Water Circulation and Management of Infectious Salmon Anemia in the Salmon Aquaculture Industry of Eastern Grand Manan Island, Bay of Fundy

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ABSTRACT

Chang, B.D., Page, F.H., Losier, R.J., Greenberg, D.A., Chaffey, J.D., and McCurdy, E.P. 2006. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of eastern Grand Manan Island, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2621: iii + 34 p.

Infectious salmon anemia (ISA) was first detected in salmon farms in southwestern New Brunswick in 1996. In an effort to help estimate the potential for water-borne exchange of the ISA virus among farms in this area, we used a three-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. In this report, we examined the water exchange among farms in the eastern Grand Manan Island area. We also examined the potential for the water-borne spread of disease between farms in the eastern Grand Manan Island area and farms in the adjacent southern Grand Manan Island area.

RÉSUMÉ

Chang, B.D., Page, F.H., Losier, R.J., Greenberg, D.A., Chaffey, J.D., and McCurdy, E.P. 2006. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of eastern Grand Manan Island, Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2621: iii + 34 p.

Au Canada, l'anémie infectieuse du saumon (AIS) a été décelée pour la première fois dans des salmonicultures du sud-ouest du Nouveau-Brunswick en 1996. Nous avons utilisé un modèle tridimensionnel de circulation des eaux de marée et un modèle de transport des particules pour estimer le potentiel de transmission hydrique du virus de l'AIS entre les fermes de la région. Puis nous avons comparé des scénarios d'échange d'eau reposant sur la circulation des particules durant une marée, telle que prédite par le modèle, et des scénarios estimés à l'aide d'une méthode simple qui supposent que l'échange d'eau autour de chaque ferme se produit dans un rayon de 5 km. Nous examinons ici l'échange d'eau entre les fermes établies dans le secteur est de l'île Grand Manan. Nous évaluons aussi le potentiel de propagation hydrique des maladies des poissons entre les fermes établies dans ce secteur et celles établies dans le secteur sud de l'île, situé à proximité.

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 also been used in the Scottish salmon farming industry (JGIWG 2000; Stagg 2003). 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. Larger Surveillance Zones (or Management Areas) consist 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 SWNB were provided by NBDAFA and were entered into a Geographic Information System (MapInfo Professional® 7.0). The eastern Grand Manan Island area includes five farms in BMA 17 and four farms in BMA 18. The adjacent southern Grand Manan Island area includes 12 licensed farms in BMAs 19-21. See Page et al. (2005) for detailed results using the same methodology as in this report for farms in BMAs 19-21.

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. The maximum possible area of a 5-km radius buffer zone (i.e. if there were no land areas within the zone) is 78.5 km^2.

More precise estimates of the tidal excursions around farms were made through the use of a three-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 simulates wetting and drying of intertidal areas. Although the generic model code has the capability of including boundary forcing using multiple tidal constituents, 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 semi-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). Particles were released simultaneously from 36 points, usually in a 200 × 200 m grid. In one farm, because of its shape, the grid was rectangular, rather than square. The particles were released and maintained at 1 m below the sea surface. Each particle was tracked and its position recorded 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 visited by at least one particle track 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.

We then examined the influence (due to water circulation) each farm had on other farms, as well as the influence other farms had on each farm. To measure the influence 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 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.

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 particles released from each farm) which overlapped farm sites and farm tidal excursion areas. We used PRIMER 5 software (Clarke and Warwick 1994) to compare the similarity of overlaps among farms by performing cluster analyses using group-average linking of Bray-Curtis similarity coefficients calculated on the presence/absence of overlaps and on the non-transformed numbers of particle tracks which overlapped farm sites and tidal excursion areas.

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 eastern Grand Manan Island area, as well as buffer zones of farms in the southern Grand Manan Island area. The figure suggests considerable water exchange among farms in the eastern Grand Manan Island area, and some water exchange between farms in the eastern and southern Grand Manan Island areas. Figures 3 and 4 show the buffer zones for all farms in BMAs 17 and 18, respectively. The areas of the buffer zones of farms in these two BMAs ranged from 46.8-66.9 km^2 (Table 1).

The presence or absence of overlaps of buffer zones with farm sites is shown in Table 2. In 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.

The buffer zones of farms in BMA 17 overlapped an average of 7.2 farm sites (including the originating farm site), including all farm sites in BMA 17 and some farm sites in BMA 18 (see Fig. 5, Table 6). The buffer zones of every farm in BMA 17 overlapped the buffer zones of all nine farms in BMAs 17 and 18, but with no buffer zones from other BMAs (Fig. 6, Tables 3 and 7).

The buffer zones of farms in BMA 18 overlapped an average of 7.0 farm sites (including the originating farm site), including all four farm sites in BMA 18 (see Fig. 5, Table 6). The buffer zone of farm MF-172 did not overlap any farm sites in BMA 17, but did overlap one farm site in BMA 19 (MF-316); conversely, the buffer zone of farm MF-316 overlapped farm site MF-172. The buffer zones of the other three farms in BMA 18 overlapped some farm sites in BMA 17, but none in BMA 19. The buffer zones of every farm in BMA 18 overlapped the buffer zones of all farms in BMAs 17, 18, and 19, as well as at least one buffer zone from BMA 21; the buffer zone of farm MF-172 also overlapped with the buffer zones of two farms in BMA 20 (Fig. 6, Tables 3 and 7).

The cluster analysis, based on the presence or absence of overlaps between buffer zones and farm sites, indicated considerable similarity among farms (Fig. 7). No farms were completely separate from all other farms (at 0% similarity). At a similarity level of 1%, there were two clusters: all farms in BMAs 17, 18, and 19 in one cluster and all farms in BMAs 20 and 21 in the other cluster. At a similarity level of 5%, the first cluster was separated into two smaller clusters: all farms in BMAs 17 and 18 in one cluster and all farms in BMA 19 in the other. 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. 8); there were no completely separate clusters at 0-29% similarity.

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

Figure 9 shows the model-derived tidal excursion areas (all hourly releases from each farm combined) of all farms in the eastern Grand Manan Island area, as well as the model-derived tidal excursion areas of farms in the southern Grand Manan Island area. Figures 10 and 11 show the tidal excursion areas of all farms in BMAs 17 and 18, respectively. Figures 12 and 13 show the tidal excursion areas for each individual farm in BMAs 17 and 18, including the relative density of particle tracks present in 100 × 100 m grid cells. The tidal excursion area of farms in BMAs 17 and 18 were much smaller than the 5-km buffer zones, ranging from 1.4-16.9 km^2 (Table 1), and were elongated in shape. For maps of tidal excursion areas of farms in BMAs 19-21, see Page et al. (2005).

The tidal excursion areas of all farms in BMA 17 (Fig. 12) were small (1.4-2.6 km^2) and oval-shaped. In all cases the maximum displacements from the starting grids were about 2 km or less and these tidal excursion areas were mostly confined within BMA 17. The tidal excursion areas of farms MF-282 and MF-298 in BMA 18 (Fig. 13) were slightly larger than those of farms in BMA 17 (4.7-5.9 km^2) and were mostly confined within BMA 18, while those of farms MF-300 and MF-172 were much larger (11.7-16.9 km^2) and extended several kilometers south into BMA 19.

The presence or absence of overlaps of tidal excursion areas with farm sites for the 21 farms in the eastern and southern Grand Manan Island areas is shown in Table 4. There were 33 overlaps of tidal excursion areas with other farm sites (excluding the 21 overlaps of tidal excursion areas with their originating farm sites), of which there were 19 instances (58%) 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.

The tidal excursion areas of farms in BMA 17 overlapped an average of 2.8 farm sites, all within BMA 17 (see Fig. 14, Table 8). The tidal excursion areas of farms in BMA 18 overlapped an average of 3.5 farm sites (see Fig. 14, Table 8); the overlapped farm sites were mostly within BMA 18, but the tidal excursion areas of farms MF-172 and MF-300 also overlapped farm sites MF-316 and MF-381 in BMA 19. The intensity of the overlaps between farms in BMA 18 and farms in BMA 19 were small: less than 34 of the 432 particles (<8%) released from either farm MF-172 or MF-300 overlapped each of the two farm sites in BMA 19, while none of the particles released from farms in BMA 19 overlapped any farm sites in BMA 18.

Farm sites in BMA 17 were overlapped by an average of 2.8 tidal excursion areas, all from farms in BMA 17 (see Fig. 15, Table 8). Farm sites in BMA 18 were overlapped by an average of 2.5 tidal excursion areas, all from farms in BMA 18 (see Fig. 15, Table 8).

The tidal excursion areas of farms in BMA 17 overlapped with an average of 5.0 tidal excursion areas (see Fig. 16, Tables 5 and 9). Of the farms in BMA 17, three tidal excursion areas (of farms

MF-213, MF-350, and MF-368) overlapped only with tidal excursion areas of farms in BMA 17, and two tidal excursion areas (of farms MF-002 and MF-349) also overlapped with the tidal excursion area of farm MF-282 (BMA 18). The tidal excursion areas of farms in BMA 18 overlapped with an average of 6.5 tidal excursion areas (see Fig. 16, Tables 5 and 9). Of the farms in BMA 18, the tidal excursion area of farm MF-298 overlapped only with tidal excursion areas of farms in BMA 18; the tidal excursion area of farm MF-282 overlapped with the tidal excursion areas of farms in BMAs 17 and 18; and the tidal excursion areas of farms MF-172 and MF-300 overlapped with the tidal excursion areas of farms in BMAs 18, 19, and 21.

The cluster analysis, based on the number of farms sites overlapped by each farm's tidal excursion area (Fig. 17), showed that at 0% similarity, the farms in BMA 17 formed a completely separate cluster, as did the pair of farms MF-202 and MF-292 (BMA 20), farm MF-303 (BMA 21) by itself, and farm MF-413 (BMA 20) by itself; and there were two other clusters, one of all farms in BMAs 18 and 19 together, and one of the remaining farms in BMAs 20 and 21. Farms in BMA 18 could only be separated from those in BMA 19 at a similarity level of 25%. The cluster analysis based on the number of farm tidal excursion areas overlapping each farm site (Fig. 18) produced a similar clustering pattern to that in Fig. 17; farms in BMA 18 could be separated from farms in BMA 19 at a similarity level of 19%.

The cluster analysis, based on the presence or absence of overlaps among tidal excursion areas (Fig. 19), showed two separate clusters at 0% similarity: farms MF-202, MF-292 and MF-413 (BMA 20) in one cluster and all other farms in the other cluster. At 6% similarity, the larger cluster could be separated into two smaller clusters: all farms in BMA 17 plus farms MF-282 and MF-298 (BMA 18) in one cluster; and farms MF-172 and MF-300 (BMA 18) together with all farms in BMAs 19 and 21, plus the two other farms (MF-003 and MF-270) in BMA 20, in the other cluster.

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; see Fig. 20), showed a very similar clustering pattern to that of Fig. 17, but with lower similarity values. Farms in BMA 18 could be separated from farms in BMA 19 at a similarity level of 2%.

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, 21), was basically similar to that shown in Fig. 19. At 0% similarity, farm MF-413 (BMA 20) was completely separate, as was the pair of farms MF-202 and MF-292 (BMA 20), with all other farms in one cluster. At 2% similarity, the large cluster could be broken into two smaller clusters: all farms in BMA 17 in one cluster and all farms in BMAs 18, 19, and 21, with the two other farms in BMA 20 in the other cluster. At 15% similarity, the latter cluster could be separated into two smaller groups: farms in BMAs 18 and 19 in one group and farms in BMA 21 and two farms in BMA 20 in the other group.

DISCUSSION

Because the model results generally agree with field data (Page et al. 2004), we expect that the model-derived tidal excursion areas are more accurate predictors of water exchange areas than the circular buffer zones. The simple approach using 5-km radius buffer zones to estimate water exchange areas suggests considerable water exchange between farms in BMAs 17 and 18 in the eastern Grand Manan Island area. The buffer zone estimates also predict a small amount of water exchange between farms in the eastern and southern Grand Manan Island areas, with the overlap of one buffer zone from a farm in BMA 18 with one farm site in BMA 19, and vice versa. This suggests that the current scenario of having all farms in the eastern Grand Manan Island area as even year-class farms and all farms (except one) in the southern Grand Manan area as odd year-class farms provides a high degree of water separation between these areas (as predicted by the buffer zones), but does carry a small amount of risk of water-borne disease transmission between the two areas. Removal or relocation of either farm MF-172 or MF-316 could eliminate any overlaps of buffer zones of farms in one area with farm sites in the other area.

The model-derived tidal excursion areas suggest a somewhat different pattern of water exchange among the BMAs in the eastern and southern Grand Manan Island areas. The tidal excursion areas indicate that there is relatively little water exchange between farms in BMA 17 and farms in BMA 18. There is, however, some water exchange between farms in BMAs 18 and 19, but this is only from the two southernmost farms in BMA 18 (MF-172 and MF-300) to two farms in BMA 19, but not in the reverse direction, and the intensity of this overlap is quite small. As with the buffer zone method, the suggestion is that there is a small risk of water-borne disease spread between the eastern and southern areas, but in this case the risk is only in one direction, from the eastern area to the southern area. In order to achieve complete separation (in terms of water exchange based on one tidal excursion), farms MF-172 and MF-300 would have to be removed or relocated further north. Alternatively, if farm MF-282 was removed or moved further south, then the farms in BMA 18 could be grouped together with the farms in the southern Grand Manan Island area (BMAs 19-21), separate from the farms in BMA 17.

The model-derived tidal excursion areas can also be useful in developing site-specific farm management plans. Farm sites with large tidal excursion areas will have high water current speeds (at least during some phases of the tide). Such sites may require stocking with larger smolts, because small smolts can be more stressed by high water velocities and thus may suffer higher rates of disease and mortality (Brian Glebe, Biological Station, St. Andrews, NB, pers. comm.).

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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Stewart, J.E. 1998. Sharing the waters: an evaluation of site fallowing, year class separation and distances between sites for fish health purposes on Atlantic salmon farms. Can. Tech. Rep. Fish. Aquat. Sci. 2218: vii + 56 p.

Table 1. Water exchange areas of finfish farms in the eastern and southern Grand Manan Island areas. 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)	Model tidal excursion area (km^2)	Farm site	5-km radius buffer zone (km^2)	Model tidal excursion area (km^2)
Eastern Grand Manan Island area			**Southern Grand Manan Island area**		
BMA 17			**BMA 19**		
MF-002	56.1	2.6	MF-316	68.2	49.0
MF-213	51.7	1.5	MF-381	70.3	81.6
MF-349	51.8	2.3	MF-416	71.7	96.2
MF-350	60.9	1.4	Mean ± SD	70.1 ± 1.4	75.6 ± 19.7
MF-368	46.8	1.9			
Mean ± SD	53.5 ± 5.3	1.9 ± 5.2	**BMA 20**		
			MF-003	48.4	2.9
BMA 18			MF-202	32.0	2.2
MF-172	57.4	16.9	MF-270	53.4	9.3
MF-282	60.1	4.7	MF-292	35.6	3.3
MF-298	66.9	5.9	MF-413	59.0	4.0
MF-300	61.7	11.7	Mean ± SD	45.7 ± 10.3	4.3 ± 2.6
Mean ± SD	61.5 ± 4.0	9.8 ± 5.7			
			BMA 21		
			MF-303	46.8	5.3
			MF-403	63.5	21.9
			MF-408	71.6	31.0
			MF-491	63.2	8.6
			Mean ± SD	61.3 ± 9.0	16.7 ± 10.3
All eastern Grand Manan Island area			**All southern Grand Manan Island area**		
Mean ± SD	57.0 ± 6.2	5.4 ± 5.4	Mean ± SD	57.0 ± 13.2	26.3 ± 31.2

Table 4. Overlaps (indicated by shaded squares) of model-derived tidal excursion areas with finfish farm sites in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas.

Overlaps of originating farm tidal excursion areas with receiving farm sites		Originating farm: BMA 17					BMA 18				BMA 19			BMA 20					BMA 21			
Receiving farm		MF-002	MF-213	MF-349	MF-350	MF-368	MF-172	MF-282	MF-298	MF-300	MF-316	MF-381	MF-416	MF-003	MF-202	MF-270	MF-292	MF-413	MF-303	MF-403	MF-408	MF-491
BMA 17	MF-002	■	■	■	■	■																
	MF-213		■																			
	MF-349	■		■		■																
	MF-350	■	■		■																	
	MF-368		■			■																
BMA 18	MF-172						■	■		■												
	MF-282							■	■	■												
	MF-298								■													
	MF-300							■	■	■												
BMA 19	MF-316						■			■	■	■										
	MF-381						■			■	■	■										
	MF-416										■	■	■									
BMA 20	MF-003													■		■						
	MF-202														■		■					
	MF-270													■		■						
	MF-292														■		■					
	MF-413																	■				
BMA 21	MF-303																		■			
	MF-403																			■	■	■
	MF-408															■				■	■	■
	MF-491															■						■

Table 5. Overlaps (indicated by shaded squares) among model-derived tidal excursion areas of finfish farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas.

Overlaps of originating farm tidal excursion areas with receiving farm tidal excursion areas			**Originating farm**																				
			BMA 17					BMA 18				BMA 19			BMA 20					BMA 21			
			MF-002	MF-213	MF-349	MF-350	MF-368	MF-172	MF-282	MF-298	MF-300	MF-316	MF-381	MF-416	MF-003	MF-202	MF-270	MF-292	MF-413	MF-303	MF-403	MF-408	MF-491
Receiving farm	BMA 17	MF-002	■	■	■	■	■		■														
		MF-213	■	■	■	■	■																
		MF-349	■	■	■	■	■		■														
		MF-350	■	■	■	■																	
		MF-368	■	■	■		■																
	BMA 18	MF-172						■	■		■	■	■	■							■	■	
		MF-282	■		■			■	■	■	■												
		MF-298							■	■	■												
		MF-300						■	■	■	■	■	■	■							■	■	
	BMA 19	MF-316						■			■	■	■	■							■	■	
		MF-381						■			■	■	■	■							■	■	
		MF-416						■			■	■	■	■							■	■	
	BMA 20	MF-003													■		■				■	■	
		MF-202														■		■					
		MF-270													■		■				■	■	■
		MF-292														■		■	■				
		MF-413																■	■				
	BMA 21	MF-303																		■	■	■	■
		MF-403						■			■	■	■	■	■		■			■	■	■	■
		MF-408						■			■	■	■	■	■		■			■	■	■	■
		MF-491															■			■	■	■	■

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 eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. 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 17 (n=5)	BMA 18 (n=4)	BMA 19 (n=3)	BMA 20 (n=5)	BMA 21 (n=4)	All
17	5.0 ± 0.0	2.2 ± 1.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	7.2 ± 1.1
18	2.8 ± 2.1	4.0 ± 0.0	0.3 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	7.0 ± 1.6
19	0.0 ± 0.0	0.3 ± 0.6	3.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.6	3.7 ± 1.2
20	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	5.0 ± 0.0	3.4 ± 1.3	8.4 ± 1.3
21	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.5	4.3 ± 0.5	4.0 ± 0.0	8.5 ± 0.6

Table 7. Mean numbers of overlaps among 5-km radius buffer zones, by BMA, for finfish farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. 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 17 (n=5)	BMA 18 (n=4)	BMA 19 (n=3)	BMA 20 (n=5)	BMA 21 (n=4)	All
17	5.0 ± 0.0	4.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	9.0 ± 0.0
18	5.0 ± 0.0	4.0 ± 0.0	3.0 ± 0.0	0.5 ± 1.0	1.8 ± 1.0	14.3 ± 1.9
19	0.0 ± 0.0	4.0 ± 0.0	3.0 ± 0.0	2.7 ± 2.3	3.7 ± 0.6	13.3 ± 2.9
20	0.0 ± 0.0	0.4 ± 0.6	2.2 ± 1.8	5.0 ± 0.0	4.0 ± 0.0	11.6 ± 1.8
21	0.0 ± 0.0	1.8 ± 1.7	2.8 ± 0.5	5.0 ± 0.0	4.0 ± 0.0	13.5 ± 2.1

Table 8. Mean numbers of overlaps between model-derived tidal excursion areas and finfish farm sites, by BMA, for farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. 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 17 (n=5)	BMA 18 (n=4)	BMA 19 (n=3)	BMA 20 (n=5)	BMA 21 (n=4)	All
17	2.8 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.8 ± 0.8
18	0.0 ± 0.0	2.5 ± 1.0	1.0 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	3.5 ± 1.0
19	0.0 ± 0.0	0.0 ± 0.0	2.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0	2.3 ± 1.2
20	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.8 ± 0.5	0.4 ± 0.9	2.2 ± 1.1
21	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.0 ± 0.8	2.0 ± 0.8

BMA of receiving farms	BMA of originating farms					
	BMA 17 (n=5)	BMA 18 (n=4)	BMA 19 (n=3)	BMA 20 (n=5)	BMA 21 (n=4)	All
17	2.8 ± 1.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.8 ± 1.5
18	0.0 ± 0.0	2.5 ± 1.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.5 ± 1.0
19	0.0 ± 0.0	1.3 ± 1.2	2.3 ± 0.6	0.0 ± 0.0	0.0 ± 0.0	3.7 ± 0.6
20	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.8 ± 0.5	0.0 ± 0.0	1.8 ± 0.5
21	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.6	2.0 ± 1.2	2.5 ± 1.3

Table 9. Mean numbers of overlaps among model-derived tidal excursion areas, by BMA, for finfish farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. 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 17 (n=5)	BMA 18 (n=4)	BMA 19 (n=3)	BMA 20 (n=5)	BMA 21 (n=4)	All
17	4.6 ± 0.6	0.4 ± 0.6	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	5.0 ± 1.0
18	0.5 ± 1.0	3.5 ± 0.6	1.5 ± 1.7	0.0 ± 0.0	1.0 ± 1.2	6.5 ± 2.7
19	0.0 ± 0.0	2.0 ± 0.0	3.0 ± 0.0	0.0 ± 0.0	2.0 ± 0.0	7.0 ± 0.0
20	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.2 ± 0.5	1.0 ± 1.4	3.2 ± 1.3
21	0.0 ± 0.0	1.0 ± 1.2	1.5 ± 1.7	1.3 ± 1.0	4.0 ± 0.0	7.8 ± 3.8

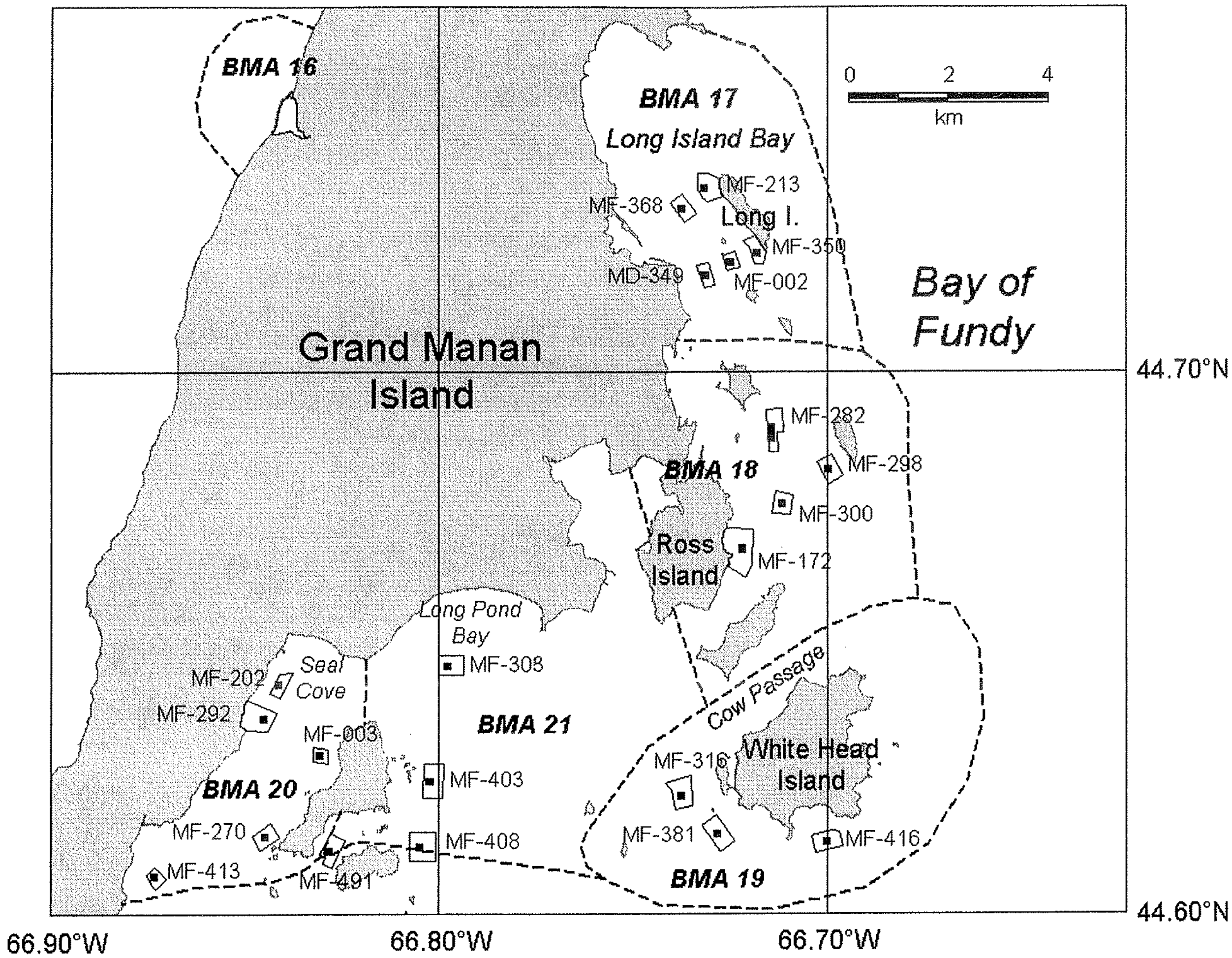


Fig. 1. Map of the Grand Manan Island area, showing BMAs, finfish farm sites (white polygons) and starting grid locations (small black squares or rectangles inside farm sites) for model particle releases from farms in the eastern Grand Manan Island area (BMAs 17 and 18) and the southern Grand Manan Island area (BMAs 19-21).

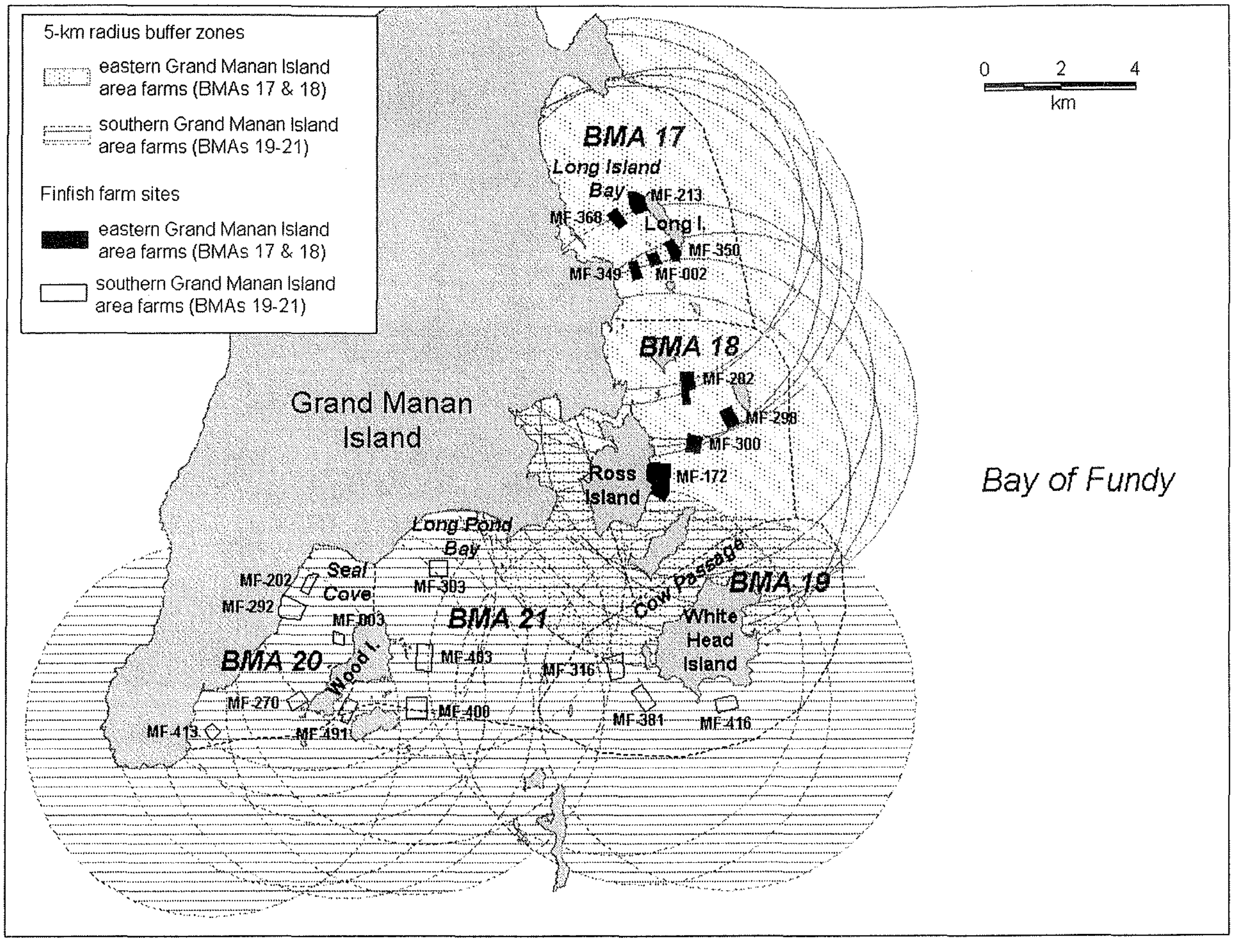


Fig. 2. Map showing 5-km radius buffer zones of all finfish farms in the eastern Grand Manan Island area (BMAs 17 and 18). Also shown are buffer zones of finfish farms in the southern Grand Manan Island area (BMAs 19-21).

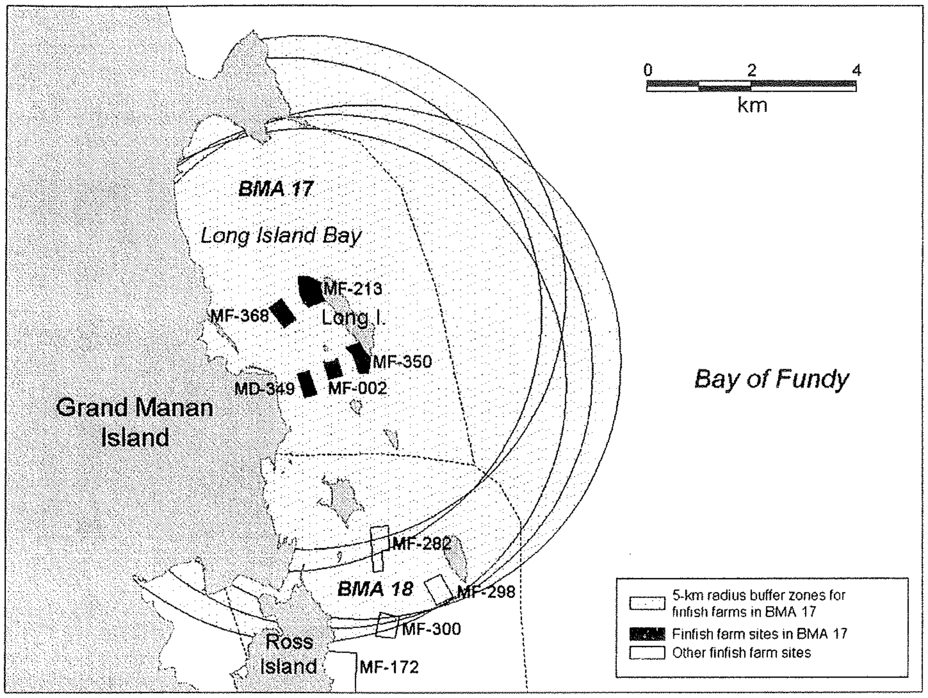


Fig. 3. Map showing 5-km radius buffer zones of finfish farms in BMA 17, eastern Grand Manan Island area.

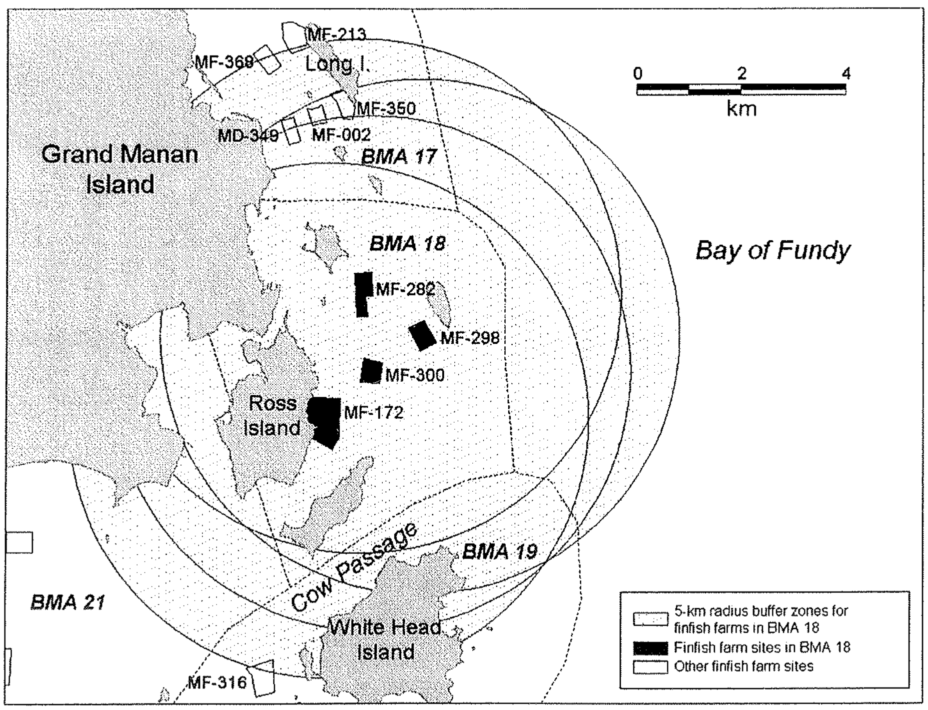


Fig. 4. Map showing 5-km radius buffer zones of finfish farms in BMA 18, eastern Grand Manan Island area.

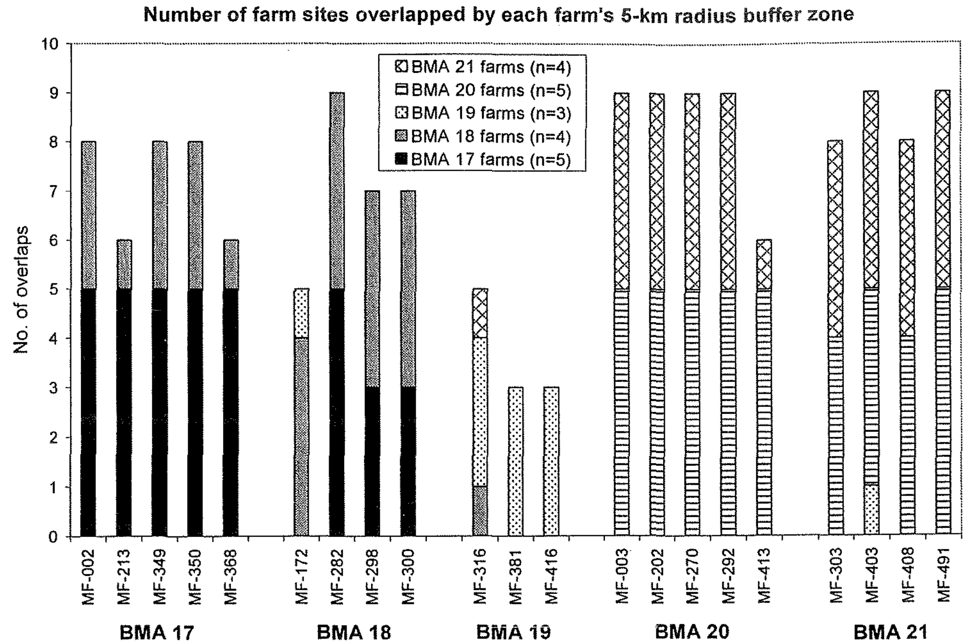


Fig. 5. Number of finfish farm sites overlapped by each farm's 5-km radius buffer zone in the eastern Grand Manan Island area (BMAs 17 and 18). Also shown are overlaps with farm sites in the southern Grand Manan Island area (BMAs 19-21). The numbers include overlaps with the originating farm.

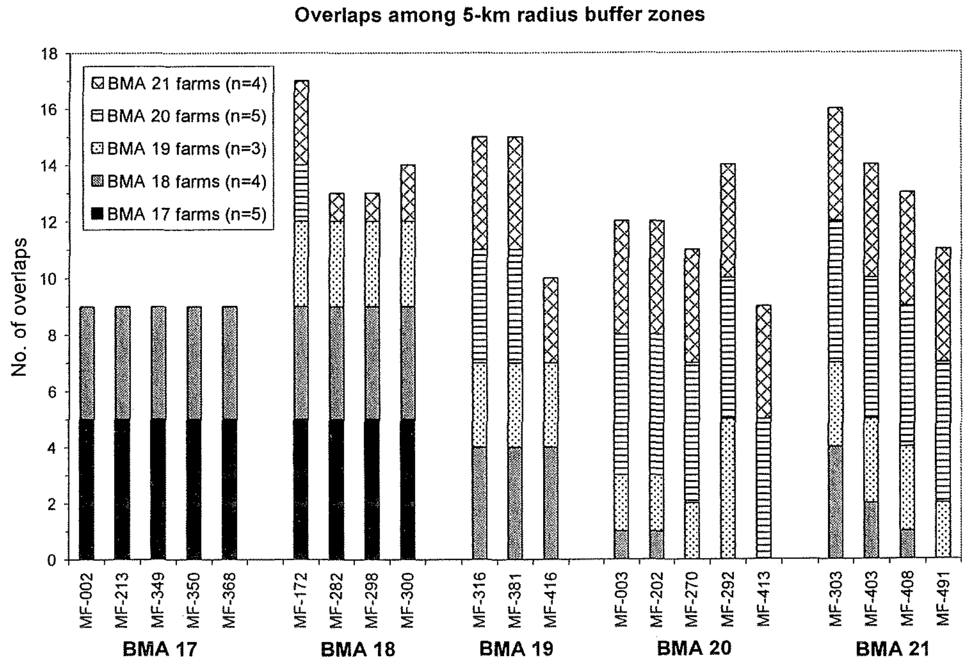
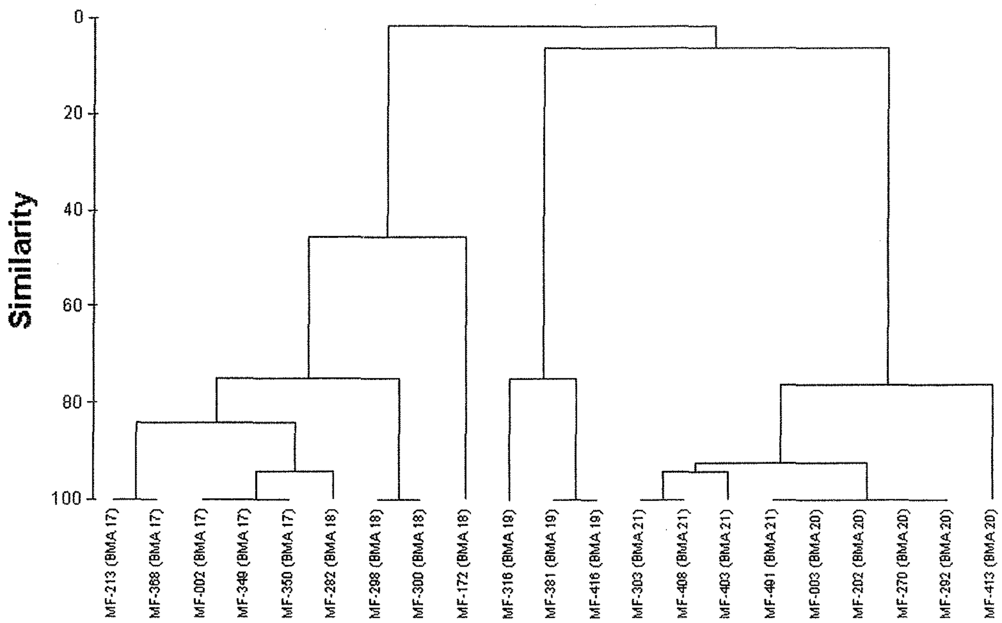
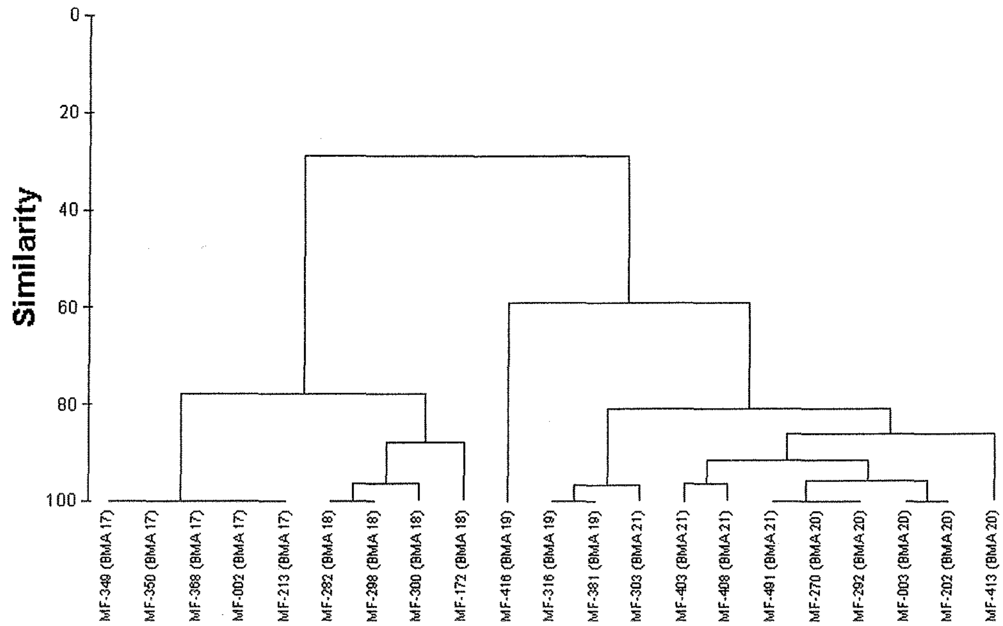


Fig. 6. Number of overlaps among 5-km radius buffer zones of finfish farms in the eastern Grand Manan Island area (BMAs 17 and 18). Also shown are overlaps with buffer zones in the southern Grand Manan Island area (BMAs 19-21). The numbers include overlaps with the originating farm.



Fig, 7. 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 farm sites in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas.



Fig, 8. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps among 5-km radius buffer zones of farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas.

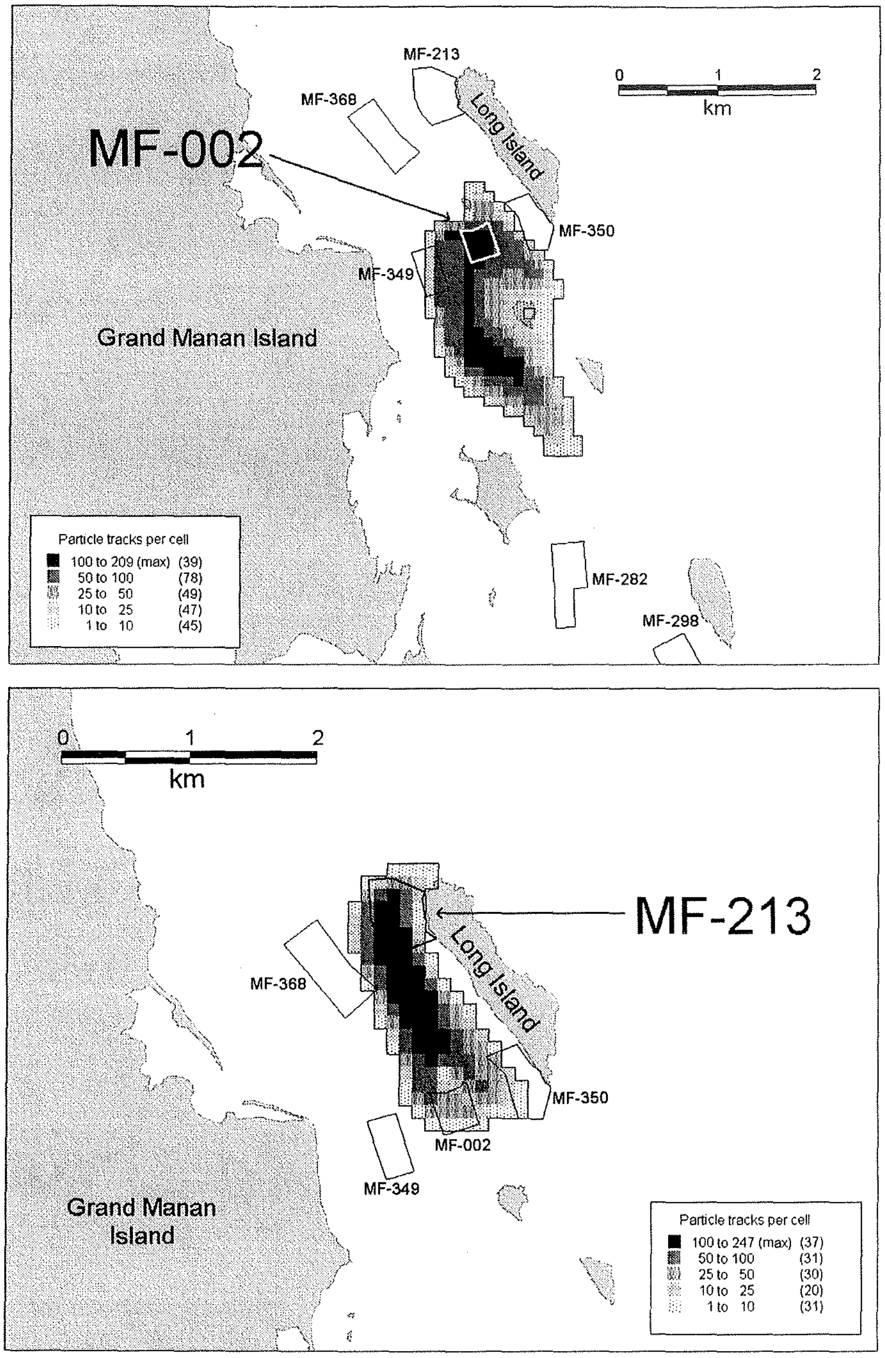


Fig. 12. Model-derived tidal excursion areas of each finfish farm in BMA 17, eastern Grand Manan Island area. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm at hourly intervals over a 12-h 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.

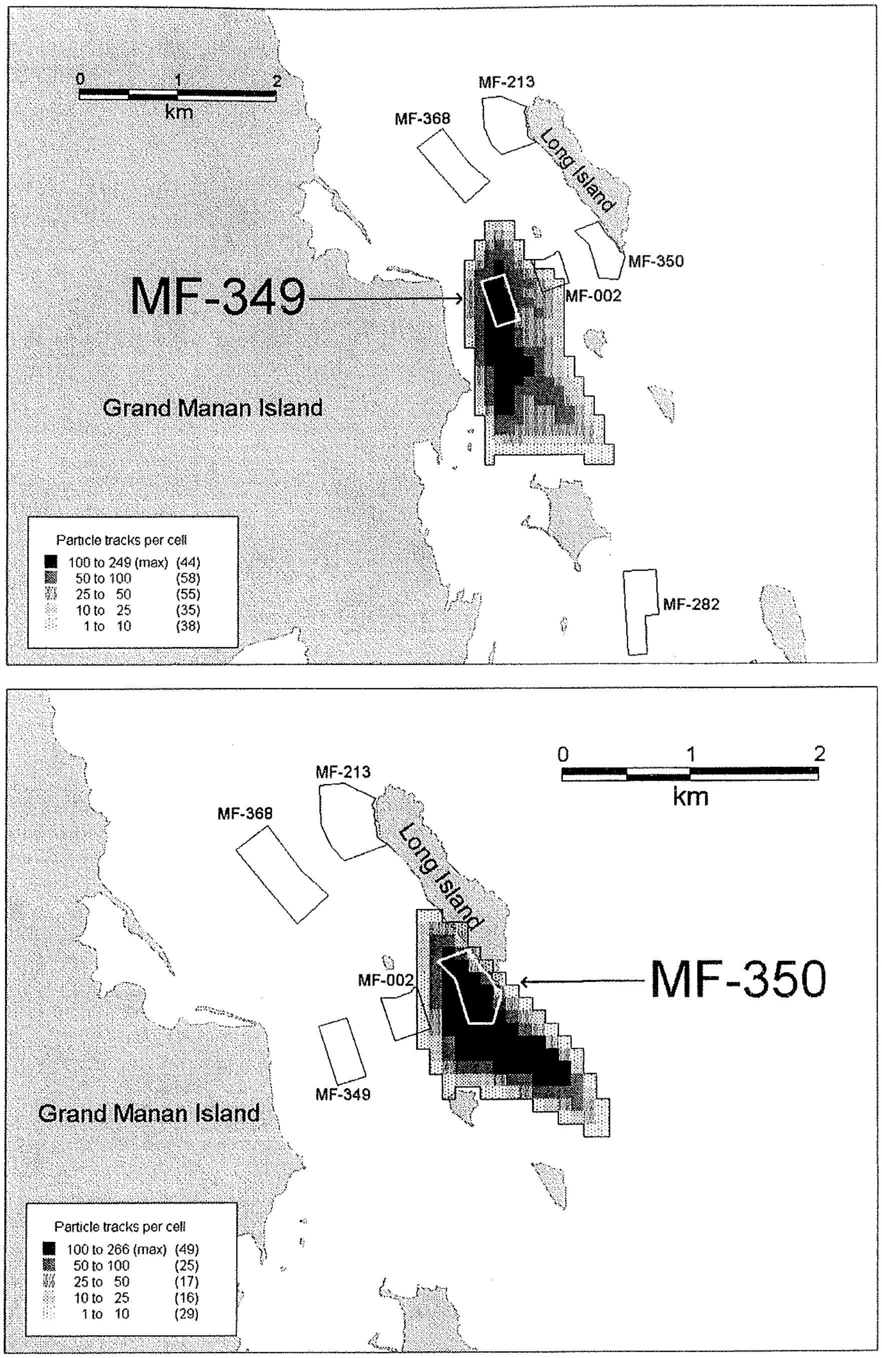


Fig. 12 continued.

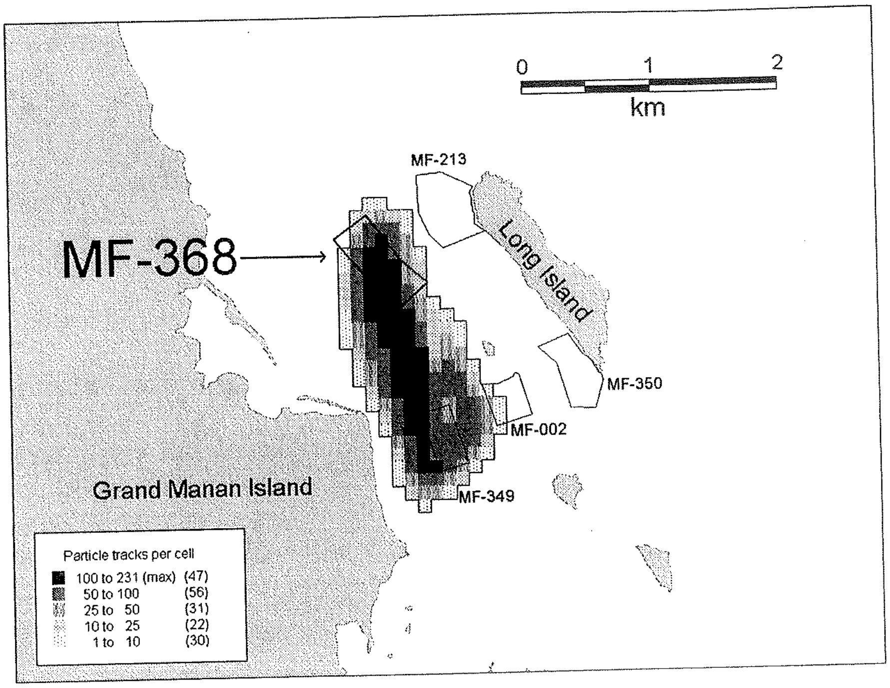


Fig. 12 concluded.

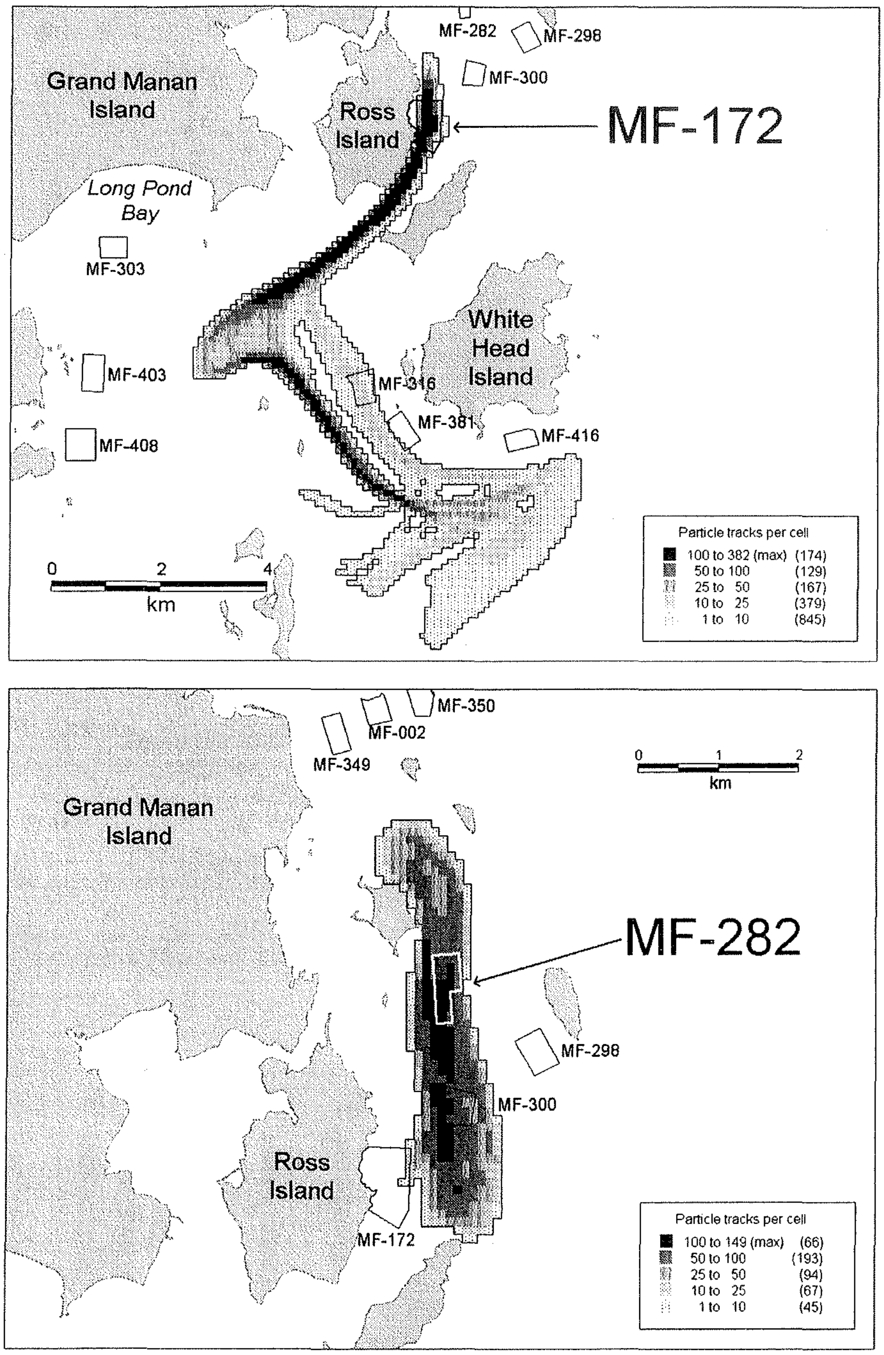


Fig. 13. Model-derived tidal excursion areas of each finfish farm in BMA 18, eastern Grand Manan Island area. The shading represents the number of model-derived particle tracks intersecting each 100 × 100 m square cell. Thirty-six particles were released from each farm (slightly fewer in some cases) 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.

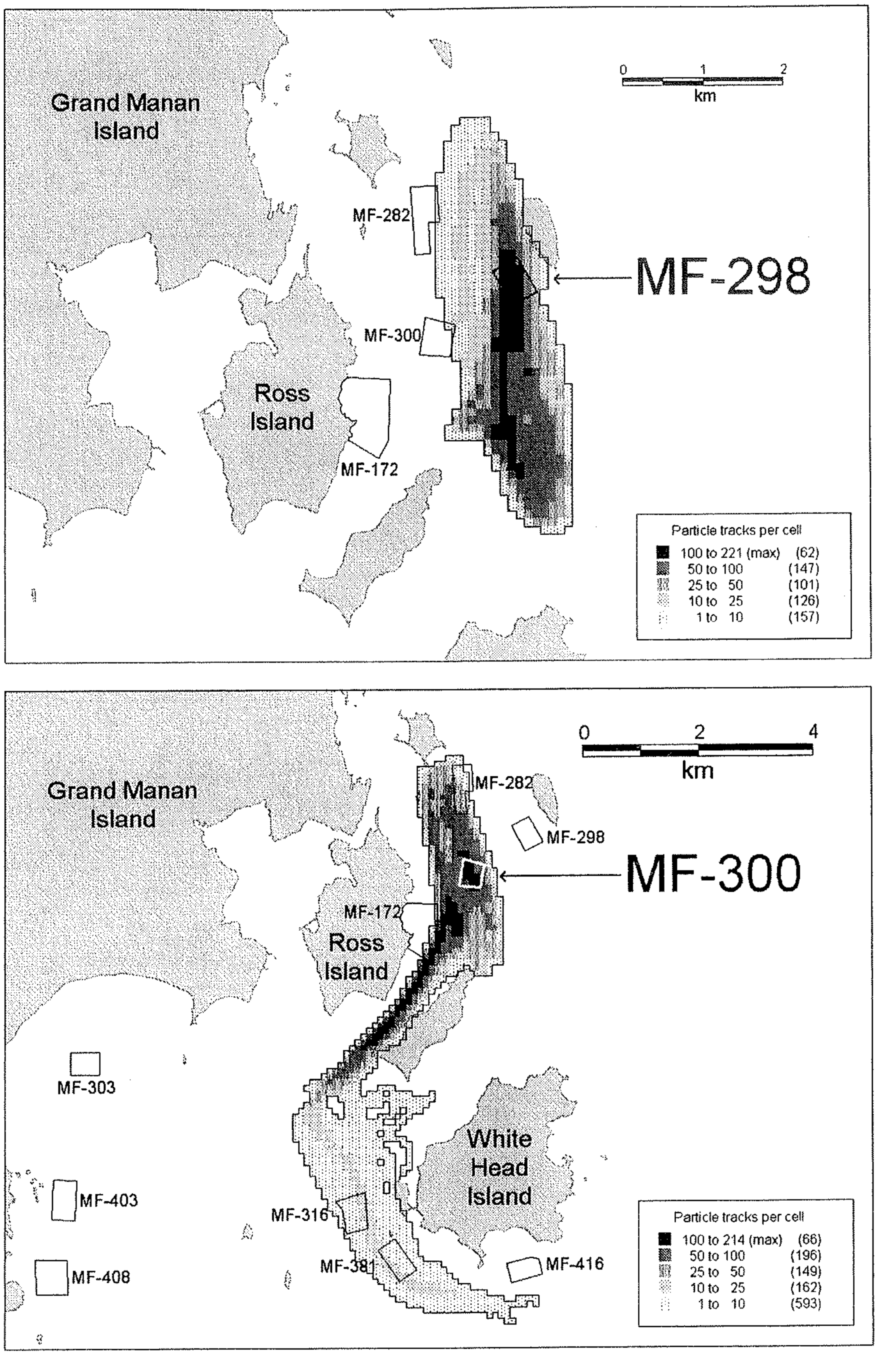


Fig. 13 concluded

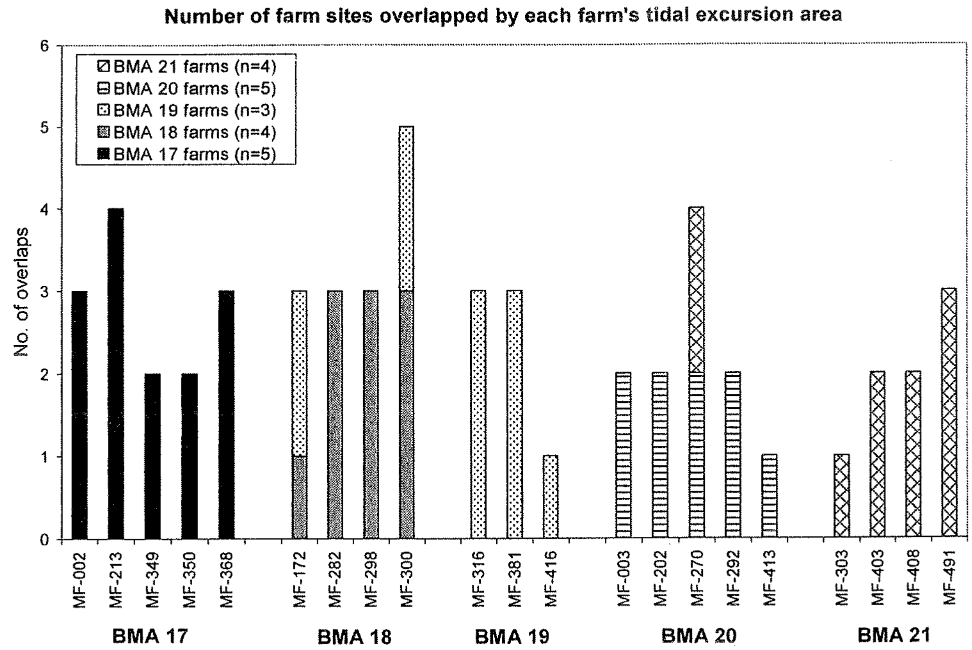


Fig. 14. Number of finfish farm sites overlapped by each farm's model-derived tidal excursion area in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. The x-axis lists the farms from which the tidal excursion areas originated. The numbers include overlaps with the originating farm.

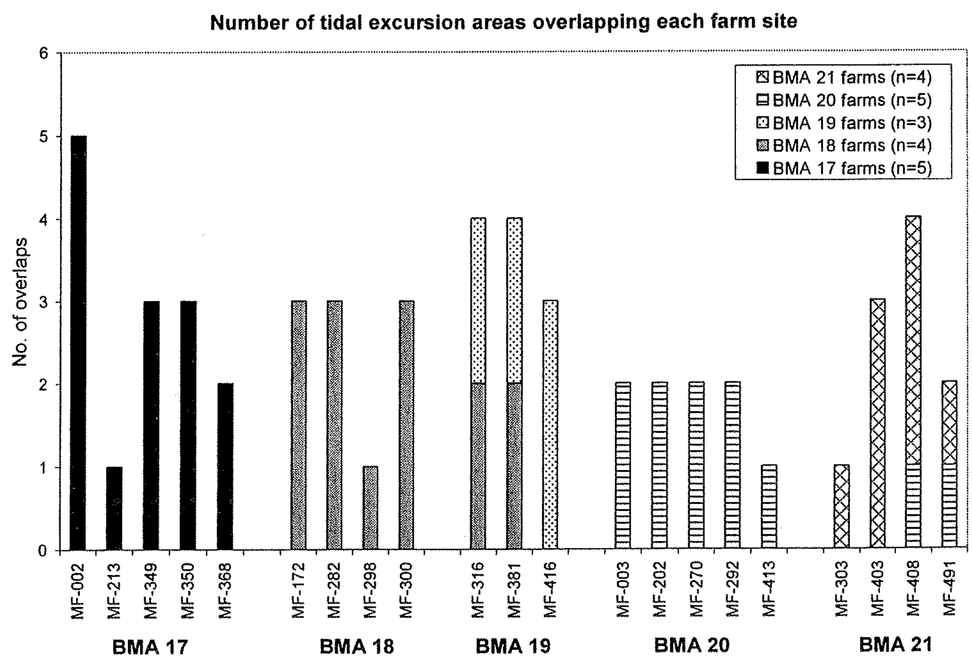


Fig. 15. Number of model-derived tidal excursion areas overlapping each finfish farm site in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. The x-axis lists the receiving farms. The numbers include overlaps with the originating farm.

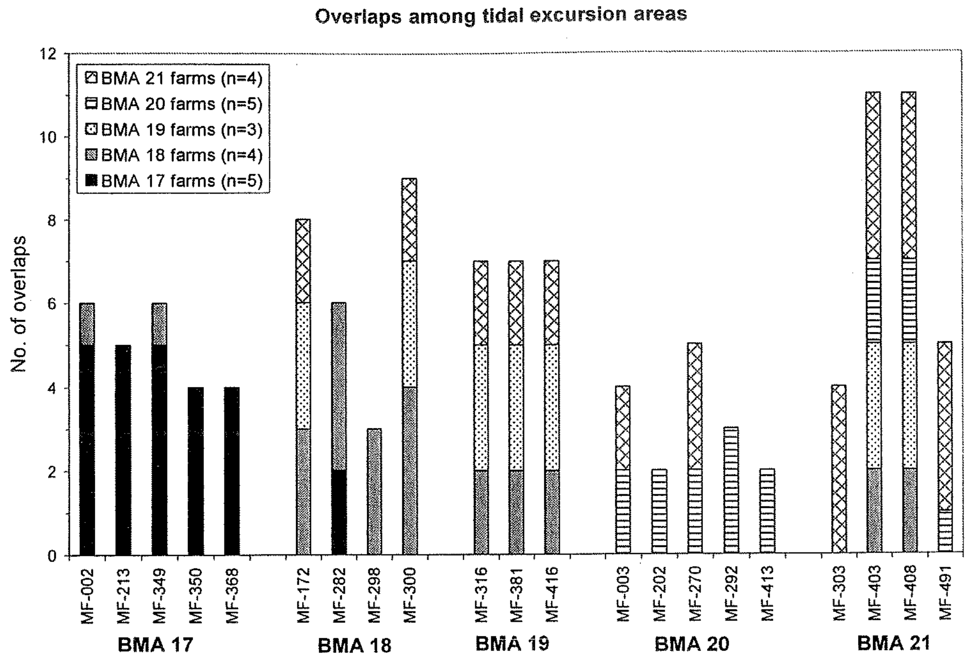
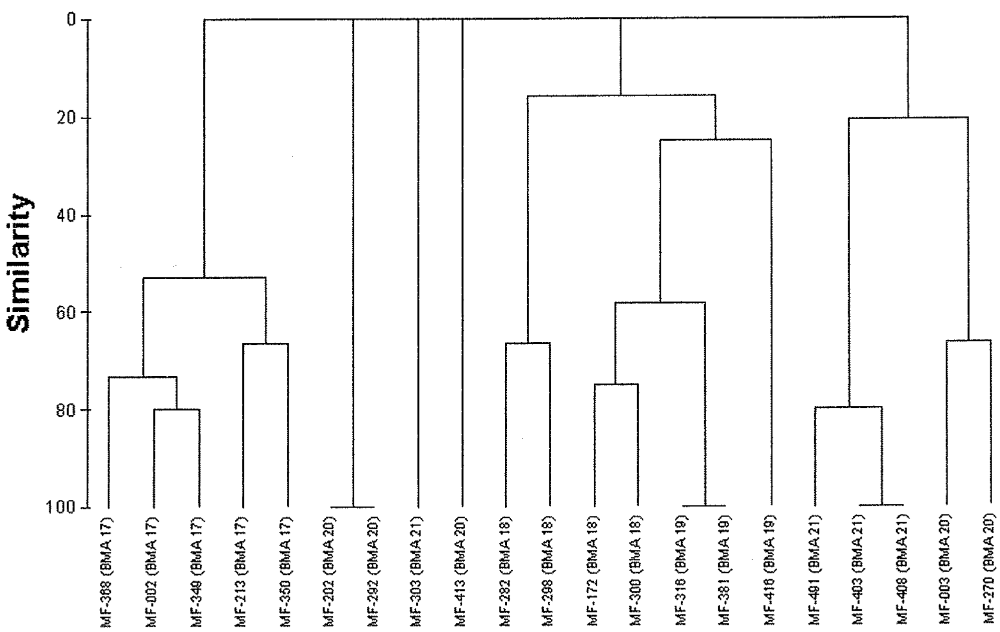
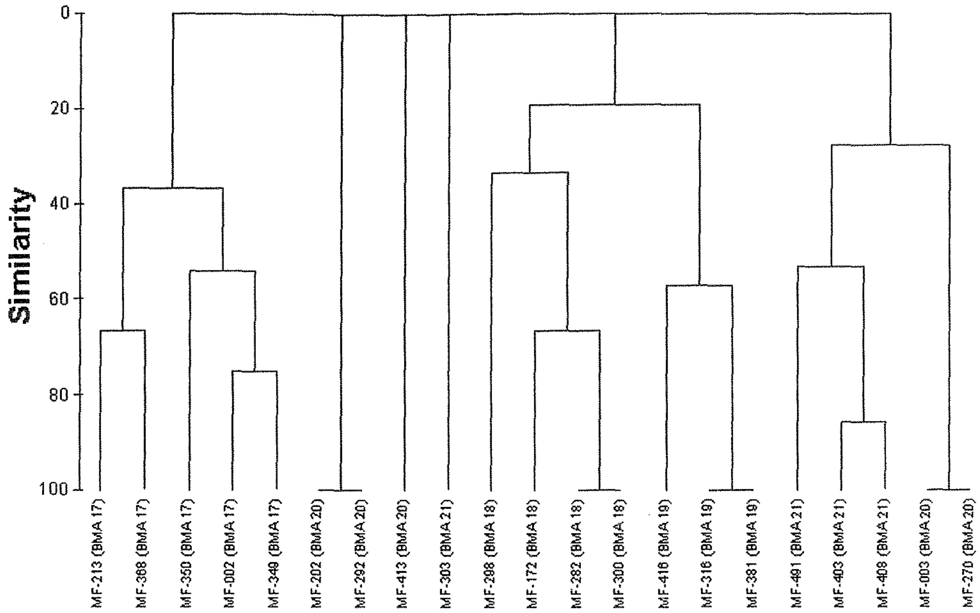


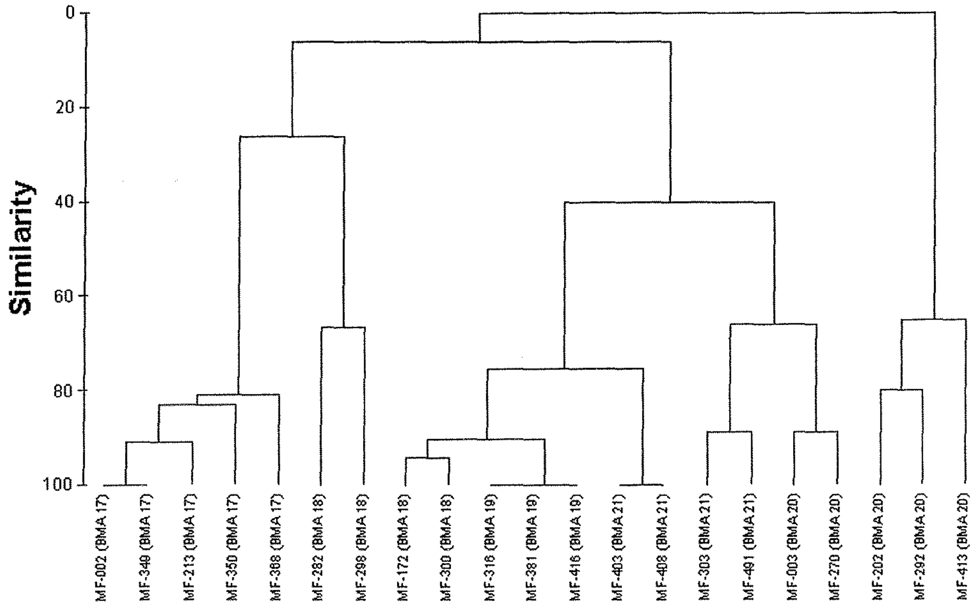
Fig. 16. Number of overlaps among model-derived tidal excursion areas of finfish farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. The numbers include overlaps with the originating farm.



Fig, 17. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps of model-derived tidal excursion areas with farm sites for farms in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. The x-axis lists the farms from which the tidal excursion areas originated.



Fig, 18. Cluster analysis using Bray-Curtis similarity coefficients calculated on the presence or absence of overlaps of model-derived tidal excursion areas with receiving farm sites in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas. The x-axis lists the receiving farms.



Fig, 19. 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 the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas.

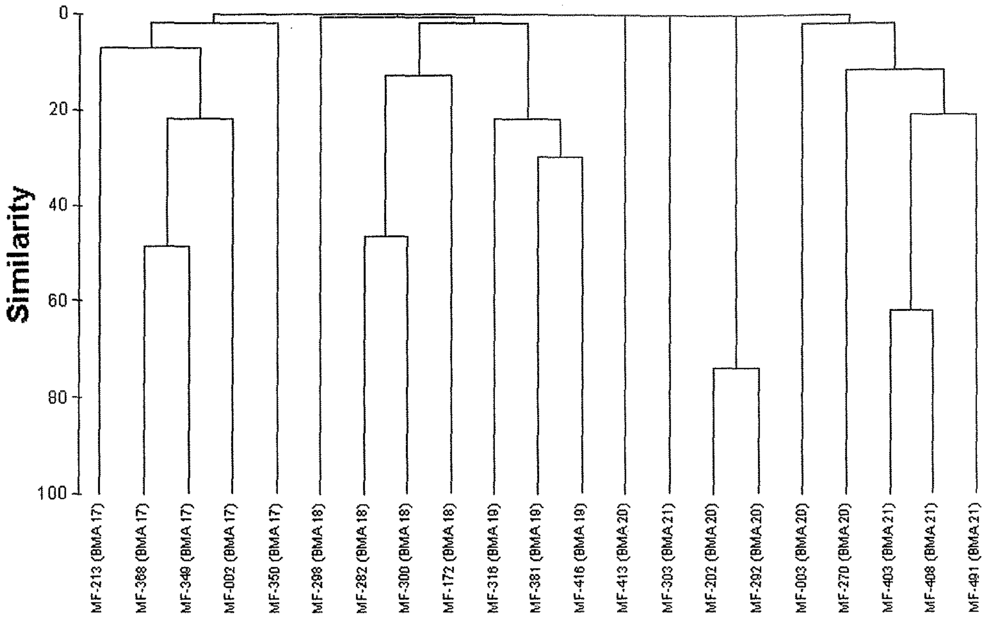


Fig. 20. Cluster analysis using Bray-Curtis similarity coefficients calculated on the number of model-derived particle tracks from each finfish farm in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas which overlapped receiving farm sites. The x-axis lists the farms from which the particle tracks originated.

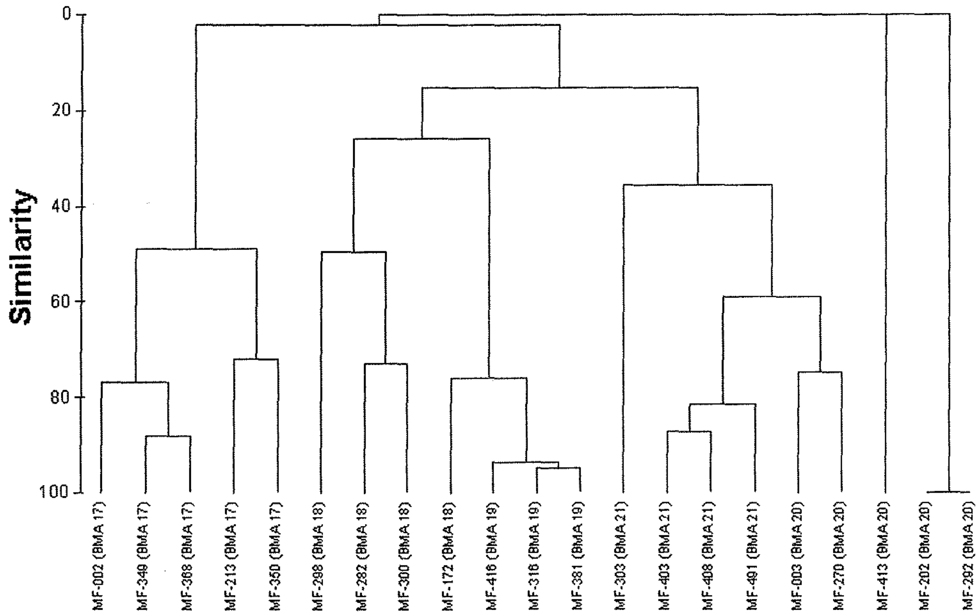


Fig. 21. Cluster analysis using Bray-Curtis similarity coefficients calculated on the number of model-derived particle tracks from each finfish farm in the eastern (BMAs 17 and 18) and southern (BMAs 19-21) Grand Manan Island areas which overlapped tidal excursion areas of receiving farms. The x-axis lists the farms from which the particle tracks originated.