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Fleet Dynamics of the Commercial Lake Trout Fishery in Michigan Waters of Lake Superior during 1929–1961

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ABSTRACT. *Understanding fishing fleet dynamics is important when using fishery dependent data to infer the status of fish stocks. We analyzed data from mandatory catch reports from the commercial lake trout* (Salvelinus namaycush) *fishery in Michigan waters of Lake Superior during 1929–1961, a period when lake trout populations collapsed through the combined effects of overfishing and sea lamprey* (Petromyzon marinus) *predation. The number of full-time fishermen increased during 1933–1943 and then decreased during 1943–1957. Addition of new fishermen was related to past yield, market prices, World War II draft exemptions, and lost fishing opportunities in Lake Huron and Lake Michigan. Loss of existing fishermen was related to declining lake trout density. Large mesh (≥ 114-mm stretch-measure) gill net effort increased during 1929–1951 because fishermen fished more net inshore as lake trout density declined, even though catch per effort (CPE) was often higher in deeper waters. The most common gill net mesh size increased from 114-mm to 120-mm stretch-measure during 1929–1957, as lake trout growth increased. More effort was fished inshore than offshore and the amount of inshore effort was less variable over time than offshore effort. Relatively stable yield was maintained by increasing gill net effort and by moving some effort to better grounds. Because fishing-up caused yield and CPE to remain high despite declining lake trout abundance, caution must be used when basing goals for lake trout restoration on historical fishery indices.*

INDEX WORDS: *Great Lakes,* Salvelinus namaycush*, effort dynamics.*

INTRODUCTION

In most fisheries, fish behavior and fish population dynamics are better understood than fishermen behavior or fishing fleet dynamics (Hilborn 1985, Hilborn and Walters 1992). The top predators of many aquatic systems are fishermen, so fishermen's behavior and fishing fleet dynamics must be understood to better manage fisheries (Hilborn and Walters 1992).

Fleet dynamics include discarding and by-catch, harvest efficiency, fleet size, and effort allocation (Hilborn 1985, Hilborn and Walters 1992). Discarding and by-catch, particularly of highly regulated species, can nullify the effectiveness of catch limits and thereby lead to overexploitation. Harvest efficiency changes through time as harvest methods improve, and can mask changes in stock size when fisheries are monitored through reporting of catch and effort. Fleet size changes through the loss of existing vessels and entry of new vessels; some of which are motivated by changing value of landings, and all of which must be dealt with when regulating fisheries. Effort allocation by individual fishermen includes when to fish, where to fish, and what gear

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to use. These factors collectively influence the effect of fishing effort on fish stocks.

In Lake Superior, stocks of lake trout (*Salvelinus namaycush*), a highly-valued species, collapsed to near extirpation during the 1950s partly through overexploitation (Lawrie and Rahrer 1972, 1973; Lawrie 1978; Hansen *et al.* 1995a), but fleet dynamics have never been examined during the period of collapse. Discarding of undersized lake trout and lake whitefish (*Coregonus clupeaformis*) may have been important in the late 1800s because a minimum allowable mesh size for gill nets (114-mm stretch-measure) and a minimum size limit for both species (0.68 kg round weight) were implemented to reduce waste of fish (Smiley 1882, Brege and Kevern 1978). By-catch of lake trout in nets set for lake whitefish probably biased lake trout abundance indices low in some areas (Eshenroder 1992, Wilberg *et al.* 2003). Harvest efficiency for lake trout increased greatly over time through improvements in fishing vessels and gears (Goodier 1989), which partly masked the dramatic decline of lake trout abundance during the 1950s (Hile *et al.* 1951a). Fleet size, which increased during 1820–1880 (Smiley 1882) and remained relatively stable during 1900–1922 (Koelz 1926), was probably determined by lake trout abundance (Hile 1949, Hile *et al.* 1951b, Pycha and King 1975), the price of lake trout (Goodier 1989), and diminishing fishing opportunities in Lake Huron and Lake Michigan (Pycha and King 1975, Jensen 1978, Hansen 1999). Effort allocation changed spatially and temporally during development of the lake trout fishery, from a fishery that targeted inshore stocks in early spring and autumn to a fishery that targeted offshore stocks through much of the year (Hile *et al.* 1951a, Lawrie and Rahrer 1972, Goodier 1989, Hansen 1999). In Michigan waters of Lake Superior, the commercial fishery for lake trout was closed in the summer of 1962 (Brege and Kevern 1978) because a viable method was found to control sea lamprey and it seemed worthwhile to conserve remaining lake trout populations (Pycha and King 1975). The commercial lake trout fishery remained closed until tribal fisheries expanded in the early 1980s (Hansen *et al.* 1995a).

Understanding fleet dynamics of the historical lake trout fishery in Lake Superior is important because current goals for lake trout restoration are based on an understanding of historical lake trout abundance (Hansen 1996) indexed from fishery yield and CPE during a period when fleet dynamics were likely changing. Therefore, our objective was to determine if fleet dynamics of the commercial lake trout fishery were related to lake trout stock dynamics in Michigan waters of Lake Superior during 1929–1961. To achieve our objective, we first quantified temporal trends in the number of full-time lake trout fishers in Michigan's waters of Lake Superior during 1929–1961. We then quantified temporal and spatial trends in effort allocation of large-mesh gillnets, the predominant method of harvest during 1929–1961, including: (1) temporal changes in the amount of fishing effort, (2) distribution of fishing effort inshore and offshore, (3) temporal changes in mesh sizes fished, (4) movement of the mean location fished, and (5) spatial distribution and stability of fishing effort.

METHODS

Since 1927, every licensed commercial fisherman in Michigan has been required to submit monthly reports detailing their daily catch by species, effort (type and amount), and fishing location. Historical commercial catch reports from 1929 to 1961 are archived on microfiche transparencies at the Great Lakes Science Center, Ann Arbor, Michigan. We used lift-specific information on the lake trout fishery from these reports to develop a database of commercial catch, effort, and fishing locations. Before 1929, the data were incomplete and inaccurate, but by 1929 were deemed to be sufficiently accurate for statistical analyses (Hile 1962). Fishing locations were rarely recorded as recognizable site names and were usually reported as compass bearings and running times. Therefore, fishing locations were approximated using these compass bearings and running times from the port of origin, using an assumed cruising speed of 14.8 km (8 nautical miles) per hour for fish tugs. The end of each course allowed the approximation of fishing depth, which was not reported, and the assignment of the catch and effort to a 10-minute latitude by 10-minute longitude statistical grid. Because hundreds of fishing licenses were issued historically, the database was developed using information only from large fishing operations (major operators) and from odd years during 1929–1959, and 1960 and 1961. Major operators were defined as fishermen who fished at least ten times per month during most months. Major operators accounted for 76% of the large mesh gill net effort in Michigan waters of Lake Superior during 1929–1957 (U.S. Geological Survey, Great Lakes Science Center, Ann Arbor, MI, unpublished data).

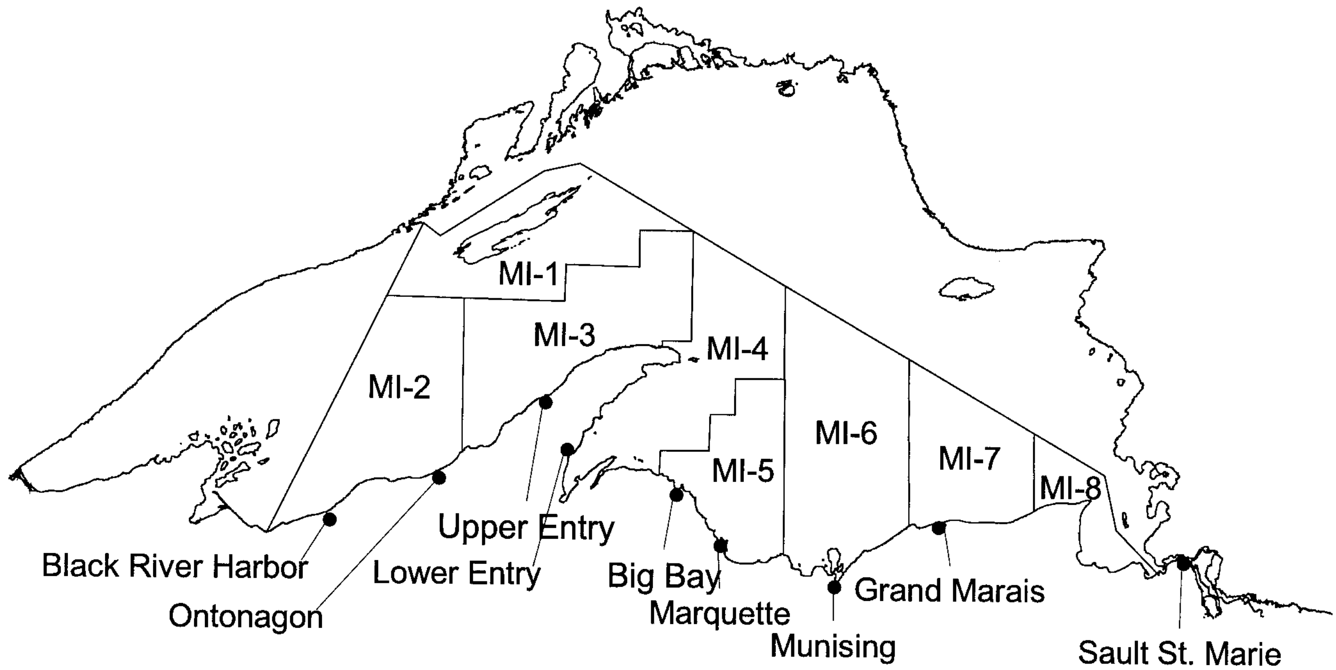

FIG. 1. Major ports and lake trout management areas in Michigan's waters of Lake Superior (Hansen 1996).

We computed lake trout catch per effort (CPE) as the number of lake trout caught per km of gill net set for one night. Gill net catches vary among mesh sizes (Hansen *et al.* 1997), so the CPE for commercial fishery lifts was calculated only for 114–120-mm (4-½ to 4-¾ in stretch-measure) gill nets. Gill net CPE is not a linear function of time, so CPE was standardized to a soak time of one night using the saturation curve from Hansen *et al.* (1998). To use this relationship, the commercial catch was converted from dressed weight to numbers by dividing the dressed weight by 1.09 kg (2.4 lb), the average dressed weight of lake trout during 1933–1953 (Rahrer 1967, Lawrie and Rahrer 1973). About 25% of gill nets fished in 1950 were multifilament nylon, about 50% fished in 1951 were multifilament nylon, and nearly all gill nets fished in 1952 were multifilament nylon (Pycha and King 1975). Therefore, we multiplied all catches during 1929–1949 by 2.25 and all catches during 1951 by 1.65 to compensate for the increased efficiency of multifilament nylon gill nets over cotton and linen gill nets (Pycha 1962).

To quantify changes over time in the number of full-time fishermen, the number of major operators was counted for each year in all Michigan waters of Lake Superior (Fig. 1). Each different name was considered to be a different fisherman. New fishermen for a year were defined as any name that was not considered a major operator before that year. Because data only covered odd years, the number of new fishermen for a year represents fishermen who entered the fishery during that year or the previous year. The number of $\log_e$-transformed new fishermen was regressed against gill net yield 2 years earlier to test whether entrance into the fishery was related to prior catches. A $\log_e$-transformation was used to normalize the residuals.

To quantify changes in the amount of gill net fished over time, large mesh (≥114 mm) gill net effort was summarized by management area and for all Michigan waters. To determine whether the amount of large mesh gill net fished was related to the number of fishermen, total gill net effort was regressed against the total number of major operators.

To quantify the extent of offshore fishing during 1929–1961, fishing effort was summarized as either being offshore or inshore. Inshore effort was considered to be any effort in a grid that was adjacent to either the main shore of Lake Superior or the shore of Isle Royale. Any effort that was not inshore was considered to be offshore. To determine whether patterns of inshore versus offshore effort were related to lake trout abundance, we estimated relative lake trout abundance by depth and compared abundance to the amount of offshore effort. Yearly relationships between relative lake trout abundance and depth were estimated by regressing average $\log_e$-transformed CPE (number of lake trout/km gill net/night) at each depth (CPE data were averaged in 0.3 m increments) against fishing depth. A $\log_e$-transformation was used to normalize the residuals. Slopes of linear relationships between CPE and depth were considered statistically significant if $P \leq 0.05$.

To describe changes in the mesh size of gill nets fished during 1929–1961, the number of gill net lifts was summarized by mesh size and year. Fishermen were first separated into three periods, 1929–1937, 1939–1945, and 1947–1957, based on when they began fishing in the Michigan waters of Lake Superior, to test whether the preferred mesh size of fishermen was related to the period of entry into the fishery. Fishermen were separated into these three groups because effort began to decline in the Lake Huron fishery after 1937 (Hile 1949) and in the Lake Michigan fishery after 1945 (Hile *et al.* 1951b). To determine whether mesh sizes fished were related to when fishermen entered the fishery, relative frequencies of 114-mm, 117-mm (4⅝ in), and 120-mm gill net lifts were compared among fishermen groups for both the 1939–1945 and 1947–1957 periods and among periods for the 1929–1937 and the 1939–1945 fishermen groups with chi-square analyses of contingency tables.

To quantify movement of the fishery over time, the mean fishing location was estimated for each management area each year. Locations of each statistical grid were determined as the centroid of each 10-minute latitude by 10-minute longitude statistical grids. The grid map was transformed from a latitude-longitude coordinate system to 1983 state plane coordinates (SPC) projection using the northern Michigan zone. SPC coordinates were used because it is easier to calculate distances with a rectangular coordinate system than a spherical coordinate system, such as latitude-longitude. Mean fishing location consists of two values, a mean north-south value (northing) and a mean east-west value (easting). Mean northing and easting values were calculated by weighting the location of each grid by the percentage of effort fished in that grid that year. The northing of mean fishing location, $\overline{N}_y$, for each year was calculated as:

$$\overline{N_y} = \sum_{i=1}^{n} \left(N_i \times \frac{f_{i,y}}{\sum_{i=1}^{n} f_{i,y}} \right) \tag{1}$$

where N_i is the northing SPC value for grid i and $f_{i,y}$ is the effort in grid i in year y. The easting of mean fishing location, $\overline{E_y}$, for each year was calculated similarly:

$$\overline{E_y} = \sum_{i=1}^{n} \left(N_i \times \frac{f_{i,y}}{\sum_{i=1}^{n} f_{i,y}} \right) \tag{2}$$

where E_i is the easting SPC value in grid i and $f_{i,y}$ is the effort in grid i in year y. Means were calculated over all Michigan waters and for each management area. To test whether fishermen systematically changed their fishing locations over time, such as fishing farther from port, we regressed easting and northing of the mean fishing location against years with linear and quadratic models for each Michigan management area.

To quantify the distribution and stability of gill net fishing effort for lake trout, mean annual effort was estimated for each 10-minute by 10-minute grid during 1929–1961 (odd years only during 1929–1959). Standard deviation (SD) and coefficient of variation (CV) in effort fished were also estimated for each grid during 1929–1961. The mean, SD, and CV of annual effort fished was then plotted for each statistical grid to illustrate distribution and stability of the fishery through time.

RESULTS

The number of full-time fishermen operating in Michigan waters of Lake Superior varied erratically during 1929–1961 (Fig. 2). The number of new entrants to the fishery was significantly related to the gill net yield two years earlier ($F = 5.0$; df = 1, 15; $P = 0.041$) (Fig. 3). New fishermen entered the fishery at a positive exponential rate as the yield two years earlier increased.

The amount of gill net effort in Michigan waters of Lake Superior increased from 1929 to 1949, but did not follow the same pattern in individual management areas (Table 1). During 1929–1941 more effort was fished in MI-7 than in any other area, and in most years, MI-5 was a close second. Between 1941 and 1943, effort increased greatly in MI-4 (Keweenaw Bay); from 1943 to 1961 more ef-

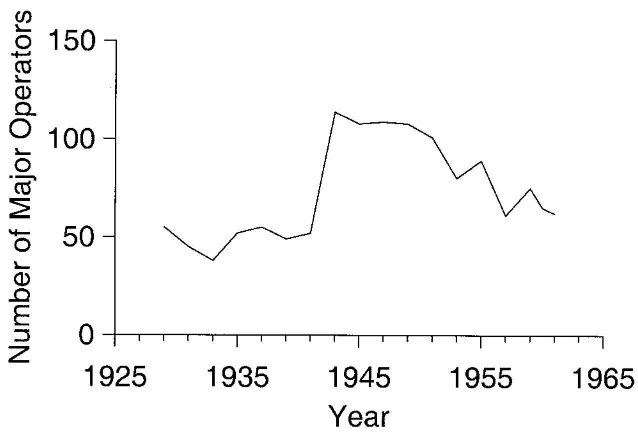

FIG. 2. Number of full-time commercial lake trout fishermen (major operators) in Michigan waters of Lake Superior during 1929–1961.

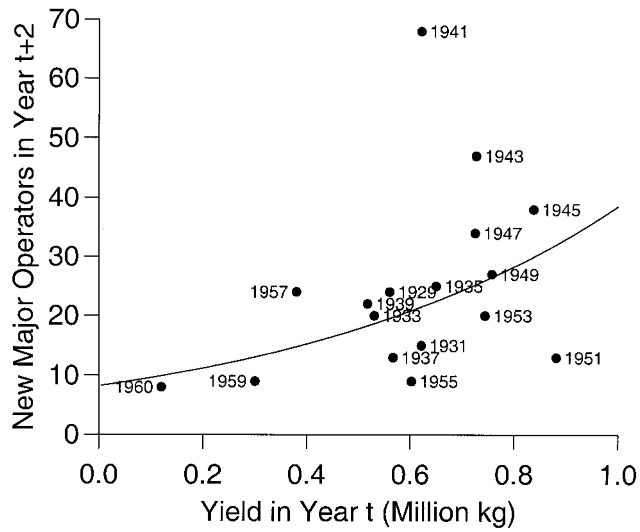

FIG. 3. Relationship between lake trout yield from large mesh (≥ 114-mm stretch-measure) gill nets and the number of new fishermen recruited to the fishery during the next 2 years in Michigan waters of Lake Superior during 1929–1961. Labels on the points indicate the year that the yield was produced.

fort was fished in MI-4 than in any other management area. In most years MI-2, MI-3, or MI-8 had the lowest amount of effort. The amount of gill net fished was positively related to the number of fishermen during 1929–1955 ($F = 35.2$; df = 1, 16; $P < 0.001$) (Fig. 4). However, the amount of gill net fished was not significantly related to the number of fishermen during 1929–1941 ($F = 1.3$; df = 1, 5; $P = 0.29$) or 1943–1955 ($F = 0.7$; df = 1, 5; $P = 0.427$).

Temporal changes of offshore and inshore effort differed (Fig. 5). Offshore effort increased during 1929–1949 and decreased during 1949–1961. Offshore effort increased at a lower rate than inshore effort for all areas except MI-7. In MI-7, offshore and inshore levels of effort were nearly equal. In the other seven management areas, inshore effort

TABLE 1. Total annual (1,000 km) large mesh (≥ 114-mm stretch-measure) gill net fishing effort in Michigan waters of Lake Superior during 1929–1961.

Area	MI-1	MI-2	MI-3	MI-4	MI-5	MI-6	MI-7	MI-8	Total
1929	1.73	1.05	0.3	1.03	1.81	0.85	3.58	0.06	10.41
1931	1.26	1.24	0.35	1.67	2.64	1.58	2.22	0.3	11.27
1933	1.4	0.75	0.49	1.12	1.89	0.84	1.91	0.21	8.61
1935	1.19	0.56	0.33	0.99	2.22	1.34	2.48	0.48	9.58
1937	1.47	1.44	0.97	1.27	1.91	1.51	2.65	1.53	12.76
1939	0.82	1.22	0.64	1.36	2.34	2.35	3.48	1.04	13.25
1941	0.76	0.94	0.92	2.24	3.13	2.2	3.14	1.62	14.94
1943	2.9	1.2	2.36	7.39	2.55	2.1	1.99	1.32	21.81
1945	3.06	1.81	1.9	8.49	3.01	3.18	1.86	2.09	25.39
1947	3.12	1.69	3.68	9.75	3.3	2.72	2.46	1.91	28.62
1949	3.91	1.93	3.37	10.53	5.43	3.7	4.36	2	35.24
1951	4.08	0.83	2.27	10.39	4.9	6.18	3.87	2.28	34.81
1953	3.31	0.55	1.75	11.37	5.58	4.67	2.01	2.01	31.26
1955	3.15	0.45	2.65	10.77	4.64	3.93	2.22	1.46	29.26
1957	1.54	0.55	0.98	6.66	3.37	3.93	1.37	1.2	19.59
1959	0.77	0.78	0.73	5.54	3.02	4.12	1.65	0.08	16.69
1960	0.76	0.52	0.44	3.51	1.6	2.1	1.28	0.2	10.4
1961	0.58	0.38	0.58	2.59	1.27	1.95	0.58	0.35	8.28

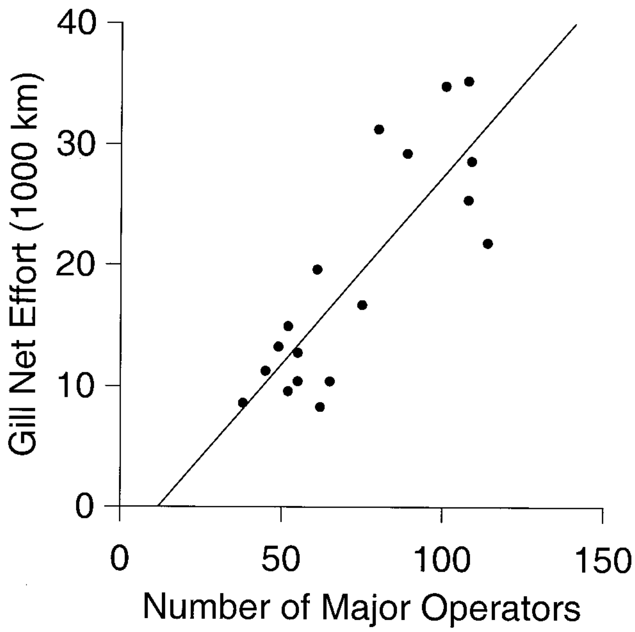

FIG. 4. Relationship between large mesh (≥ 114-mm stretch-measure) gill-net fishing effort and the number of major operators in Michigan waters of Lake Superior during 1929–1961.

was always higher than offshore effort. Mean lake trout CPE increased significantly with depth in 9 of 18 years (see Wilberg 2000). Slopes ranged from 1.7×10^{-3} to -7×10^{-4}, which corresponds to a 95% increase and a 24% decrease in geometric mean CPE with fishing depth between 30.5 and 152.4 m (100 and 500 ft) respectively. Between 1929 and 1949, CPE was positively related to depth in 7 of 11 years, whereas between 1951 and 1961, CPE and depth were positively related in only 2 of 7 years.

The preferred gill net mesh size of fishermen increased during 1929–1957 (Fig. 6). The use of 114-mm mesh decreased from 1929 to 1931 and remained relatively stable around 4,000 km per year during 1931–1961. During 1929–1939, 114-mm mesh was the most common mesh size used and very little 117-mm mesh was used. During 1935–1945, the use of 117-mm mesh increased dramatically, to a peak of over 12,000 km, and decreased thereafter. During 1941–1945 and 1959–1961, 117-mm was the most common mesh size fished. Very few fishermen used 120-mm mesh during 1929–1939. The use of 120-mm mesh increased to a peak of over 16,000 km during 1939–1953 and decreased thereafter. The predominant mesh size fished during 1947–1957 was 120 mm.

Mesh sizes used by fishermen differed among periods of entry into the fishery and among periods of fishing, but changes were more strongly related to periods of fishing than to periods of entry into the fishery. During 1939–1945, fishermen who had entered the fishery during 1929–1937 used different mesh sizes than those who entered the fishery during 1939–1945 (Fig. 7; $\chi^2 = 272.6$, df = 2, $P < 0.001$). Similarly, during 1947–1957, fishermen who entered the fishery during 1929–1937 used different mesh sizes than those who entered the fishery either during 1939–1945 or 1947–1957 ($\chi^2 = 348.1$, df = 4, $P < 0.001$). However, changes in mesh sizes used by fishermen were more strongly related to periods of fishing than to periods of entry into the fishery (Group 1929–1937: $\chi^2 = 3707.9$, df = 4, $P < 0.001$; Group 1939–1945: $\chi^2 = 2131.7$, df = 2, $P < 0.001$).

The mean fishing locations for six of eight individual management areas changed significantly over time (Figs. 8–9). The mean fishing location moved to the northeast for MI-1, to the southwest for MI-2, and to the east for MI-8. The mean fishing location moved nonlinearly through time in MI-4, MI-5, and MI-6. The mean fishing location for MI-4 moved north during 1929–1949 and returned southward during 1951–1961. The mean fishing location for MI-5 moved west during 1929–1943 and east during 1945–1961, whereas the mean fishing location for MI-6 moved east during 1929–1943 and west during 1945–1961.

The mean amount and variation (SD) of gill net fished in each statistical grid during 1929–1961 were generally highest in the grids adjacent to the southern shoreline of Lake Superior and the shoreline of Isle Royale, whereas relative variation (CV) was higher offshore (Fig. 10). During 1929–1961, the mean amount of gill net fished per grid ranged from zero to 1,158 km, the SD in gill net effort ranged from zero to 701 km, and the CV in gill net effort ranged from 0 to 424%. Areas near major ports tended to have the highest mean effort and lowest relative variation of fishing effort.

DISCUSSION

Changes in Fleet Size

We found that entry into the lake trout fishery in Lake Superior was related to lake trout yield 2 years prior, which suggests that fishermen recruitment was related to lake trout abundance (Hile 1949, Hile *et*

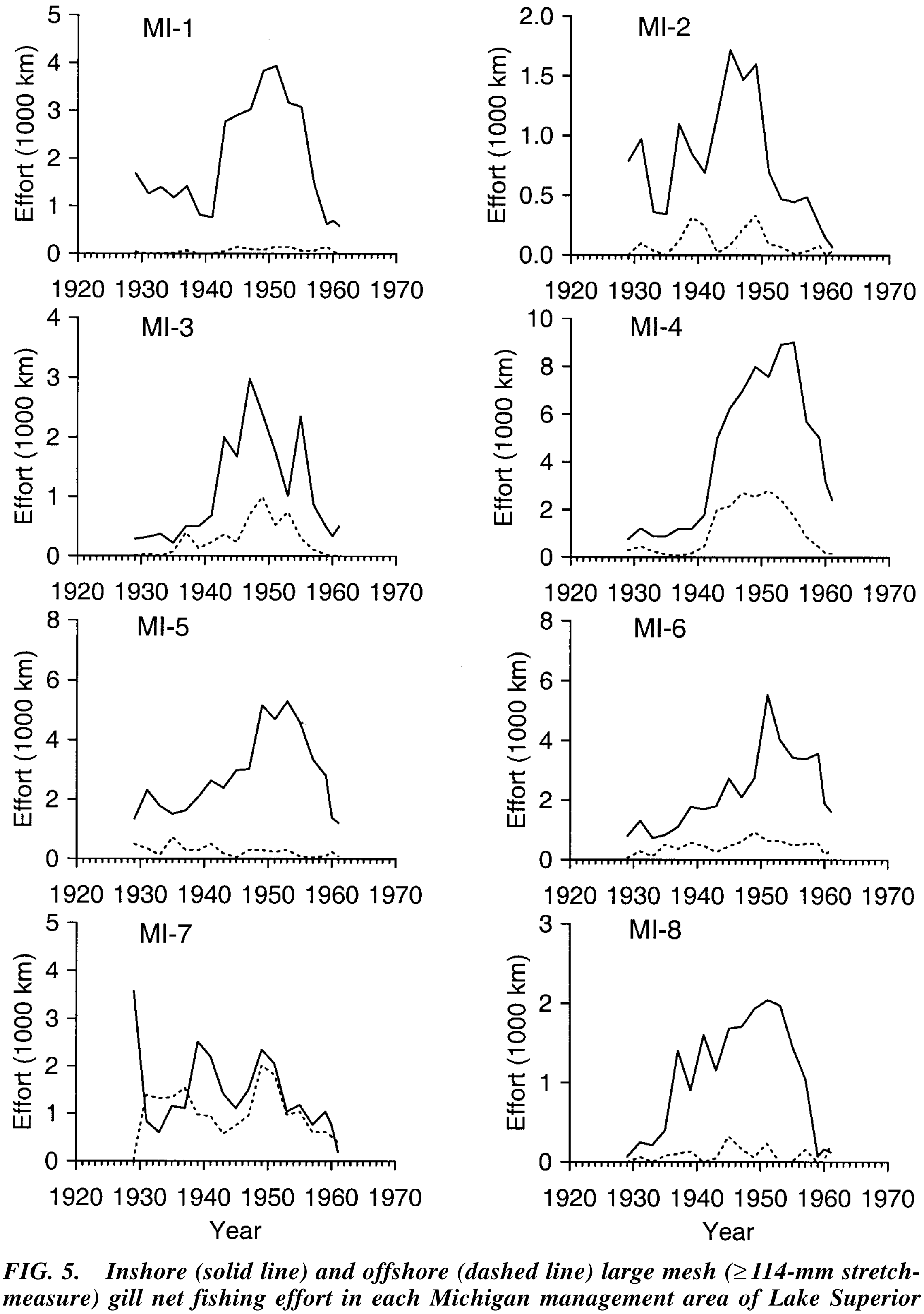

FIG. 5. Inshore (solid line) and offshore (dashed line) large mesh (≥114-mm stretch-measure) gill net fishing effort in each Michigan management area of Lake Superior during 1929–1961.

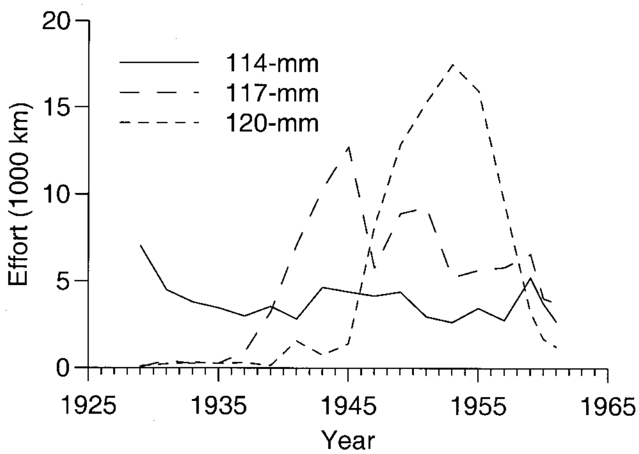

FIG. 6. Changes in the preferred gill net mesh size in Michigan waters of Lake Superior during 1929–1961.

al. 1951a, Hile *et al.* 1951b) or the price of lake trout (Hile *et al.* 1951a, Goodier 1989). In addition, fishing opportunities on Lake Huron and Lake Michigan were disappearing as lake trout stocks collapsed in those lakes (Pycha and King 1975, Jensen 1978, Hansen 1999), which may have forced fisherman from Lake Huron and Lake Michigan to move to Lake Superior (Hansen 1999). We found that fisherman attrition, rather than fisherman recruitment, appeared to be related to lake trout abundance. Hile (1949) and Hile *et al.* (1951b) documented declines in fishing effort in Lake Michigan and fishing intensity in Lake Huron were related to decreases in lake trout CPE in those fisheries. Hile (1949) and Hile *et al.* (1951b) suggested that the decrease in effort was due to fishermen leaving the fishery because of low lake trout abundance. Pycha and King (1975) stated that the most important factor in fisherman attrition from the Lake Superior lake trout fishery was declining lake trout abundance.

The price of lake trout was probably an important factor that determined fishermen recruitment. Goodier (1989) found a large increase in the number of lake trout fishermen during World War II in Canadian waters of Lake Superior because prices were highly favorable. Also, demand for Great Lake's fish was high during World War II (Regier and Goodier 1992). In the U.S., fishermen were also exempt from the draft. The two largest outliers in the regression of new fishermen against previous yield were 1941 and 1943 (Fig. 3), both of which were during World War II. These outliers could be explained by extremely favorable prices (fueled by high demand) and exemption from the draft during that period.

Diminishing fishing opportunities on lakes Huron and Michigan may have affected recruitment to the Lake Superior lake trout fishery. Pycha and King (1975), Jensen (1978), and Hansen (1999) concluded that increased lake trout effort in Michigan waters of Lake Superior during 1940–1951 was driven by fishermen migrating to Lake Superior from Lakes Huron and Michigan. However, we found that the number of fishermen increased in Michigan waters of Lake Superior only during 1933–1943. This increase was coincident with a decrease in gill net effort in Michigan waters of Lake Huron, but was before the decrease in gill net effort in Michigan waters of Lake Michigan. Therefore, the large increase in fishermen between 1941 and 1943 may have been caused by Lake Huron fishermen migrating to Lake Superior as well as favorable prices. However, Hile *et al.* (1951a) did not attribute increasing fishing intensity in Lake Superior to more fishermen, but rather to fishermen increasing their fishing effort. Our results do not preclude the fact that fishermen migrated to Lake Superior from Lake Michigan because new fishermen entered the fishery after 1947. However, more fishermen abandoned fishing than entered the fishery during that period.

More fishermen left the Lake Superior lake trout fishery than entered it during 1945–1957. Fishermen left the fishery in the 1950s because lake trout abundance declined to the point where they could not meet expenses (Pycha and King 1975). Pycha and King (1975) also attributed fisherman attrition to age (younger men tended to leave before older men), business savvy, fishing skill, size of the operation, and family ties. The number of fishermen during 1959–1961 was still higher than the number of fishermen during 1929–1941 because almost all of the fishermen during 1959–1961 fished only part-time (Pycha and King 1975).

Recruitment to and attrition from the Lake Superior lake trout fishery was similar to other fisheries that have been studied. For example, entry and exit in the North Pacific fur seal (*Callorhinus ursinus*) fishery depended on seal abundance and the price of seal pelts, which ultimately determined profitability of the fishery (Wilen 1976). Also, entry into the California Dungeness crab (*Cancer magister*) fishery occurred when fishing was good and exit occurred when fishing was poor (Botsford *et al.* 1983).

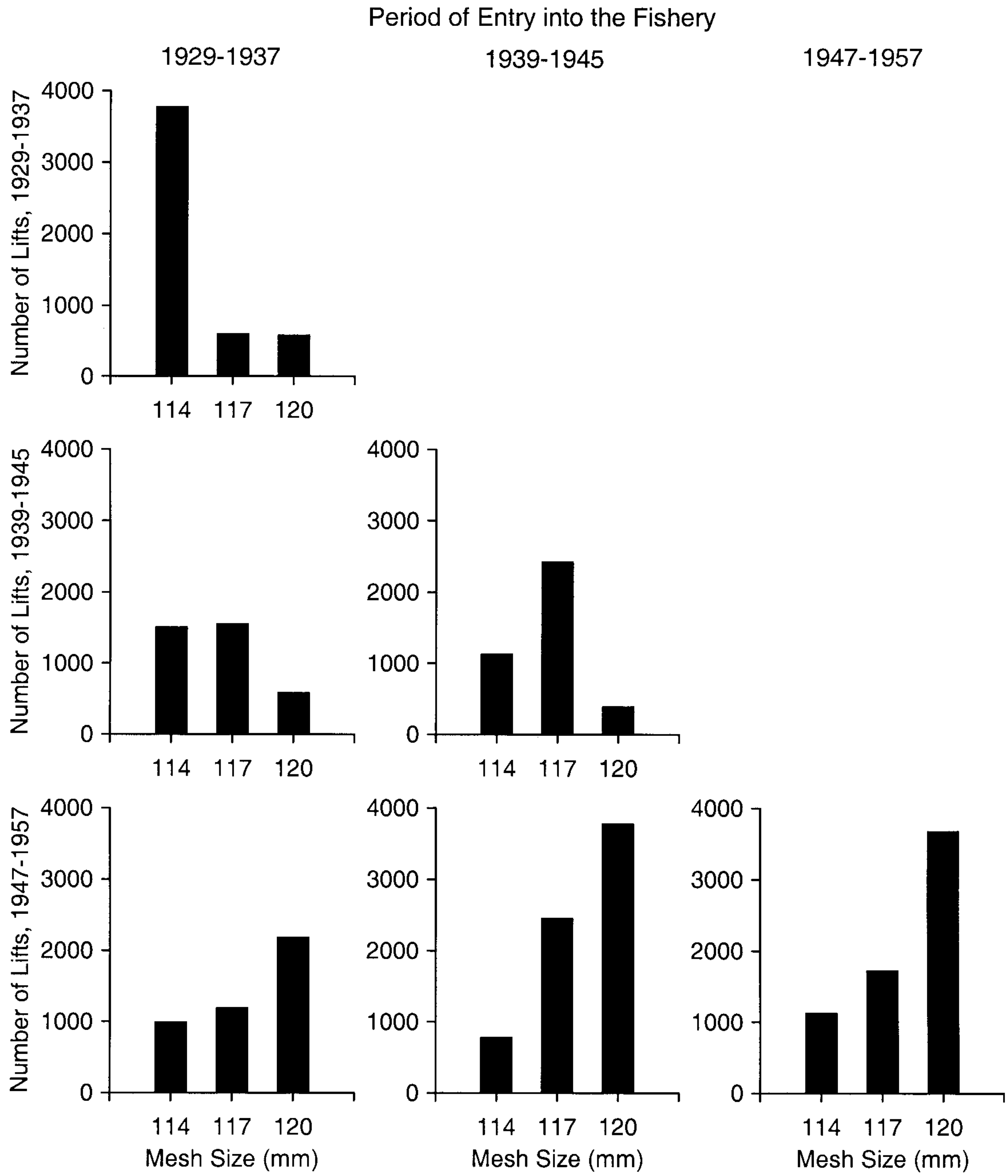

FIG. 7. Number of gill net lifts of 114-mm, 117-mm, and 120-mm stretch-measure by fishermen who entered the fishery during 1929–1937, 1939–1945, and 1947–1957 in Michigan waters of Lake Superior.

Changes in Effort

The amount of large mesh gill net fished in Michigan waters of Lake Superior increased during 1929–1951, then decreased during 1953–1959, a pattern that was also described by Hile *et al.* (1951a) and Pycha and King (1975). During 1929–1951, fishing intensity was negatively correlated with lake trout abundance (Hile *et al.* 1951a, Pycha and King 1975), which Hile *et al.* (1951a) attributed to favorable market prices because lake trout fisheries in both Lake Huron and Lake Michigan had recently collapsed and there was little

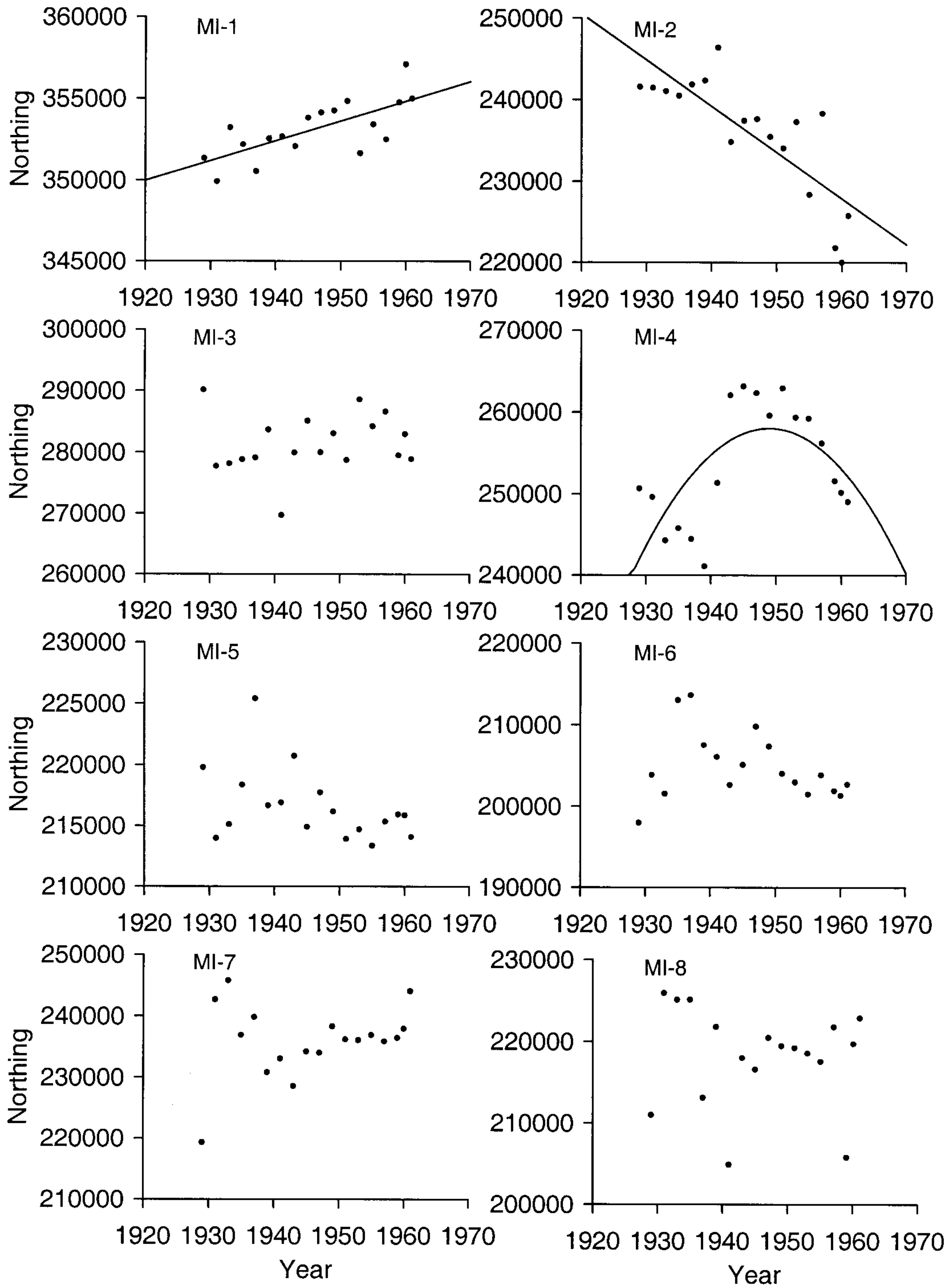

***FIG. 8.** Linear and 2nd order polynomial regression of the northing value of mean fishing location against year for each Michigan management area of Lake Superior during 1929–1961. Trend lines are shown for areas with significant trends ($P \leq 0.05$).*

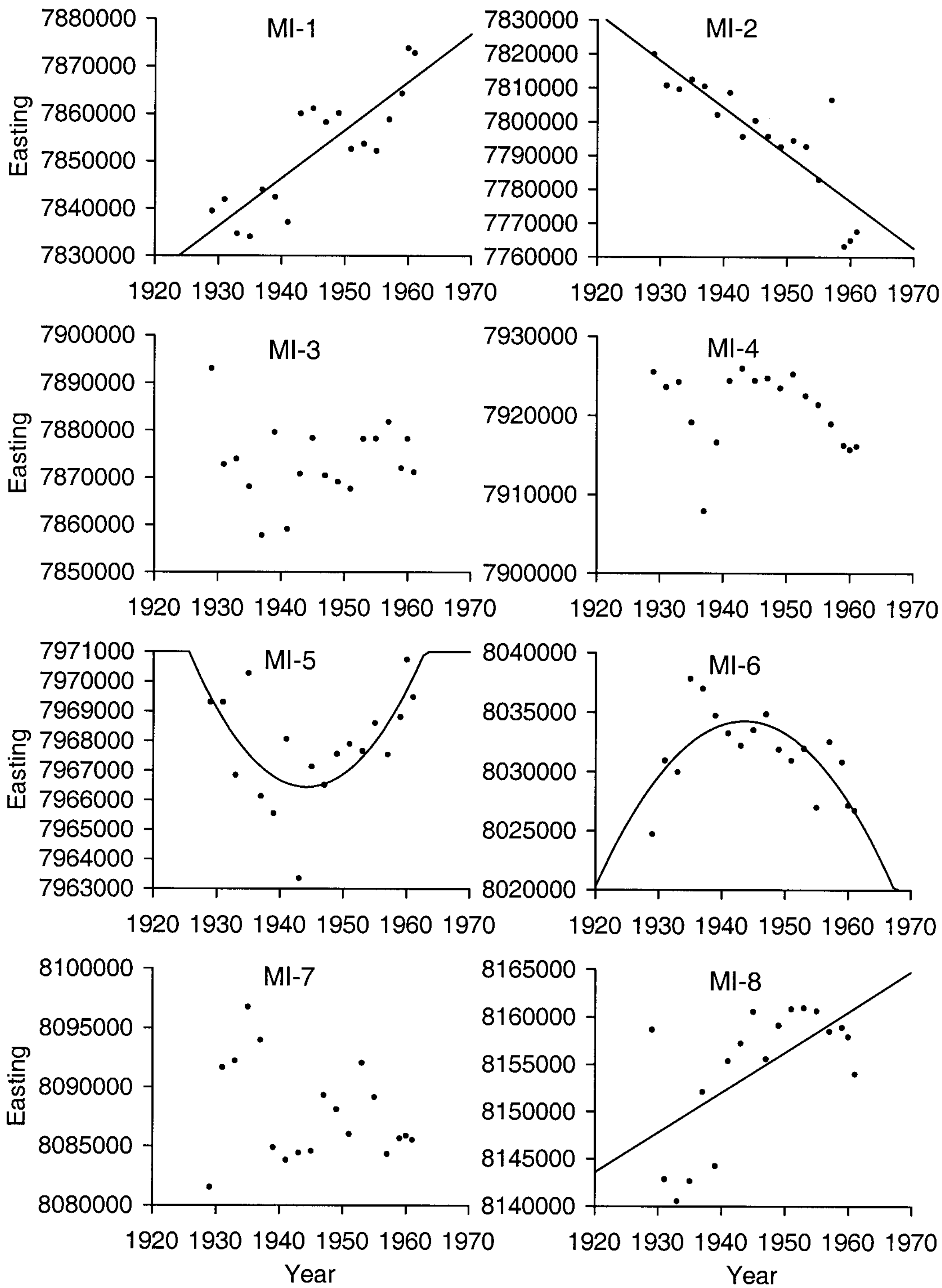

FIG. 9. Linear and 2nd order polynomial regression of the easting value of mean fishing location against year for each Michigan management area of Lake Superior during 1929–1961. Trend lines are shown for areas with significant trends ($P \leq 0.05$).

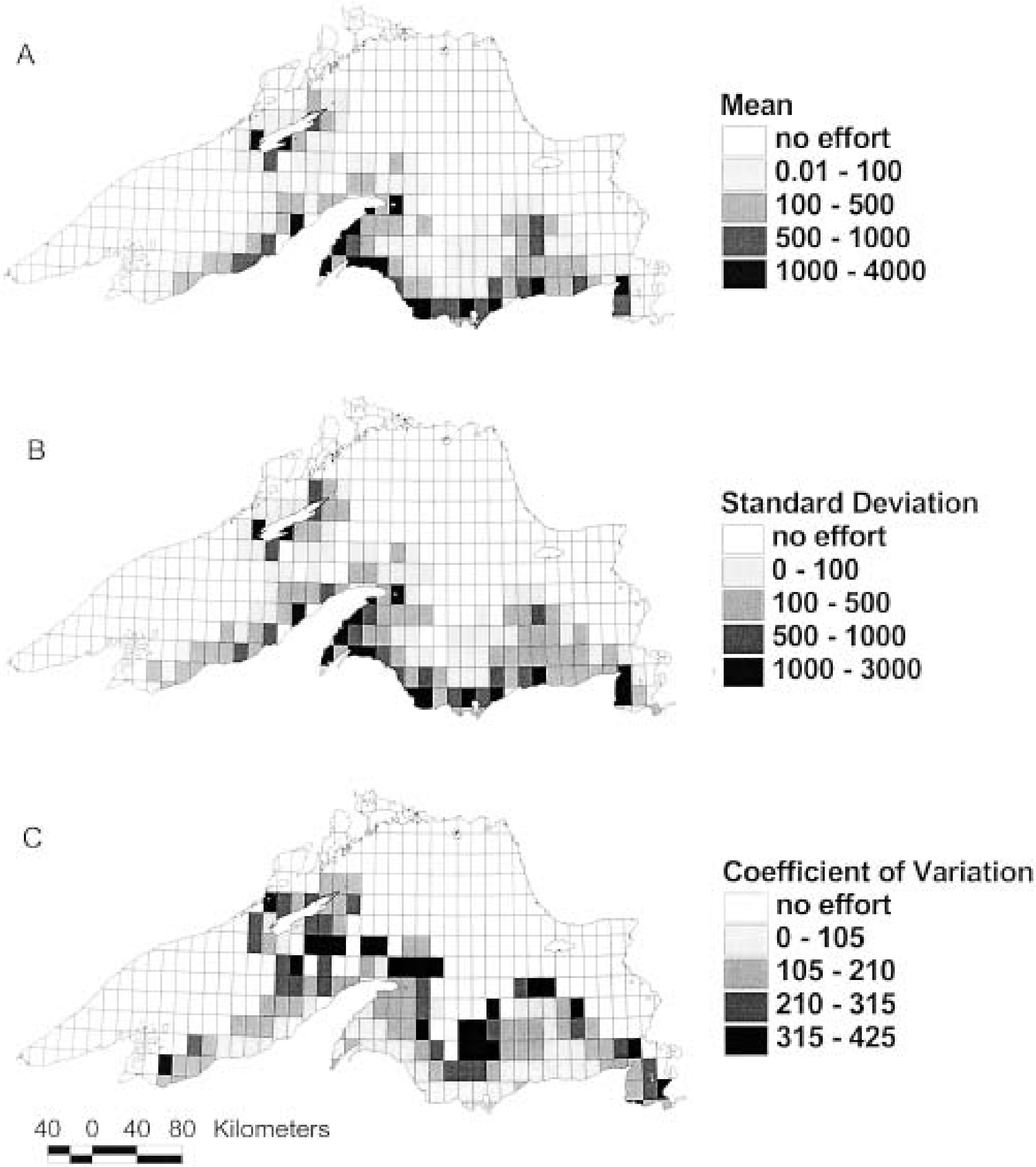

FIG. 10. Mean, standard deviation, and coefficient of variation of large-mesh gill-net fishing effort for each 10-minute latitude by 10-minute longitude grid in Michigan waters of Lake Superior during 1929-1961.

chance of market saturation. Thus, as lake trout abundance declined, fishermen increased their effort to maintain yield.

We found that fishermen primarily fished close to shore, rather than offshore, in most management areas. Fishermen likely stayed near shore because fishing sites near shore would have been easier to find than offshore fishing sites. Fishermen navigated by dead reckoning, a form of navigation that relied on knowing direction and time traveled at a repeatable speed. Fishermen also navigated with landmarks when they were available, which allowed them to set gear more accurately when they were in sight of land. Depth sonar and autopilots were not available until after World War II (Hile *et al.* 1951a). Fishing was likely more costly and more dangerous offshore; fishing offshore would require more fuel and more travel time than fishing inshore. However, lake trout CPE was generally greater in deeper water during 1929–1949 and fishermen increased their offshore effort during this period, but at a lower rate than near shore. Although depth and inshore-offshore designation were not always the same, depth generally increased farther from shore and offshore waters were usually deeper than inshore waters. Hilborn and Ledbetter (1979) found that British Columbia purse-seiners optimized profit and that some locations were more expensive to fish than others. Although CPE was higher in some high expense areas, British Columbia purse-seiners fished less often in high expense areas than would be expected if CPE was the only determinant of fishing effort (Hilborn and Ledbetter 1979). This is consistent with the Lake Superior lake trout fishery, where the more expensive, time consuming, and dangerous areas were generally offshore.

Changes in Mesh Size

We found that the most commonly fished gill-net mesh size changed through time from 114-mm to 120-mm, which is contrary to Pycha (1962) and Pycha and King (1975) who stated that 114-mm mesh was the predominant gill-net mesh size used during 1929–1961. Lake trout fishermen may have increased their mesh sizes over time to catch fish that were growing faster because lake trout exhibited compensatory increases in growth during 1948–1953, as their abundance declined (Rahrer 1967; Sakagawa and Pycha 1971, Ferreri and Taylor 1996).

The sequential increase in mesh size over time may bias CPE as an index of relative abundance. Larger gill net meshes select for larger lake trout (Hansen *et al.* 1997). The peak selectivity of 114-mm mesh gill nets is about 600 mm and the peak selectivity of 127-mm (5 in stretch-measure) mesh gill nets is about 630 mm (Hansen *et al.* 1997). Therefore, the peak selectivity of 120-mm mesh gill nets should be about 615 mm, half way between the peak selectivity of 114-mm and 127-mm mesh gill nets. These fish should have a larger average weight than those caught in 114-mm mesh. The sequential increase in mesh size over time would cause CPE to be inflated if the same number of fish were caught because of our assumption of a single average weight for the whole time series.

Changes in Fishing Locations

We found that the mean fishing location moved in most management areas away from major ports during 1929–1943, which agrees with Goodier (1989) for the Canadian fishery in Lake Superior. In MI-1, the mean fishing location moved northwest, away from the Minnesota shoreline where many of the fishermen in the area were located (Hile *et al.* 1951a). In MI-2, the mean fishing location moved southeast from Ontonagen toward Black River Harbor. In MI-4, the mean fishing location moved north away from the major ports around the Portage Canal. In MI-5, the mean fishing location moved west from Marquette toward Big Bay. In MI-6, the mean fishing location moved east away from Munising. Lake trout abundance was limited on the home grounds near some Canadian towns by the 1930s and fishermen had to travel farther from port to get to good fishing sites (Goodier 1989), which is similar to the movement in Michigan waters of Lake Superior.

In areas where the fishery moved significantly over time, CPE may not be a reliable index of relative lake trout abundance (Caddy 1975, Quinn and Deriso 1999). Fishermen would likely seek the best fishing sites with the highest CPE within any area. However, the search area for fishermen was probably smaller than current lake trout management areas (Fig. 1) because effort increased less offshore than inshore, although CPE was often higher offshore, especially during 1929–1949. If fishermen were constantly seeking local areas of highest abundance, CPE estimates may not be comparable among years. These changes in the distribution of effort would likely bias CPE estimates high and also be a mechanism to maintain yield while abundance was declining.

CONCLUSIONS

Lake trout CPE and yield during 1929–1943 have been used as targets for lake trout restoration in Lake Superior (Hansen 1996, Hansen *et al.* 1995b, Wilberg *et al.* 2003). The current objective for lake trout restoration in Lake Superior is to achieve a sustainable yield of 2.0 million kg per year, which was the average commercial yield achieved during 1929–1943 (Hansen 1996). However, this objective is based on the assumption that the commercial lake trout fishery in Lake Superior was at equilibrium during 1929–1943 (Hile *et al.* 1951a, Pycha and King 1975, Hansen *et al.* 1995b). We found that fishermen were fishing-up lake trout stocks by increasing effort, fishing larger mesh gill nets, and moving to new fishing locations within management areas as early as 1939. Yield of lake trout in the commercial fishery was maintained by fishermen changing their methods. Therefore, historic yield during 1929–1943 should not be used as a goal for lake trout restoration in Lake Superior because it probably overestimates maximum sustainable yield.

The effects of fishing-up on CPE also change the interpretation of how CPE relates to abundance. Fishing-up likely caused CPE of lake trout to be artificially high relative to abundance during the reference period that is often used as a target for lake trout restoration, 1929–1943. Wilberg *et al.* (2003) found that lake trout abundance was at least as high during 1984–1998 as during 1929–1943 in most of Michigan's waters of Lake Superior. However, lake trout abundance during 1929–1943 was likely lower than CPE indicated, which may mean that lake trout abundance is currently farther above the restoration goal than previously realized.

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