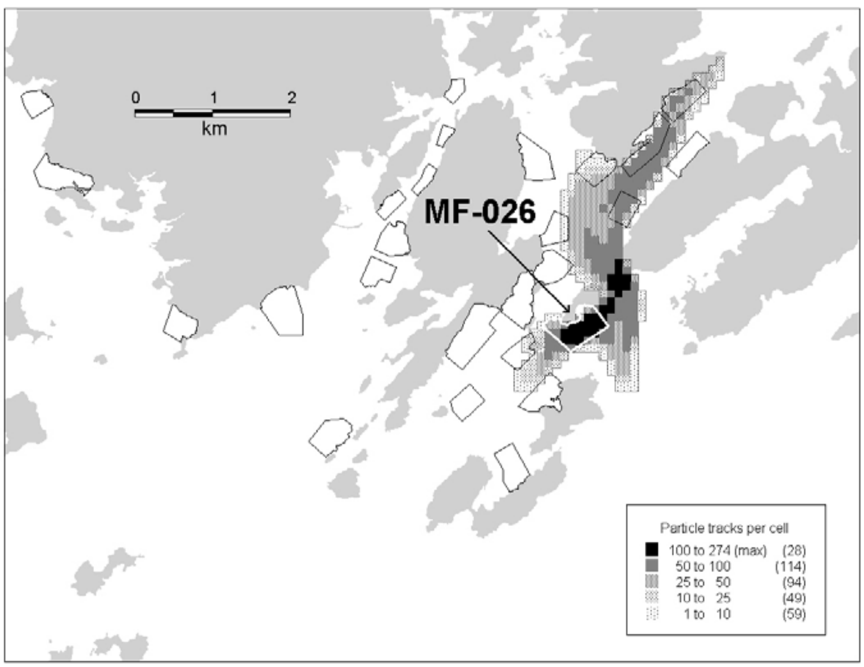


Fig. 24. Model-derived tidal excursion areas of each finfish farm in BMA 9, Bliss Harbour. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm (slightly fewer in some cases) at intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.

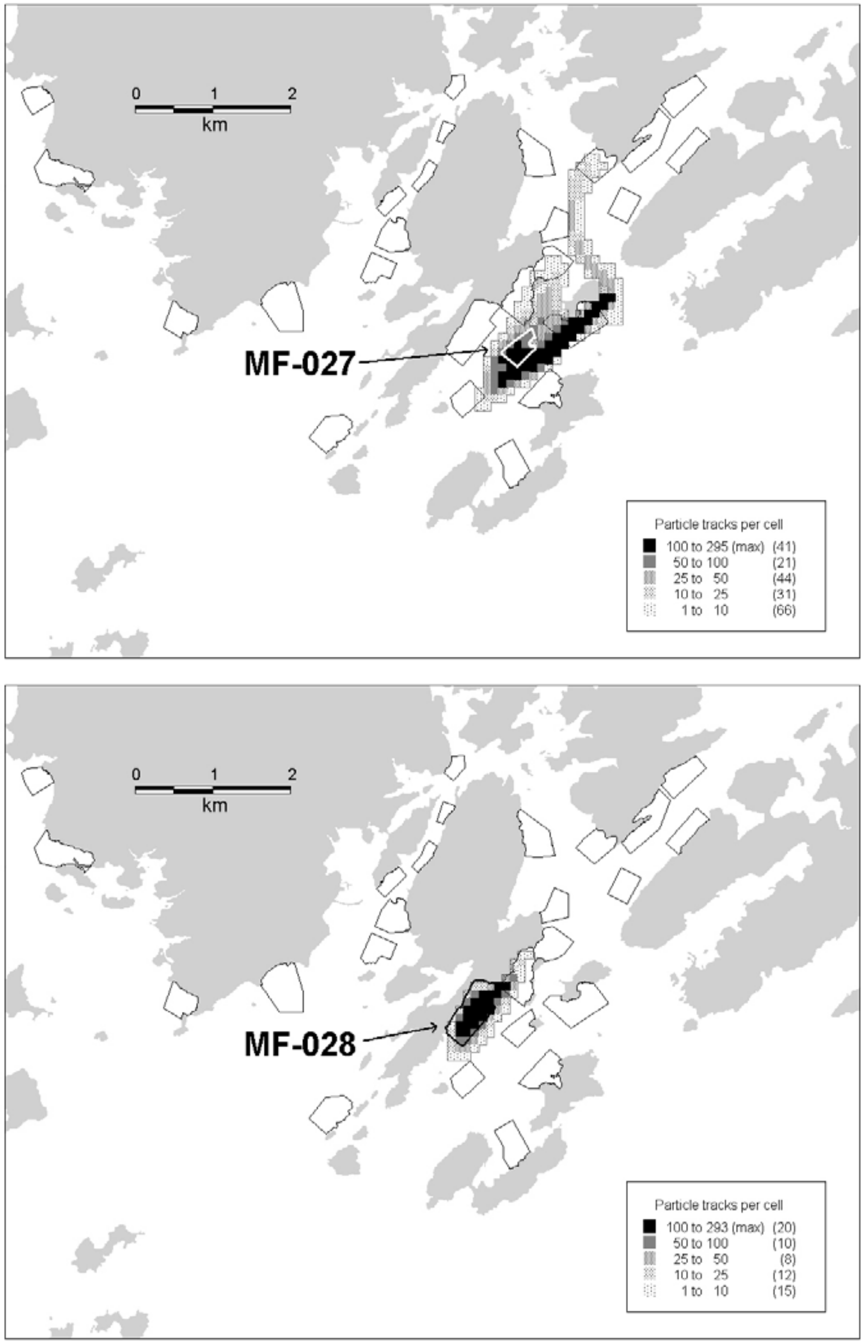
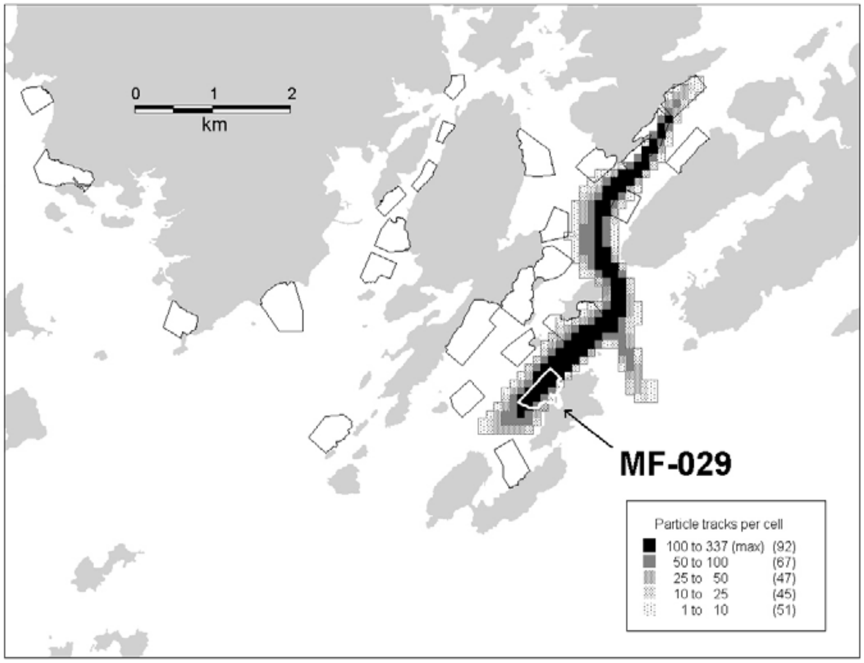


Fig. 24 continued.



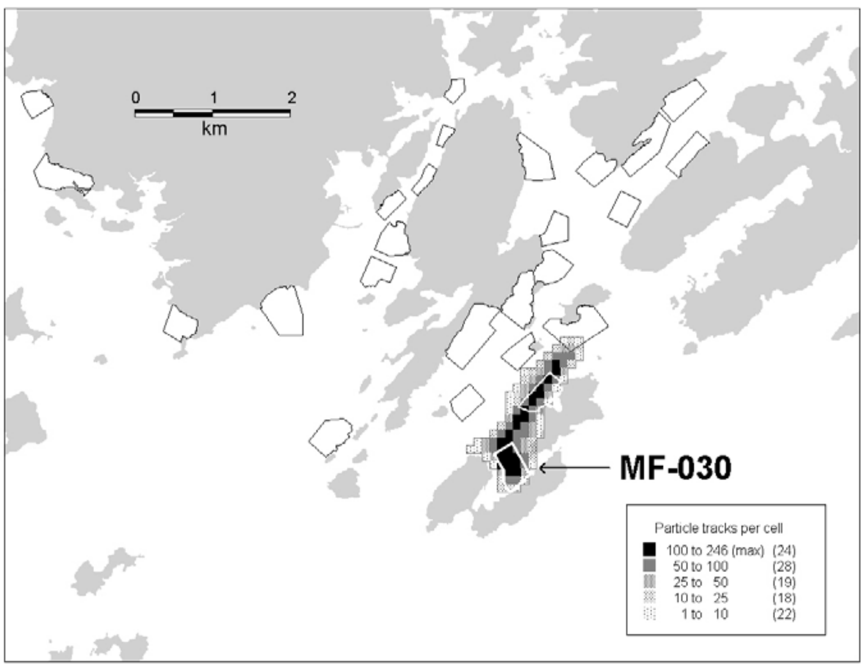


Fig. 24 continued.

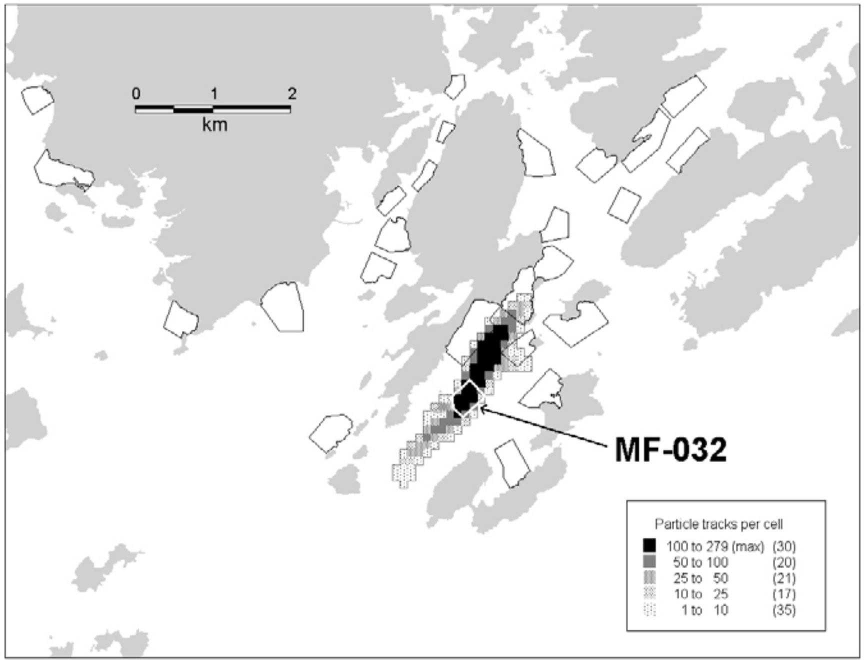


Fig. 24 concluded.

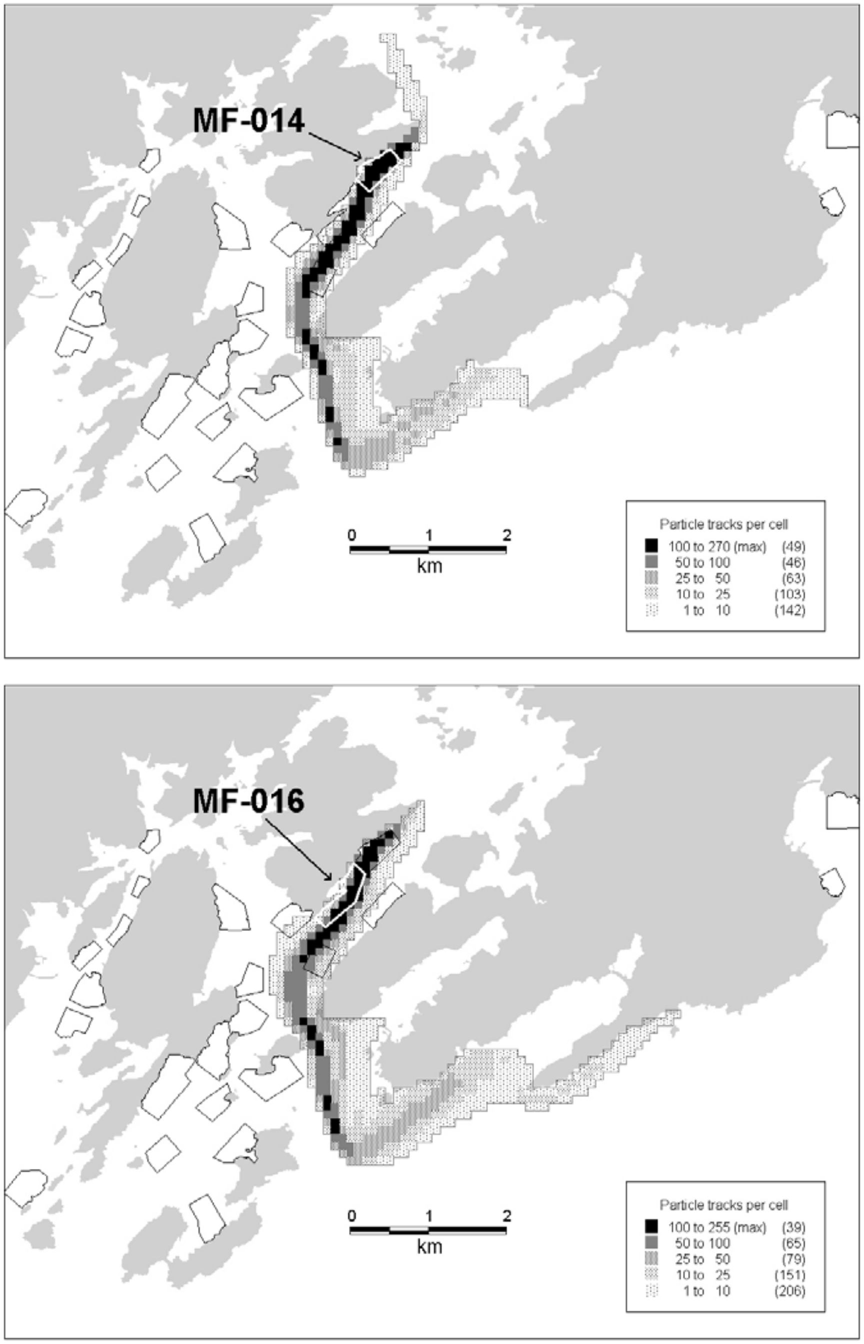
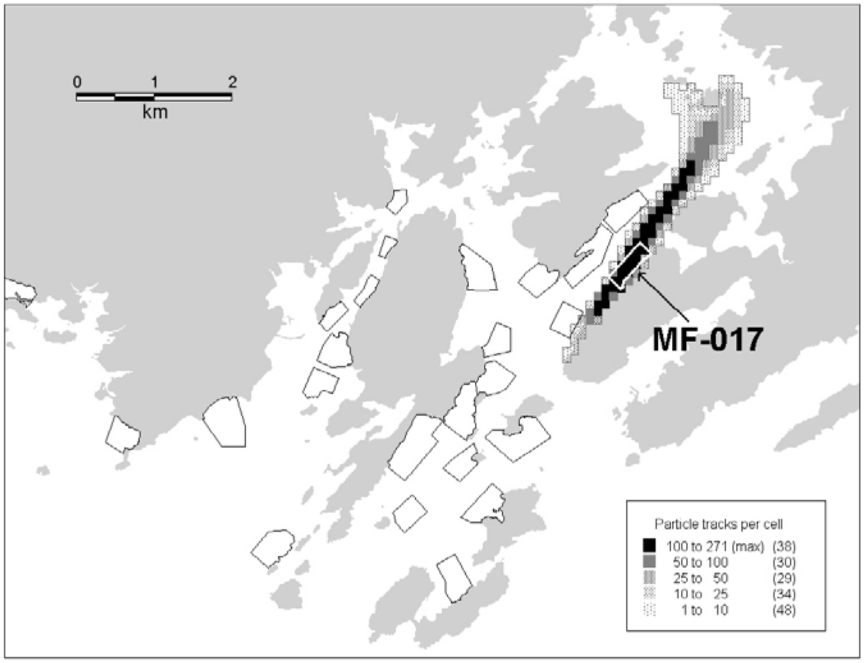


Fig. 25. Model-derived tidal excursion areas of each finfish farm in BMA 10, Lime Kiln Bay. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm (slightly fewer in some cases) at hourly intervals over a 12-h period (see text for details). Each particle was tracked for one tidal excursion (12.42 h) or until it stopped upon hitting the shore, whichever came first. Farm sites are shown as small polygons. Numbers in parentheses in the legend are the numbers of cells within each range of particle track counts.



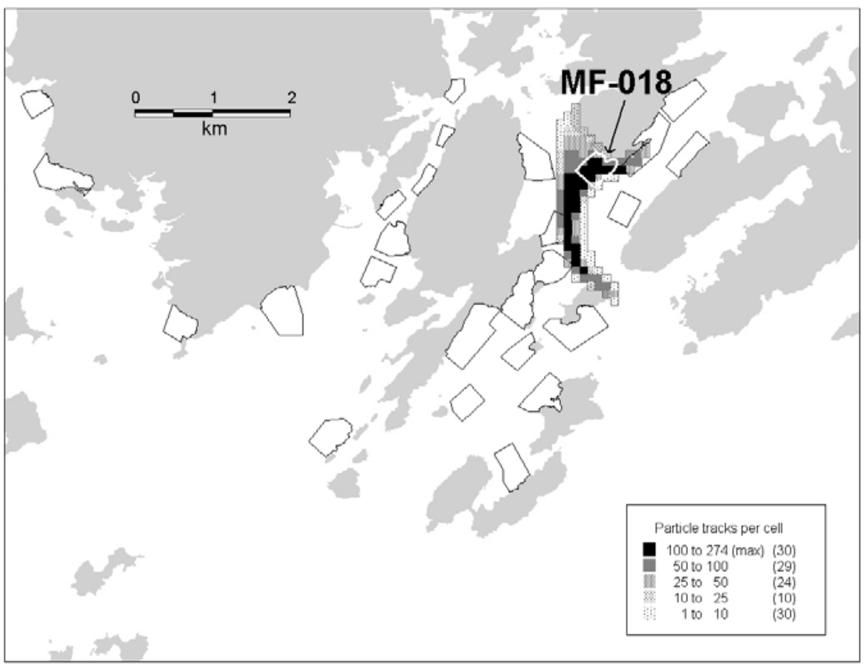


Fig. 25 continued.

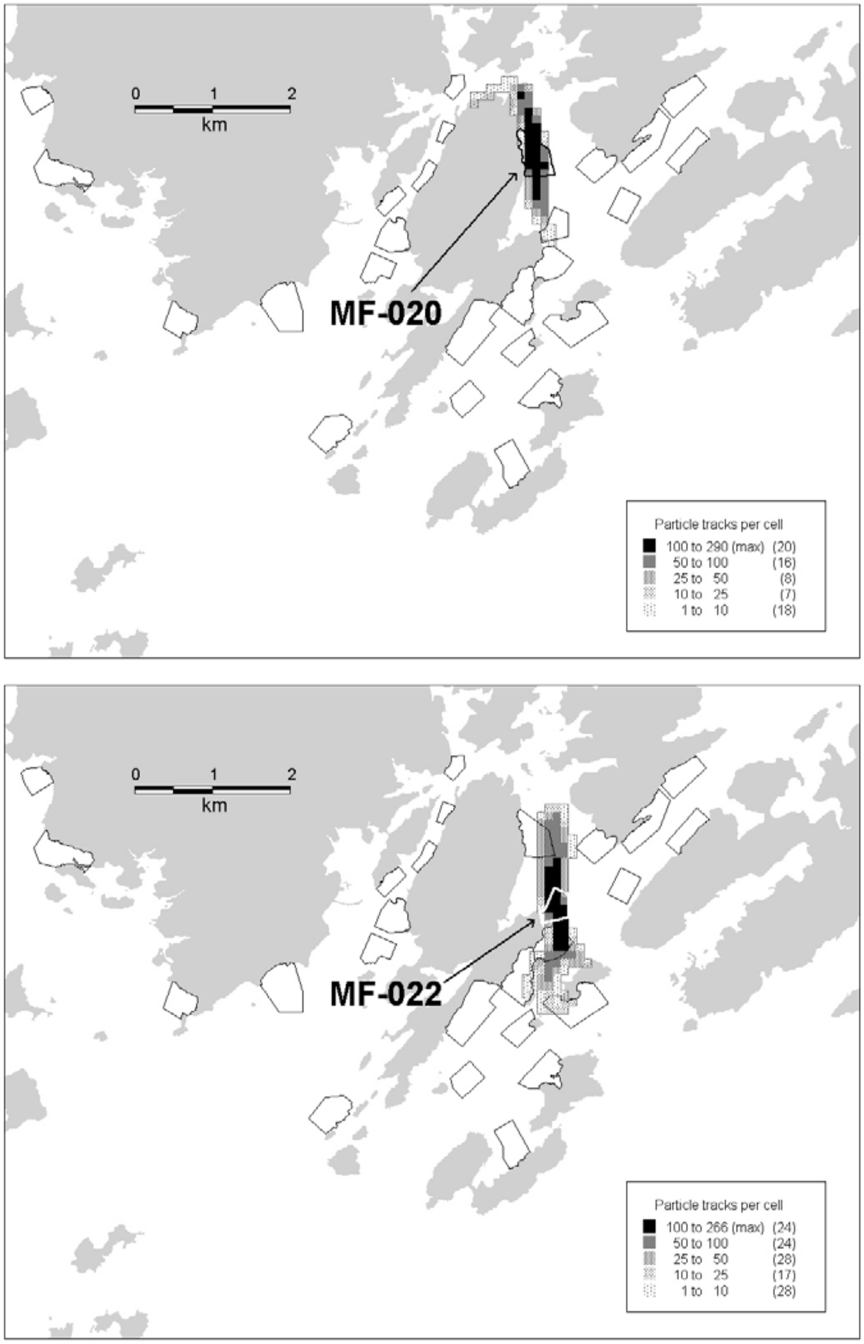


Fig. 25 continued.

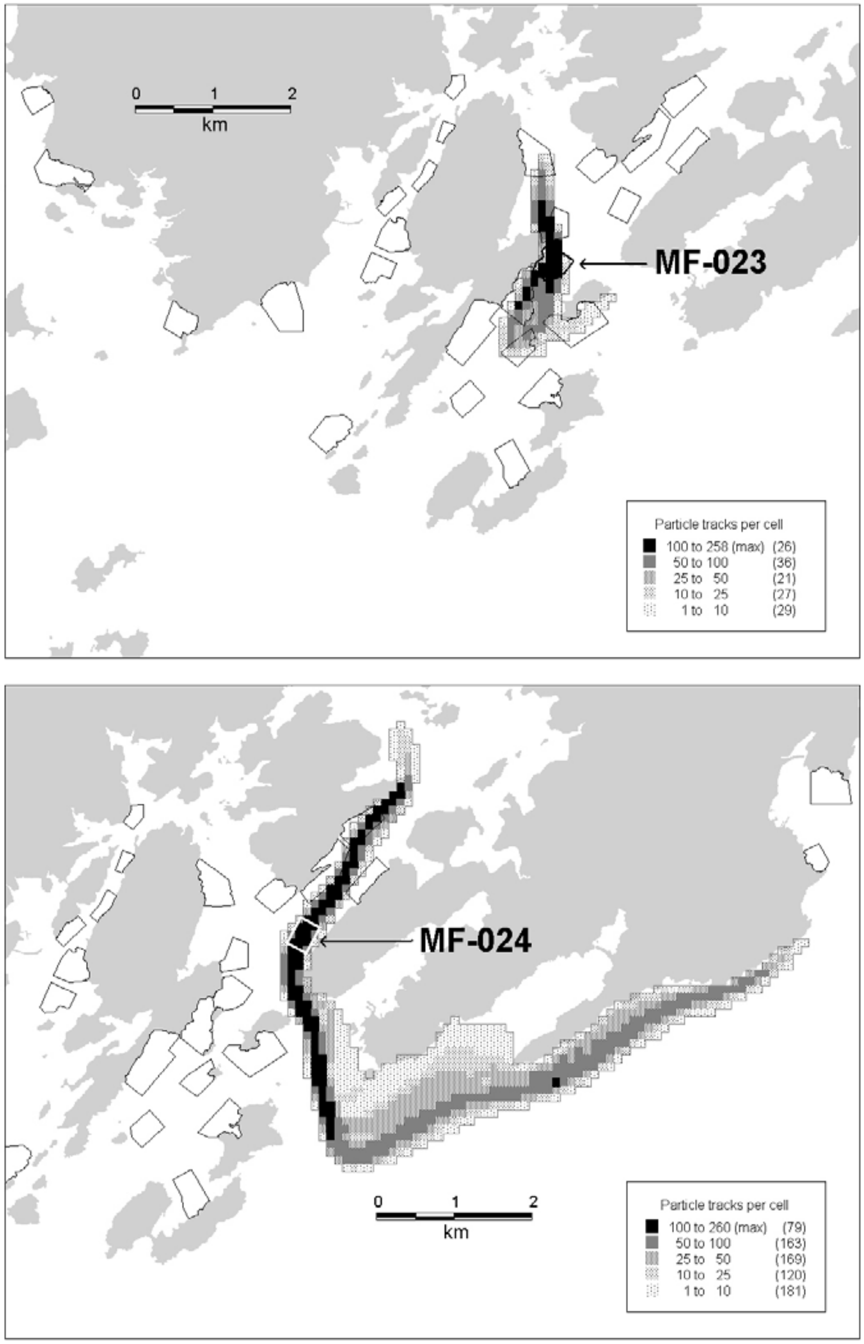


Fig. 25 concluded.

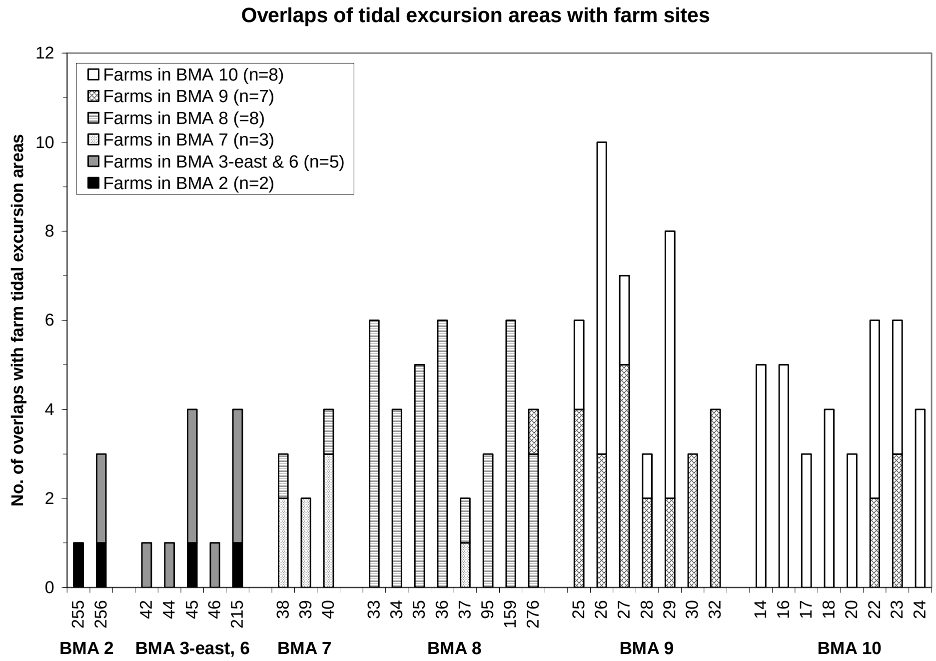


Fig. 26. Number of finfish farm sites overlapped by each farm's model-derived tidal excursion area in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the farms from which the tidal excursion areas originated. The numbers include overlaps with the originating farm.

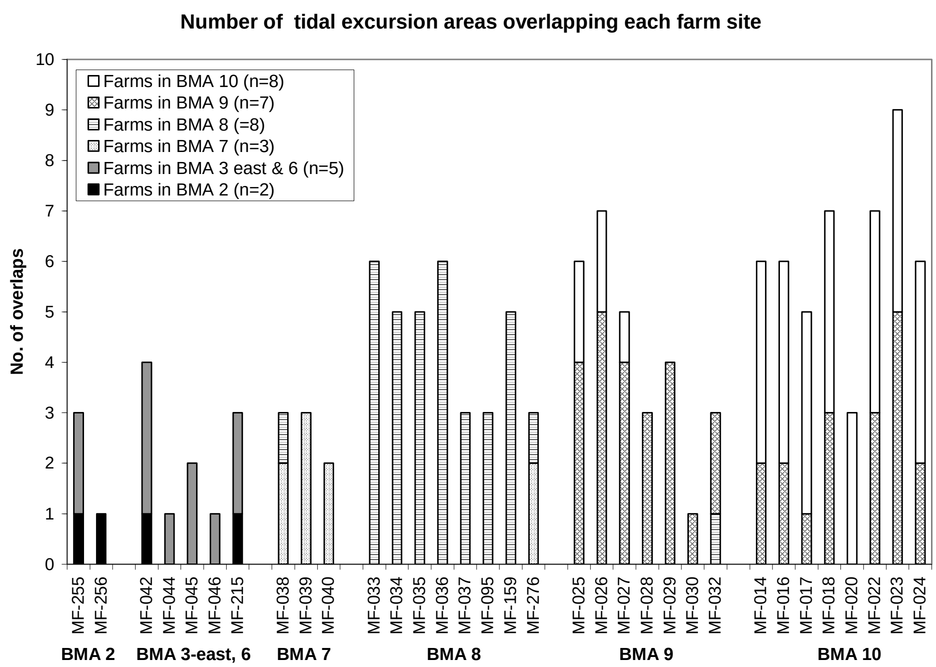


Fig. 27. Number of model-derived tidal excursion areas overlapping each finfish farm site in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the receiving farms. The numbers include overlaps with the originating farm.

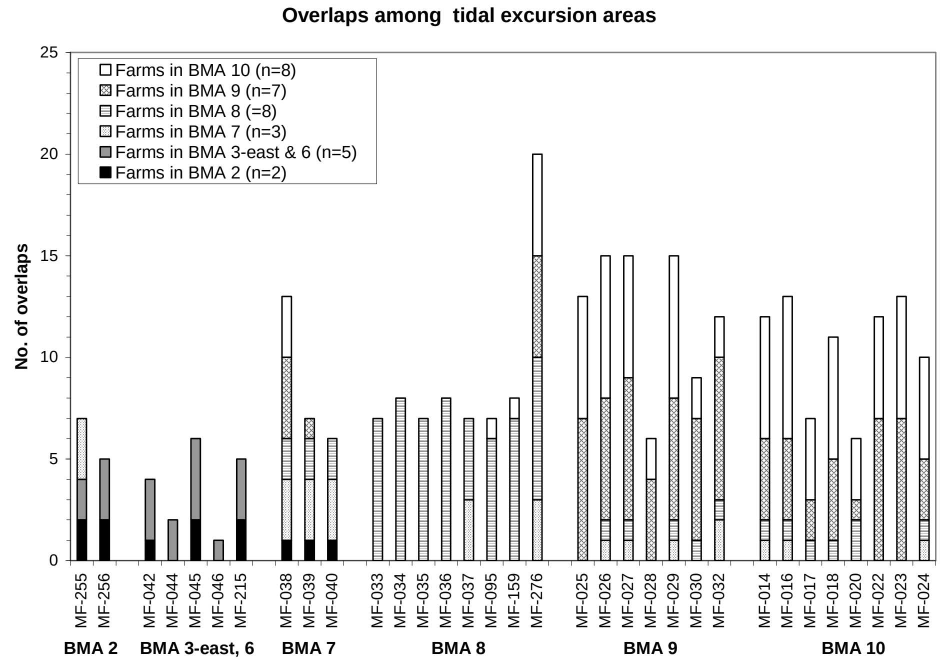
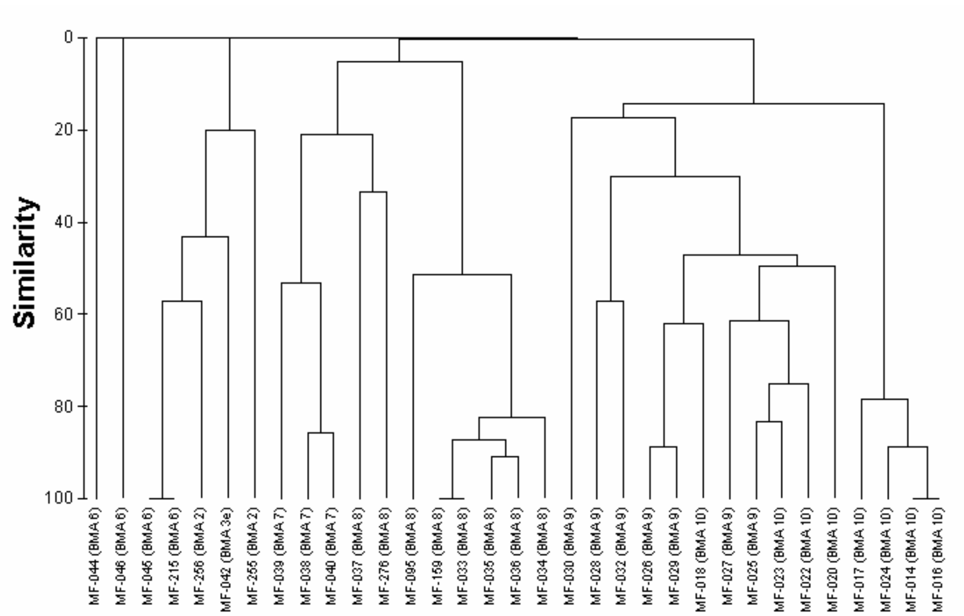
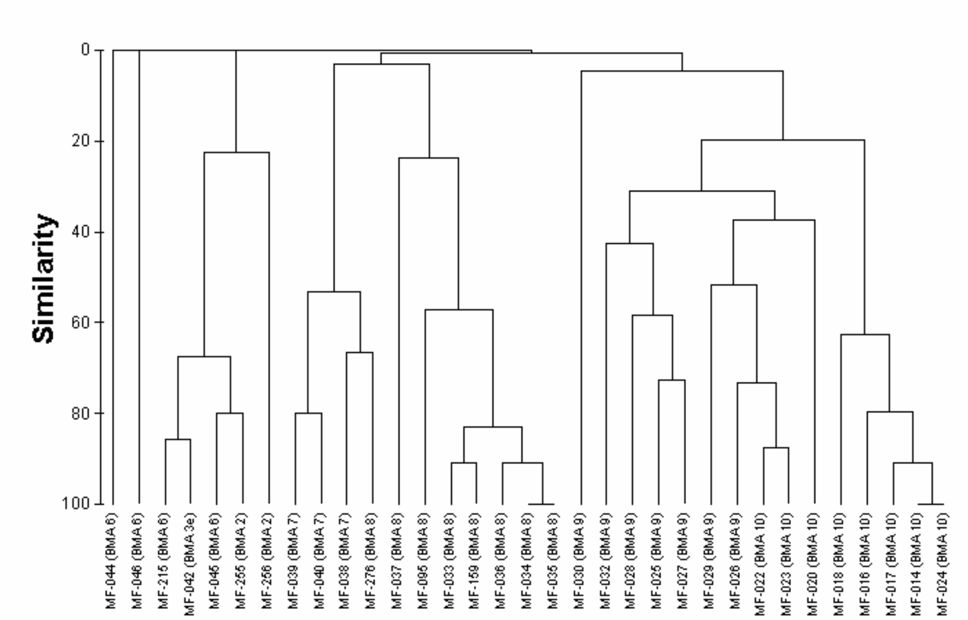


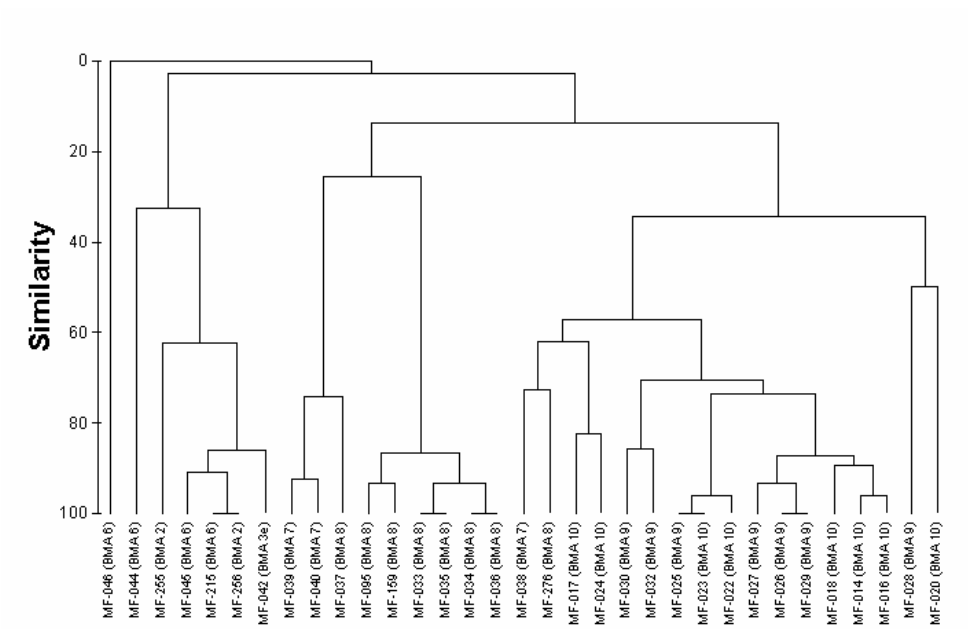
Fig. 28. Number of overlaps among model-derived tidal excursion areas of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The numbers include overlaps with the originating farm.



Fig, 29. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps of each farm's model-derived tidal excursion area with farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the farms from which the tidal excursion areas originated.



Fig, 30. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps of farm model-derived tidal excursion areas with each farm site in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the receiving farms.



Fig, 31. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps among model-derived tidal excursion areas of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10.

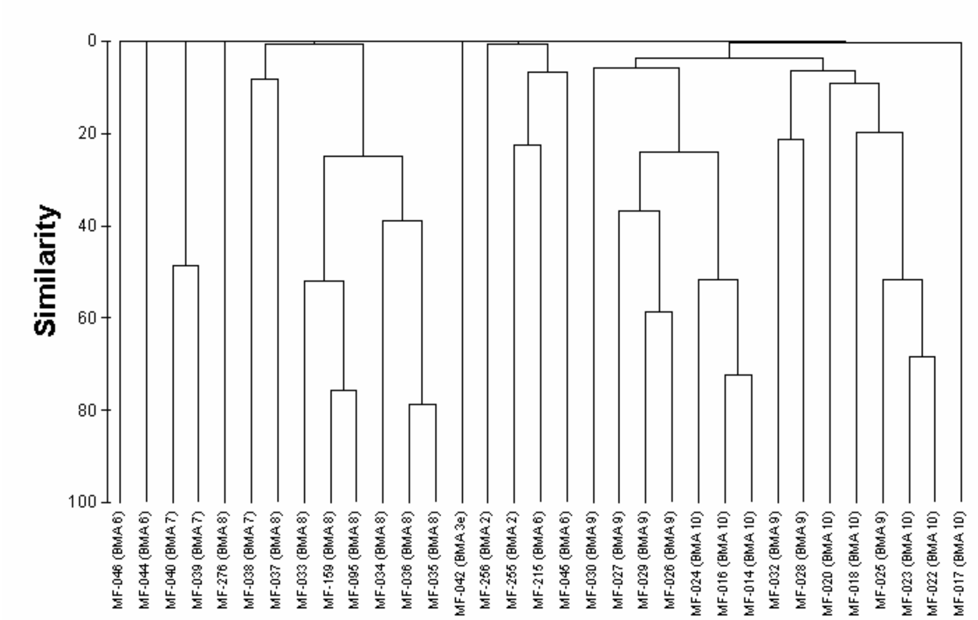


Fig. 32. Cluster analysis using Bray-Curtis similarity coefficients calculated on the number of model-derived particle tracks from each finfish farm which overlapped farm sites in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the farms from which the particle tracks originated.

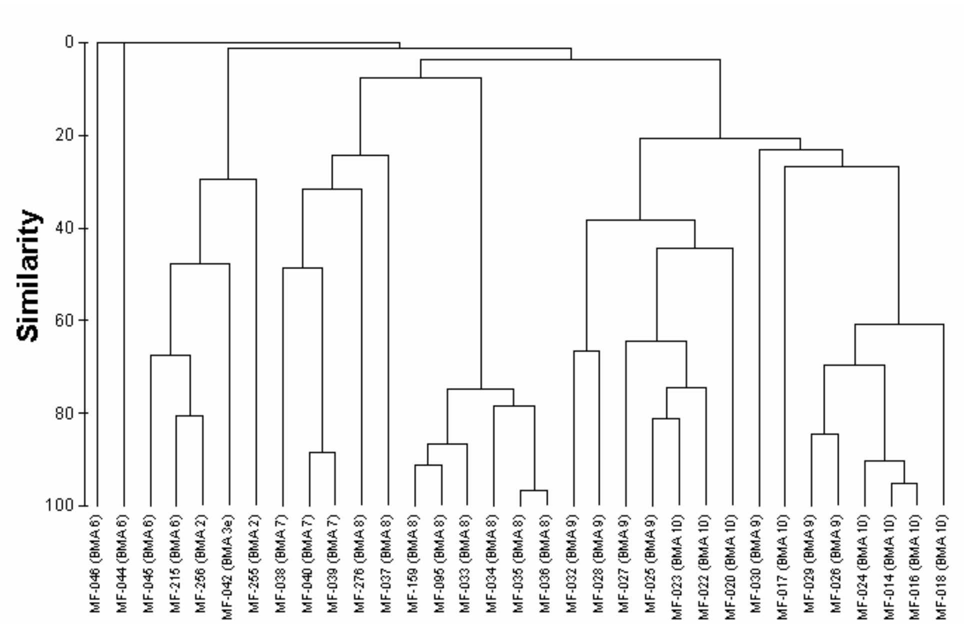


Fig. 33. Cluster analysis using Bray-Curtis similarity coefficients calculated on the number of model-derived particle tracks from each finfish farm which overlapped tidal excursion areas of farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10. The x-axis lists the farms from which the particle tracks originated.

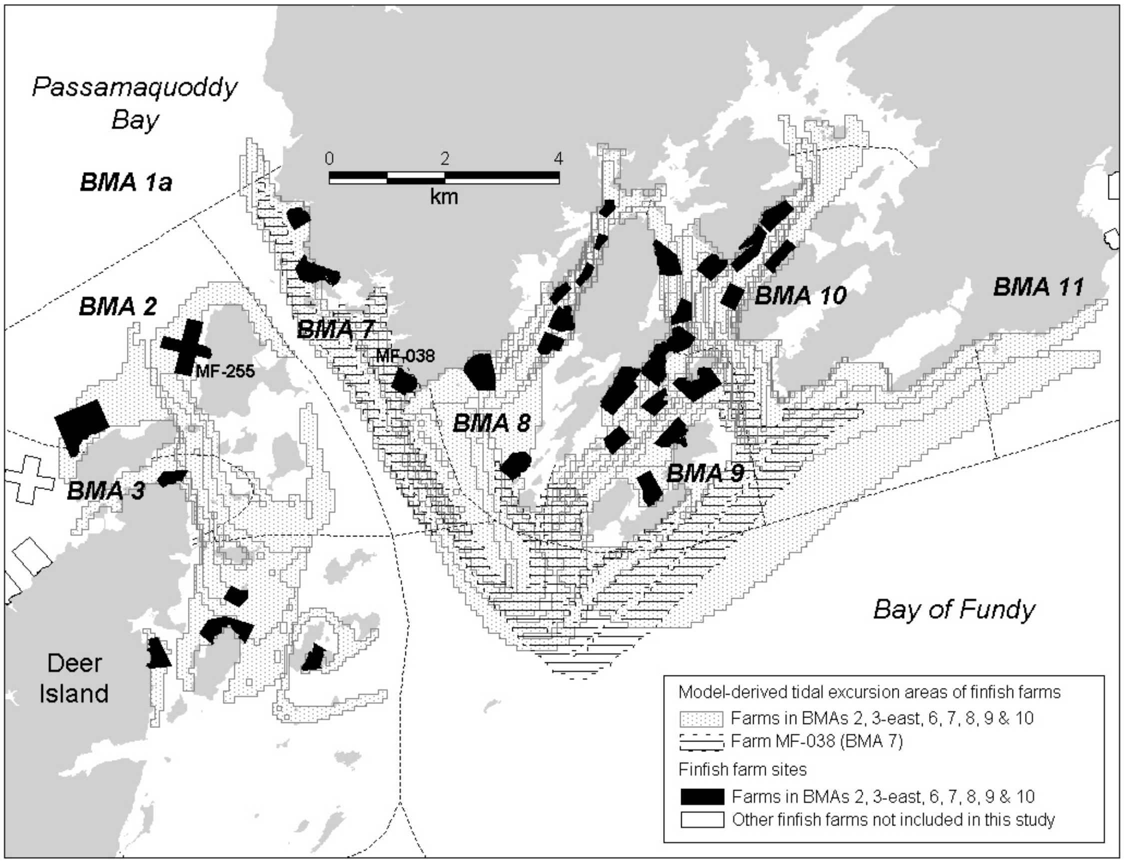


Fig. 34. Map of the northern Deer Island, Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay areas of SWNB, showing model-derived tidal excursion areas of finfish farms in BMAs 2, 3-east, 6, 7, 8, 9, and 10, excluding that of farm MF-255 (BMA 2). The tidal excursion area of farm MF-038 (BMA 7), which currently has cod (and no salmonids), is shown in different shading. Compare with Fig. 13.

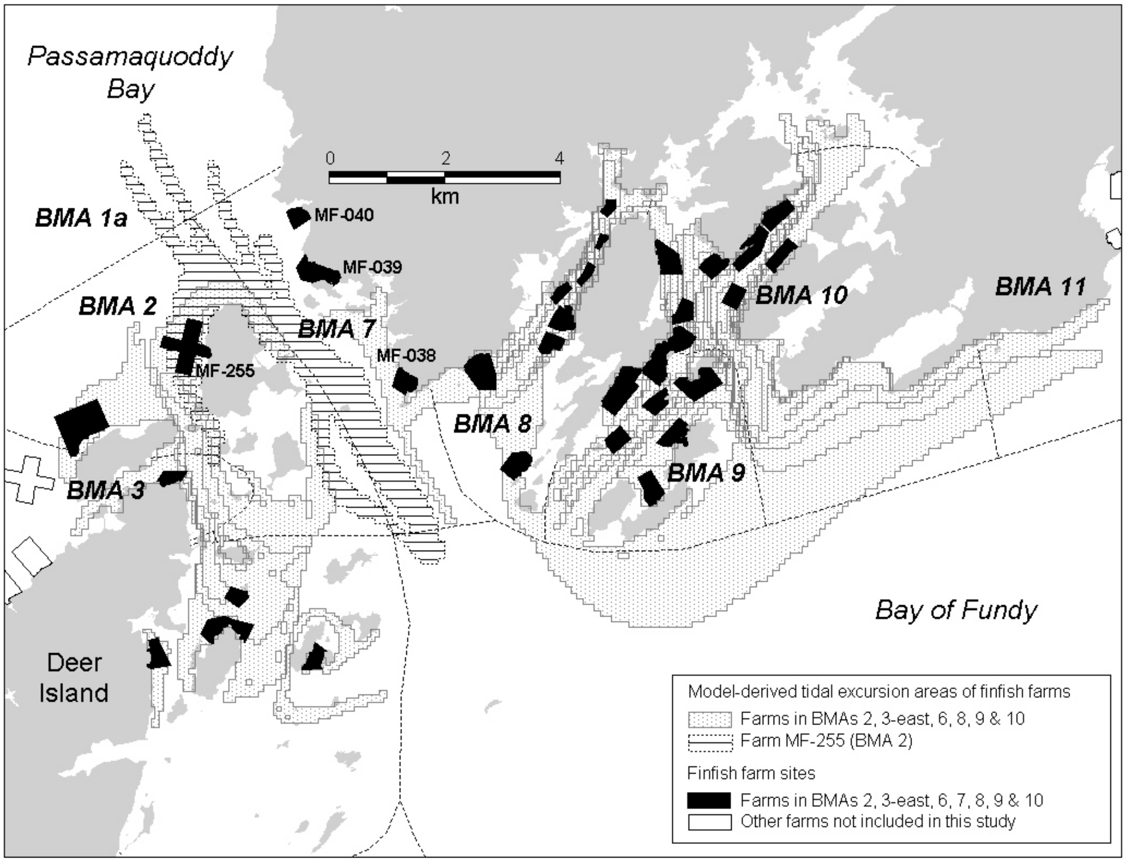


Fig. 35. Map of the northern Deer Island, Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay areas of SWNB, showing model-derived tidal excursion areas of finfish farms in BMAs 2, 3 -east, 6, 8, 9, and 10, but excluding the tidal excursion areas of farms in BMA 7 (MF-038, MF-039, and MF-040). The tidal excursion area of farm MF-255 (BMA 2) is shown in different shading. Compare with Figs. 13 and 34.