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[Article]

Using Positional Data from Vessel Monitoring Systems to Validate the Logbook-Reported Area Fished and the Stock Allocation of Commercial Fisheries Landings

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Abstract.—Stock allocations derived from vessel monitoring system (VMS) positional data from northeastern U.S. fisheries were compared with those obtained from mandatory vessel trip report (VTR) logbooks. A gear-specific speed algorithm was applied to VMS positions collected in 2005 from otter trawl, Atlantic sea scallop *Placopecten magellanicus* dredge, sink gill-net, and benthic longline fisheries to estimate the locations of fishing activity. Estimated fishing locations were used to reallocate the stock area landings of eight federally managed groundfish species. The accuracy of the VMS method relative to that of the mandatory logbooks was assessed using haul locations and catch data recorded by at-sea observers. The VMS algorithm tended to overestimate the number of statistical areas fished, such that when a trip's fishing activity occurred in a single statistical area, logbooks more accurately reflected the true fishing location. However, when fishing activity occurred in multiple statistical areas, the VMS algorithm showed appreciable gains relative to logbook data. Compared with mandatory logbooks, the VMS method achieved distributions of stock landings closer to observer estimates in 77.8% of the cases examined. The stock allocation percentages from both the VMS- and VTR-based methods were within 1.7% for all stocks, suggesting that the impacts on total stock allocations are relatively minor. However, these small differences represent major relative differences in stock landings for less abundant stocks such as southern New England–Mid-Atlantic yellowtail flounder *Limanda ferruginea*, where the VTR-based method allocated 61.9% more landings than the VMS-based method. The VMS-based method is not a replacement for the VTR-based method; however, it can and should be used as a tool to identify those vessels for which targeted outreach activities would improve the accuracy of VTR statistical area reporting.

Among the federally managed fish species in waters off the northeastern USA, eight species are managed and assessed as two or more discrete stocks: Atlantic cod *Gadus morhua*, haddock *Melanogrammus aeglefinus*, yellowtail flounder *Limanda ferruginea*, winter flounder *Pseudopleuronectes americanus*, windowpane *Scophthalmus aquosus*, goosefish *Lophius americanus*, silver hake *Merluccius bilinearis*, and red hake *Urophycis chuss*. Stock units are composed of statistical area groupings (Figure 1), stocks being defined by divisions that, in most cases, relate to oceanographic features (e.g., Gulf of Maine, Georges Bank; Table 1). All of the species are managed under the Northeast Multispecies Fisheries Management Plan (NEFMC 1985) except for goosefish, which is managed under the Monkfish Fisheries Management Plan (NEFMC 1998). These species are primarily caught in the groundfish fishery that is targeted by both small vessels (<45 metric tons) fishing bottom otter trawl, sink gill net, and benthic longline gear, and large bottom otter trawl vessels (>45 metric tons). There are some nondirected landings of these species in the dredge fishery for Atlantic sea scallop *Placopecten magellanicus*, which is primarily a large-vessel, offshore fishery. Trips can last from several hours and involve fishing effort concentrated in a very small area (<10 km^2) within a single statistical area, or up to 2 weeks and span several hundred kilometers and multiple statistical areas.

In the northeastern USA, dealer weigh-out data are assumed to be a census of commercial landings amounts. Commercial landings are allocated to management stocks using the statistical areas reported on the mandatory paper logbooks (Wigley et al. 2008). These logbooks are referred to as vessel trip reports (VTRs). Current VTR regulations require that upon completion of a fishing trip, a logbook report must be submitted that documents the total catch by species for each statistical area in which fishing occurred (USOFR 1994). Despite the regulations, it is known that misreporting of statistical area occurs, most frequently in the form of underreporting of the number of statistical areas fished when fishing occurs in more than one area (Palmer et al. 2007; A. Applegate and T. Nies, NEFMC, personal communication). While underreporting of statistical areas does not necessarily

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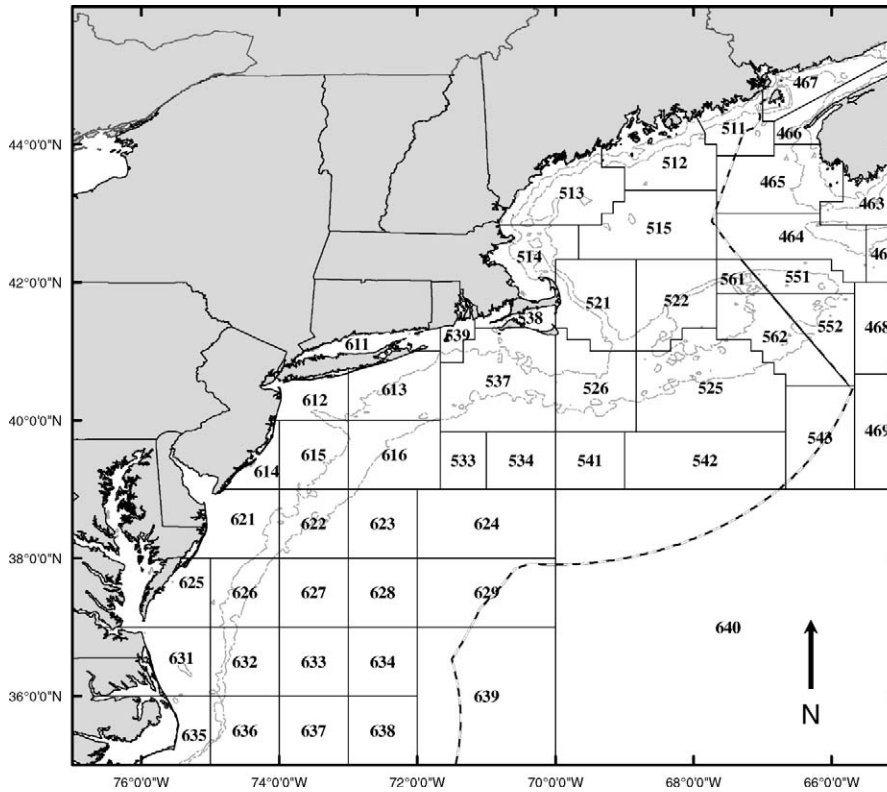

FIGURE 1.—Statistical areas used for commercial fisheries data collection by the National Marine Fisheries Service (NMFS) in the Northeast Region. The 50- and 100-m bathymetric lines are shown in light gray, and the U.S. Exclusive Economic Zone is indicated by the dashed black line.

translate to the misclassification of commercial landings to stock areas, the potential exists, and the magnitude of these effects on the allocation of commercial landings is unknown.

The most reliable source of fisheries-dependent catch-and-effort data in the northeastern USA is the information collected by at-sea fisheries observers. However, because these data are limited in their

TABLE 1.—Statistical areas used to define species stock units for eight species examined. Abbreviations are as follows: GBK = Georges Bank, GOM = Gulf of Maine; SNE = southern New England–Mid-Atlantic, NOR = North, and SOU = South.

Species	Stock area	Statistical areas
Atlantic cod	GBK	521, 522, 525, 526, 533, 534, 537–539, 541–543, 551, 552, 561, 562, 611–616, 621–629, 631–639
	GOM	464, 465, 511–515
Haddock	GBK	521, 522, 525, 526, 533, 534, 537–539, 541–543, 551, 552, 561, 562, 611–616, 621–629, 631–639
	GOM	464, 465, 511–515
Yellowtail flounder	GBK	522, 525, 551, 552, 561, 562
	Cape Cod–GOM	464, 465, 511, 512, 513, 514, 515, 521
	SNE	526, 533, 534, 537–539, 541–543, 611–616, 621–629, 631–639
Winter flounder	GBK	522, 525, 551, 552, 561, 562
	GOM	464, 465, 511, 512, 513, 514, 515
	SNE	521, 526, 533, 534, 537–539, 541–543, 611–616, 621–629, 631–639
Windowpane flounder	NOR	464, 465, 511–515, 521, 522, 525, 542, 543, 551, 552, 561, 562
	SOU	526, 533, 534, 537–539, 541, 611–616, 621–629, 631–639
Goosefish	NOR	464, 465, 511–515, 521, 522, 551, 561
	SOU	525, 526, 533, 534, 537–539, 541–543, 552, 562, 611–616, 621–629, 631–639
Silver hake	NOR	464, 465, 511–515, 521, 522, 551, 561
	SOU	525, 526, 533, 534, 537–539, 541–543, 552, 562, 611–616, 621–629, 631–639
Red hake	NOR	464, 465, 511–515, 521, 522, 551, 561
	SOU	525, 526, 533, 534, 537–539, 541–543, 552, 562, 611–616, 621–629, 631–639

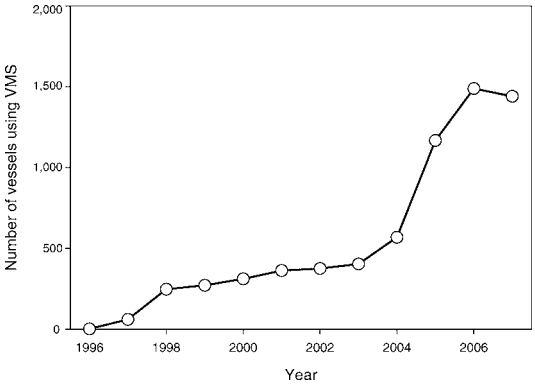

FIGURE 2.—Number of vessels using vessel monitoring systems in northeastern U.S. waters between 1998 and 2006.

coverage (e.g., less than 5% of most fisheries in a given year; Wigley et al. 2007), they cannot provide the synoptic coverage necessary to allocate commercial landings to stock area with any regularity. Vessel monitoring systems (VMS) in the northeastern USA were first implemented for the limited-access Atlantic sea scallop fisheries in 1998 (NEFMC 1993). The use of VMS has increased over time (Figure 2) and expanded to cover many fisheries (Table 2). Historically, the larger offshore vessels participating in the limited-access scallop and special-access groundfish fisheries were more likely to be equipped with VMS than the smaller, nearshore vessels. With the passage of Framework 17 and Amendment 11 to the Atlantic sea scallop FMP (NEFMC 2005, 2008) and Framework 42 to the multispecies FMP (NEFMC 2006), VMS is now required for a greater proportion of the smaller nearshore scallop and groundfish fleets. While VMS does not provide census coverage of these fleets, it does provide census coverage of trips taken by those vessels equipped with VMS. Given the increasing use of VMS in the region, this represents a potential tool to conduct large-scale validation of the statistical areas reported on VTRs.

Vessel positions obtained from VMS have been used as a proxy for the location of fishing effort in prior work (Deng et al. 2005; Murawski et al. 2005; Mills et al. 2007). Commonly, the average vessel speed is used to differentiate fishing activity from nonfishing activity

TABLE 2.—Fishery management plan (FMP) actions passed by the New England Fisheries Management Council (NEFMC) and Mid-Atlantic Fisheries Management Council (MAFMC) affecting the use of Vessel Monitoring System (VMS) in the northeast United States through October 2008. Note: if a vessel is subject to VMS regulations from multiple programs, the most restrictive regulation applies.

Date effective	Fishery	Measure	Description	Reference
May 1998	Atlantic sea scallop	Amendment 4	Required VMS for all limited access full- and part-time vessels (hourly polling; note: Amendment 4 effective March 1994, but VMS implementation delayed by NMFS until May 1998)	NEFMC 1993
May 1999	Atlantic herring *Clupea harengus*	Original FMP	Required VMS for all category 1 vessels (hourly polling)	NEFMC 1999
May 2001	Atlantic sea scallop	Framework Adjustment 14	Required VMS for all limited access occasional-category vessels when participating in area access programs (half-hour polling)	NEFMC 2001
May 2004	Northeast multispecies	Amendment 13	Required VMS for all vessels accessing the US–Canada shared resource area (half-hour polling within US–Canada area, hourly polling outside)	NEFMC 2003
Nov 2004	Atlantic sea scallop	Framework Adjustment 16	Required VMS for all general category vessels participating in area access programs (half-hour polling)	NEFMC 2004a
Nov 2004	Northeast multispecies	Framework Adjustment 40A	Required VMS for all vessels participating in special access programs and when fishing under the Regular B Days-at-Sea (DAS) Program (hourly polling)	NEFMC 2004b
Oct 2005	Atlantic sea scallop	Framework Adjustment 17	Required VMS for all general category vessels landing more than 40-lb scallop meats (half-hour polling)	NEFMC 2005
Nov 2006	Northeast multispecies	Framework Adjustment 42	Required VMS for all limited access NE multispecies DAS vessels using groundfish DAS (hourly polling)	NEFMC 2006
Jun 2007	Atlantic herring	Amendment 1	Required VMS for all vessels issued a limited access herring permit with the exception of fixed gear permits (weirs and stop seines; hourly polling)	NEFMC 2006
Jan 2008	Atlantic surfclam *Spisula solidissima* and ocean quahog *Arctica islandica*	Framework Adjustment 1	Required VMS for all vessels issued an Atlantic surfclam or ocean quahog permit (hourly polling; note: the action delayed implementation for 1 year following the effective date for vessels issued Maine mahogany quahog limited access permit)	MAFMC 2007
Jun 2008	Atlantic sea scallop	Amendment 11	Required VMS for all vessels issued Atlantic sea scallop permits (half-hour polling)	NEFMC 2008

(Deng et al. 2005; Murawski et al. 2005). Many VMS programs do not require the transmission of instantaneous vessels speeds, only a vessel position and a date and time stamp. This has recently changed in some fisheries (Mills et al. 2007); however, most users of VMS data must infer vessel speed and course from averages calculated from successive positions. Vessel monitoring system regulations for the northeastern USA only require the transmission of the position and the associated date and time. Positions are typically collected once per 30 min from vessels participating in the limited access Atlantic sea scallop fishery and once per 60 min from vessels participating in the groundfish fishery (Table 2). The average vessel speed method can achieve accuracy levels as great as 99%; however, it can also result in the incorrect classification of nontrawling activity (Mills et al. 2007), leading to an overestimation of fishing intensity. Although a more complex method utilizing both vessel speed and directionality has been attempted (Mills et al. 2007), this method did not improve the detection of fishing activity and reduced the inclusion of false positives only slightly (0.7%).

When using the vessel speed method, the amount of classification error is sensitive to the VMS polling rate (i.e., the lower the polling rate, the slower the perceived speed between two positions; Palmer 2008), the speed ranges used to define fishing activity, and the practices of the fishery under observation (e.g., how much overlap exists between the vessel speed signals of fishing and nonfishing activity and how long the individual hauls are). With the exception of Mills et al. (2007), much of the work so far published in the fisheries literature has utilized VMS data without a quantitative assessment of the classification error of fishing versus nonfishing activity when the vessel speed method is used. This paper assesses the ability of the VMS vessel speed method to detect the statistical area fished and allocate fishery landings to stock area by comparing results with matching Northeast Fisheries Observer Program (NEFOP) trips. The method is then applied to assess VTR area reporting compliance and its impacts on the current VTR-based allocation method used in the northeastern USA.

Methods

Data sources.—All analyses used data from calendar year 2005; 2005 data was used because at-sea observer coverage was at a recent high in 2005, thus providing the largest data set with which to perform a validation of the VMS allocation procedure. Trip, gear, and species catch data were extracted from the VTR database and then postprocessed to remove any overlapping trips (i.e., trips taken by the same vessel with a date of sail occurring before the date of landing of a previous trip). Overlaps occur because of VTR reporting errors, data entry errors, or both. This process resulted in the removal of 1.7% of the total reported VTR trips in 2005. Of the remaining trips, only those trips where at least one of the eight study species were reported as retained catch were retained in the data set (Atlantic cod, haddock, yellowtail flounder, winter flounder, windowpane, goosefish, silver hake, and red hake). Because the focus was on assessing the impact of statistical area misreporting on the proration of commercial landings, discards were not included in these analyses. All species weights were converted to live weight in kilograms (kg) using standard species conversion factors established by the Northeast Fisheries Science Center (NEFSC). The VTR data set was further restricted to include only the four major gear types responsible for species landings in the region: bottom otter trawl (OTF), Atlantic sea scallop dredge (DRS), sink gill net (GNS), and benthic longline (LLB). Species landings were then assigned to a stock area based on the statistical area fished reported on the logbook (Palmer and Wigley 2007; Table 1).

All available VMS data were extracted from the VMS database for each vessel and assigned to the appropriate VTR trip by matching on the vessel and assigning all VMS point locations with dates between the VTR date of sailing and the date landed to the respective trip. The average vessel speed was calculated by dividing the haversine distance (Sinnott 1984) by the time difference between consecutive VMS positions. All positions were assigned to a NMFS statistical area (Figure 1).

In the northeastern USA, at-sea fisheries observers are coordinated by the NEFOP. All NEFOP trips which could be matched to the list of VMS-VTR matched trips were extracted from the observer database. Matches were established using the vessel, date of sailing, and date landed as reported on the VTR; trips with multiple matches were removed from the analyses. For all matched trips, the associated haul duration, statistical area fished, species, and retained catch weights were also extracted; retained catch weights were converted to live weight in kilograms using standard NEFSC conversion factors. A summary of the number of matched trips across all data sets is provided in Table 3.

Method development and application.—Past research using VMS data for the northeastern USA have differentiated fishing activity from nonfishing activity by using only upper-speed bounds—less than 6.5 km/h for bottom trawl vessels (Murawski et al. 2005) and less than 9.3 km/h for Atlantic sea scallop dredge

TABLE 3.—Summary of the Vessel Trip Report (VTR), Vessel Monitoring System (VMS), and Northeast Fisheries Observer Program (NEFOP) 2005 data, by number of trips and number of vessels. The VTR subset category include only those trips where the eight target species were reported landed and one of the four target gears was used.

Category	Number of trips	Number of vessels
VTR data set	121,442	2,599
VTR, subset	33,090	1,161
VMS–VTR matched set	9,909	622
NEFOP–VMS–VTR matched set	901	252

vessels (Rago and McSherry 2001). To our knowledge, no attempt has been made to identify fishing activity from the VMS signals of fixed-gear vessels (i.e., sink gill net and benthic longline). We attempted to improve vessel speed classifications and extend the application to fixed-gear vessels through a combination of visual examination of the percent frequency distributions of VMS-derived average speeds, knowledge of fishing operations, and observations from high-frequency polled Global Positioning System (GPS) data.

Percent frequency distributions of VMS average vessel speed were plotted for all gear types (Figure 3). These were then compared with percent frequency distributions of activity-specific (fishing versus nonfishing) instantaneous vessel speeds from high-frequency polled GPS data (1 fix/10 s) collected from vessels involved in NMFS cooperative research projects (Figure 4). These data sets included precise observations of the dates and times of fishing activity. Four trips taken by four separate vessels were analyzed: two groundfish bottom trawl trips, and two Atlantic sea scallop dredge trips. Individual vessel speed observations from all trips were combined by gear type, and activity was classified as either "fishing" or "other." Fishing was defined as the period from winch brake lock to winch brake release, presumably the period when the gear is actually in contact with the bottom. Other activity encompasses all nonfishing activity and can include, for example, steaming, setting the gear, and breakdowns. Unfortunately, cooperative research data were not available for fixed-gear vessels. It is assumed that fixed gears (such as sink gill net and benthic longline gear) are likely to be fished in very

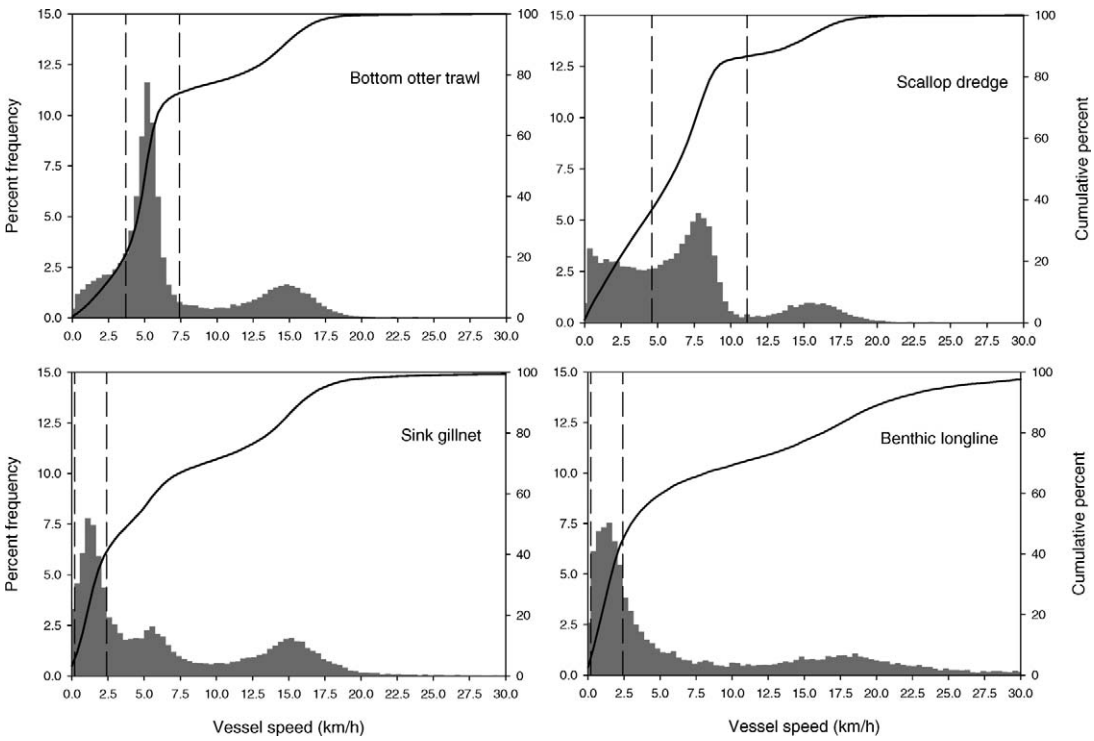

FIGURE 3.—Percent frequency (shaded bars) and cumulative percent distribution (dark lines) of average vessel speed as determined from vessel monitoring system positions for vessels fishing with bottom otter trawls, Atlantic sea scallop dredges, sink gill nets, and benthic longlines. The dashed lines represent the bounds used in this study to define fishing activity (bottom otter trawl = 3.7–7.4 km/h, scallop dredge = 4.6–11.1 km/h, sink gill net = 0.2–2.4 km/h, and benthic longline = 0.2–2.4 km/h).

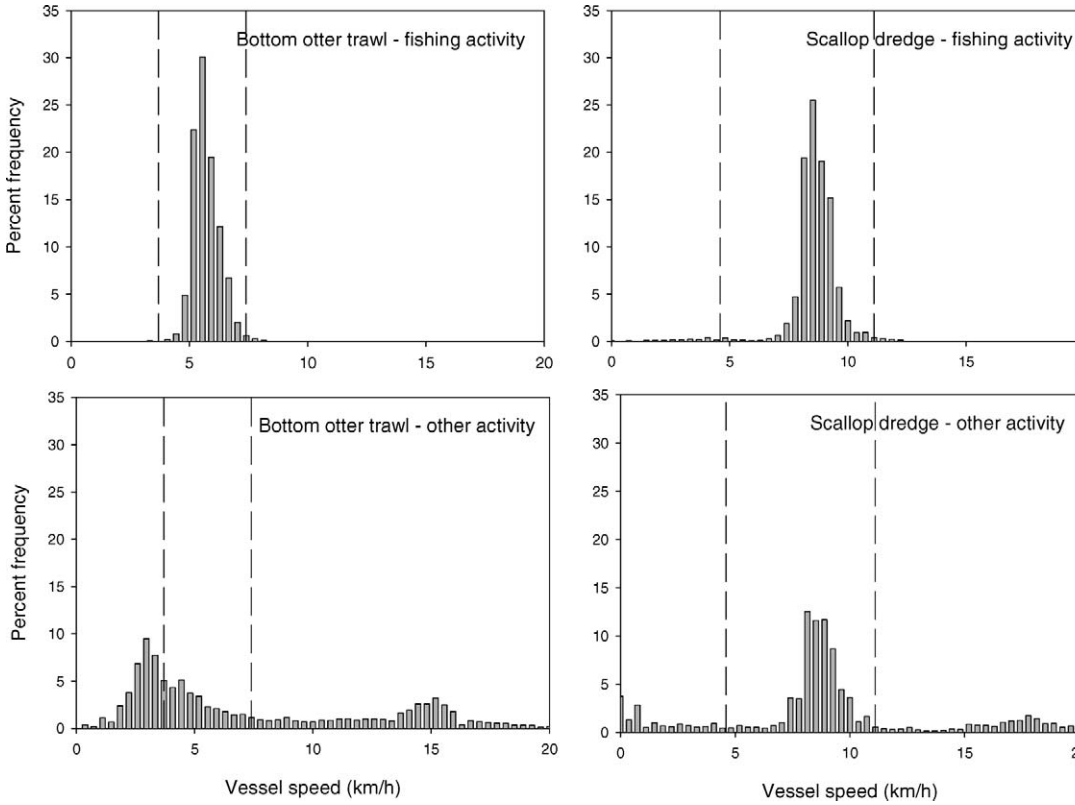

FIGURE 4.—Percent frequency distributions of instantaneous vessel speed of vessels fishing with bottom otter trawl gear and Atlantic sea scallop dredge gear characterized by both "fishing" and "other" activity. These data were collected via high-frequency polling of the vessel's global positioning unit (1 observation/10 s) and represent the aggregate of two separate fishing trips taken by different vessels per gear type. The dashed lines represent the bounds used in this study to define fishing activity (bottom otter trawl = 3.7–7.4 km/h, scallop dredge = 4.6–11.1 km/h).

specific and limited geographic areas on a given trip; thus, it is unlikely fishing is occurring on multiple fish stocks on a single trip. If this assumption is true, these analyses will not be as sensitive to misclassification of fixed-gear activity compared with mobile gear activity.

Otter trawl activity recorded by VMS exhibits a very pronounced bimodal distribution of vessel speeds. It was assumed that the first mode (5.2 km/h) represented fishing activity and the second mode (14.8 km/h) was indicative of steaming activity. Fishing activity falls within a very narrow range from approximately 3.7–9.3 km/h as evidenced by the distributions observed from the high-frequency GPS data. A fishing speed window from 3.7 to 7.4 km/h was used. This window fits the high-frequency polled GPS well, correctly classifying 99.2% of fishing activity. However, it also incorrectly categorizes 31.8% of nonfishing activity as fishing activity (Figure 4). It is expected that a portion of the nonfishing activity falling inside the window of fishing speed represents activity associated with the hauling and setting of the gear, which suggests that the impact of false-positives on statistical area fished estimation may not be as great as the 31.8% value implies.

The VMS-based average vessel speed distribution of Atlantic sea scallop dredge activity has a nearly trimodal distribution (Figure 3). Unlike bottom otter trawl speed distributions, there is a high percentage of activity close to 0.0 km/h. This may be indicative of shucking activity when vessels are drifting and allowing the crew to shuck scallops and clear the deck. The primary mode (7.8 km/h) was assumed to represent fishing activity, and the 13.0 km/h mode was assumed to represent steaming activity. Scallop dredge fishing activity occurs over a broader range than trawl activity, falling between approximately 3.7–13.0 km/h as evidenced by the distributions observed from the high-frequency GPS data (Figure 4). A fishing speed window from 4.6 to 11.1 km/h was used. This window

fit the high-frequency polled GPS well, correctly classifying 98.3% of fishing activity; however, it incorrectly categorized 69.3% of nonfishing activity.

Like Atlantic sea scallop dredge activity, VMS-observed sink gill-net average speeds have a trimodal distribution (Figure 3). Based on personal knowledge of gill-net operations, the first mode (1.1 km/h) was interpreted as representing the hauling of gill-net gear, the second mode (5.6 km/h) as resetting the nets, and the third mode (15.2 km/h) as steaming activity. Benthic longline average speeds have a bimodal distribution (Figure 3). The first mode (1.5 km/h) was interpreted as representing the hauling and setting of the longline gear, and the second mode (18.5 km/h) as steaming to and from the fishing grounds. For both sink gill-net and benthic longline gear, speed bounds from 0.2 to 2.4 km/h were used.

Those VMS locations identified as representative of fishing activity were then used to determine the statistical areas in which fishing occurred. Statistical areas fished were compared across data sources to assess whether the statistical areas derived from VMS-defined fishing activity represented an improvement over VTR-reported statistical areas relative to NEFOP data. Trips were broken into two categories: single area trips (fishing occurs in only one statistical area per trip) and multi-area trips (fishing occurs in more than one statistical area per trip). Because all stock boundaries are divided along statistical area boundaries, correct reporting of multi-area trips are of the greatest concern. These are the trips having the potential to fish on multiple stocks of fish in a single trip and where misreporting of statistical area(s) may lead to incorrect estimates of stock removals. For each trip, the levels of agreement between the NEFOP, VMS, and VTR statistical areas were categorized as in agreement ("complete"), not in agreement ("none") or in partial agreement ("partial," where at least one statistical area was in agreement but not all). Agreement levels were contingent on agreement among both the number of statistical areas reported and the identity of those statistical areas. For example, if a VTR reports that fishing occurred in statistical areas 515 and 521, and VMS positions indicate that fishing occurred in 515 and 521, then the trip would be considered to be in agreement (or complete). If the VTR reported fishing in 515 and the VMS data suggests fishing occurred in 515 and 521, then the trip would be considered to be in partial agreement (or partial). If the VTR reported fishing in 515 and the VMS data suggests fishing occurred only in 521, then the trip would not be considered to be in agreement (or none). The same analysis was repeated on the larger set of VMS- and VTR-matched trips.

A VMS-based allocation algorithm was devised using the statistical areas fished from the VMS data to reallocate VTR-reported landings to stock area. Fishing activity was assigned to stock area based on the species landed and statistical area in which the fishing activity was occurring. The time spent fishing in each stock area was estimated as the sum of fishing activity blocks occurring in each stock area. The duration of one activity block is contingent on the VMS polling frequency, which is variable but generally once per 30 min for Atlantic sea scallop vessels and once per hour for groundfish vessels. Total VTR trip landings for each species (s) were allocated to stock area (k) based on the ratio of time spent fishing in each stock area as determined from VMS locations, that is,

$$\hat{L}_{si} = \left(\sum_i l_{si}\right) \cdot \left(\frac{t_i}{\sum_i t_i}\right), \qquad (1)$$

where $\hat{L}_{si}$ is VMS prorated trip landings for species s in stock area i (kg), l_{si} is trip landings for species s in stock area i as derived from VTR reports (kg), and t_i is time spent fishing in stock area i as derived from VMS positional data (d).

The performance of the VMS- and VTR-based allocations were evaluated by comparing them against the known NEFOP-based allocation. Vessel trip report and NEFOP species landings were prorated by assigning landings to stock area based on the reported statistical area. All comparisons were performed through examination of percent allocation to stock area as opposed to absolute landings because percent allocations derived from the traditional VTR source are used to allocate the amounts of commercial landings as determined through dealer weigh-out data (Wigley et al. 2008). The same analysis was performed on the larger VMS–VTR matched data set.

The VMS-based allocation method assumes a constant species catch per unit effort (CPUE) at all fishing locations (i.e., species catch is distributed only as a function of the time spent fishing in each stock area). This assumption neglects species habitat preferences (e.g., sediment composition, water depth, and temperature) that would result in species being more likely to be caught in some locales and not others. To assess the degree to which VMS stock allocations are affected by this assumption, individual species trip allocations from the VMS method were compared with the same allocations as determined from NEFOP observations using linear regression of the difference between the two stock allocations as a function of the mean (Bland and Altman 1995).

TABLE 4.—Summary of the agreement levels between statistical areas fished recorded by the Northeast Fisheries Observer Program (NEFOP) and the statistical areas fished reported on Vessel Trip Reports (VTRs) from matched fishing trips in 2005. Trip subcategories are based on the NEFOP-reported number of statistical areas fished. Note: percentages may not sum to 100 due to rounding.

Trip category	Number of trips	Agreement level	Number of trips	Percent of total category trips
Single area	490	Complete	462	94.3
		None	27	5.5
		Partial	1	0.2
Multi-area	411	Complete	57	13.9
		None	13	3.2
		Partial	341	83.0

TABLE 5.—Summary of the agreement levels between statistical areas fished recorded by the Northeast Fisheries Observer Program (NEFOP) and the statistical areas fished as determined using Vessel Monitoring System (VMS) positional data from matched fishing trips in 2005. Trip subcategories are based on the NEFOP-reported number of statistical areas fished.

Area category	Number of trips	Agreement level	Number of trips	Percent of total category trips
Single area	490	Complete	431	88.0
		None	1	0.2
		Partial	58	11.8
Multi-area	411	Complete	306	74.5
		Partial	105	25.5

Results

Method Validation Using NEFOP Data

Complete statistical area agreement between NEFOP and VTR was greater than 94% for single-area trips but less than 14% for multi-area trips (Table 4). Nearly all disagreements among the partial multi-area trips matches (337 of 341 trips, or >98%) were due to underreporting of statistical areas (fewer statistical areas reported on the VTR compared with NEFOP). The statistical area agreement between NEFOP- and VMS-based statistical areas was lower (88.0%) for single-area trips than in the NEFOP–VTR comparisons (Table 5). The cause of disagreement among single-area trips is due to the overestimation of statistical areas fished by the VMS-based method. The overestimation results from the VMS-based method misclassifying nonfishing activity as fishing activity. Agreement among multi-area trips was greater when using the VMS method, and there was no complete disagreement among any of the trips. Among statistical areas in partial agreement, there was a tendency for the VMS method to overestimate the number of statistical areas fished (53.3% of partial matches). The performance of the VMS-based method in detecting statistical areas fished is not equivalent for all gear types; a closer examination of the VMS–NEFOP statistical area comparison showed that 80.3% (535 of 666) of trawl trips, 65.4% (17 of 26) of dredge trips, 83.8% (88 of 105) of gill-net trips and 97.1% (101 of 104) of longline trips have agreement levels of complete. This finding supports the assumption that the misclassification of the location of fixed-gear fishing activity is less likely compared with mobile gear activity.

The VMS-based allocation method arrived at annual stock allocations closer to NEFOP allocations relative to the VTR-based allocations for 14 of the 18 stocks examined (77.8%; Table 6). The two species for which the VTR-based allocations were more similar to the NEFOP allocations were Atlantic cod and haddock, though the differences between the VTR- and VMS-based methods were small (±0.6%). Overall, the differences in the allocations between the two methods were small across all species; only goosefish and silver hake exceeded 5.0%. The regression of the differences in the stock allocations between those derived from VMS and those using NEFOP to the mean stock allocations suggest that the VMS stock allocations are robust to the assumption of constant CPUE. The slope of the regression line was not significant ($b_1 = -0.05$, $P = 0.056$, $n = 514$; Figure 5); however, there was considerable spread in the residuals (Figure 5).

There are large differences in the NEFOP landings compared with the VTR landings shown in Table 6 for some species, most notably goosefish (e.g., NEFOP estimated 1,278 metric tons compared with the VTR estimate of 269 metric tons). The exact reasons for these discrepancies are unknown; however, there is a tendency for self-reported hail weights to be biased low (Palmer et al. 2007). Additionally, goosefish tails constitute a large proportion of goosefish landings, and these are often incorrectly reported on VTRs as whole goosefish (Palmer et al. 2007). A conversion factor of 3.32 is applied to goosefish tail landings to convert these to whole weights; incorrect reporting of goosefish tails as whole goosefish will results in the underestimation of VTR goosefish landings by approximately a factor of 3.

Extrapolation to the Larger Vessel Monitoring System–Vessel Trip Report Matched Data Set

The NEFOP–VMS–VTR subset of data used to validate the VMS-based method is relatively small compared with the total population of VTR-recorded trips (Table 3). The validation results suggest that for some trips monitored through VMS, the VMS-based allocation method can be used to gauge the accuracy of the stock allocations as determined through VTR

TABLE 6.—Comparison of the Northeast Fisheries Observer Program (NEFOP), Vessel Trip Reports (VTR), and Vessel Monitoring System (VMS) stock allocations of 2005 commercial landings based on 901 matched trips. Bold italic font is used to indicate which method, VTR or VMS, achieve results closest to NEFOP allocations. Stock area abbreviations defined in Table 1. Allocations may not sum to 100 due to rounding.

Species	Total observer species landings (kg)	Total VTR species landings (kg)	Stock area	NEFOP landings allocation (kg)	VTR landings allocation (kg)	VMS landings allocation (kg)
Atlantic cod	653,066	593,995	GBK	599,457	545,989	541,523
			GOM	53,609	48,006	52,472
Haddock	1,456,503	1,481,989	GBK	1,431,364	1,440,899	1,433,354
			GOM	25,139	41,090	48,635
Yellowtail flounder	780,959	817,279	GBK	758,539	773,181	791,561
			GOM	21,652	23,010	24,687
			SNE	768	21,088	1,030
Winter flounder	548,666	640,737	GBK	463,772	520,883	534,598
			GOM	9,403	26,073	8,308
			SNE	75,491	93,781	97,831
Windowpane flounder	16,477	13,851	NOR	16,460	13,398	13,780
			SOU	16	454	71
Goosefish	1,277,812	268,890	NOR	898,895	166,563	172,457
			SOU	378,917	102,327	96,433
Silver hake	75,370	72,752	NOR	23,266	26,305	26,140
			SOU	52,104	46,447	46,612
Red hake	4,165	3,877	NOR	3,139	2,592	2,769
			SOU	1,025	1,285	1,107

reports. The VMS–VTR matched set is a much larger data set. The subset of VTR reports examined (eight species caught using the four gear types) account for only approximately a quarter of the total VTR reports (Table 3); however, this data set accounts for greater than 98% of the landings of all the study species in 2005 (Table 7). Similarly, VMS coverage is available for only 9,909 of the VTR trips (Table 3), but these trips account for 28.1–92.0% of the total landings of individual species (Table 7). Coverage of goosefish landings is expectedly low because there are no specific VMS requirements for the goosefish fishery. All demersal species examined are primarily caught by the bottom otter trawl fishery except goosefish, where gill-net gear is responsible for the majority of the landings. Gill net is the secondary gear type for all species, except for haddock and silver hake (Table 8).

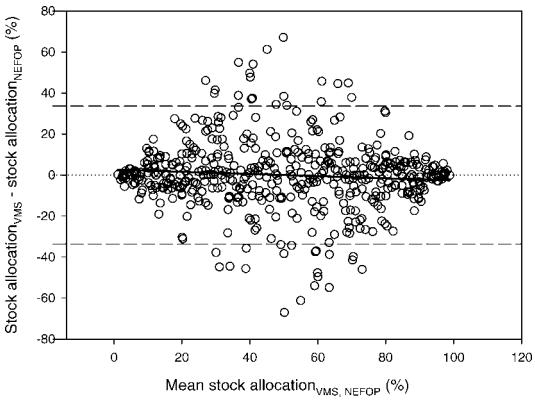

FIGURE 5.—Difference between stock allocations derived from the VMS approach and those derived from observer (NEFOP) data as a function of the mean stock allocation from the two methods. The mean difference across all comparisons (–0.04; dotted line) is shown, along with the 95% confidence intervals about the mean difference (dashed lines). The regression line is shown as a solid line.

Examination of the VTR statistical area reporting using VMS-based statistical areas fished showed patterns similar to those observed in the NEFOP–VMS–VTR comparisons. The agreement level was 93.6% for single-area trips and 6.2% for multi-area trips (Table 9). This level of agreement is less than observed in the NEFOP–VTR comparison. It is unclear whether these lower rates of agreement are due to the overestimation of the number of statistical areas fished by the VMS method, an observer effect (i.e., improved reporting of VTRs when an observer is present), or some other factor. Closer examination of the partial matches revealed that the number of vessels apparently underreporting the number of statistical areas fished was 477 in 2005. Those vessels that frequently underreport trips (more than five trips in a year) are responsible for the majority of the potentially under-reported trips. In 2005, there were 221 vessels in this category, accounting for 2,787 of the 3,837 partial agreement trips (72.6%).

It is important to consider the implications of the matched trip set composition when interpreting the performance of the VMS-based method. The performance relative to the VTR method is contingent upon the gear composition of the matched data set. Those trips fishing on multiple stocks are predominantly

TABLE 6.—Extended.

Species	NEFOP stock allocation (%)	VTR stock allocation (%)	VTR difference (%)	VMS stock allocation (%)	VMS difference (%)
Atlantic cod	91.8	***91.9***	***−0.1***	91.2	0.6
	8.2	***8.1***	***0.1***	8.8	−0.6
Haddock	98.3	***97.2***	***1.0***	96.7	1.6
	1.7	***2.8***	***−1.0***	3.3	−1.6
Yellowtail flounder	97.1	94.6	2.5	***96.9***	***0.3***
	2.8	2.8	0.0	***3.0***	***−0.2***
	0.1	2.6	−2.5	***0.1***	***0.0***
Winter flounder	84.5	81.3	3.2	***83.4***	***1.1***
	1.7	4.1	−2.4	***1.3***	***0.4***
	13.8	14.6	−0.9	***15.3***	***−1.5***
Windowpane flounder	99.9	96.7	3.2	***99.5***	***0.4***
	0.1	3.3	−3.2	***0.5***	***−0.4***
Goosefish	70.3	61.9	8.4	***64.1***	***6.2***
	29.7	38.1	−8.4	***35.9***	***−6.2***
Silver hake	30.9	36.2	−5.3	***35.9***	***−5.1***
	69.1	63.8	5.3	***64.1***	***5.1***
Red hake	75.4	66.9	8.5	***71.4***	***3.9***
	24.6	33.1	−8.5	***28.6***	***−3.9***

(≥99.0%) mobile-gear vessels (Table 10), implying that fixed-gear fishing effort occurs primarily in localized geographic areas such that landings from fixed-gear trips are unlikely to have come from multiple stocks. This supports the prior assumption that the misinterpretation of the VMS speed signals from fixed-gear trips is unlikely to result in the misallocation of landings.

The perceived underreporting of statistical areas in the VTR data led to minor (<1.7%) differences in the overall species allocations (Table 11). These figures are similar to the total proportion of species landings potentially misallocated, which was less than 3.4% for all species years examined. However, these small differences in percent allocation have a disproportionate effect on the less abundant stock such as such as Gulf of Maine haddock, southern New England yellowtail flounder, and Gulf of Maine winter flounder. For these stocks, minor differences in percent allocation can represent large differences (≥5.0%) relative to the percent of the total species landings allocated to that stock (Table 11). These impacts are most notable in the stock allocations of the southern New England–Mid-Atlantic yellowtail flounder. The stock allocation difference between the VTR and VMS methods was 1.3%; however, the small difference in stock allocation percentage translates to a large (61.9%) relative difference in total stock landings. Of the 18 stocks analyzed, seven of the comparisons exhibited greater than or equal to 5.0% relative difference between the VMS-based stock allocation and the VTR-based allocations.

There was a tendency for the VTR method to overallocate the predominant Atlantic cod and haddock stocks (i.e., Georges Bank). For yellowtail flounder, there was a tendency for the VTR method to underallocate the predominant Georges Bank stock and overallocate the Gulf of Maine and southern New England stocks. This trend was generally the same for winter flounder; however, there was a perceived underallocation of VMS-based landings estimate of

TABLE 7.—Species-level summary of the Vessel Monitoring System (VMS) data set and Vessel Trip Reports (VTR) subset compared with total VTR landings (kg) in 2005.

Species	Total VTR landings (kg)	VTR subset (kg)	Percent of total (%)	VMS matched set (kg)	Percent of total
Atlantic cod	5,072,510	4,983,113	98.2	2,754,687	54.3
Haddock	6,198,222	6,155,937	99.3	5,700,737	92.0
Yellowtail flounder	3,925,078	3,922,078	99.9	3,475,993	88.6
Winter flounder	3,473,132	3,457,729	99.6	2,800,639	80.6
Windowpane flounder	81,693	81,532	99.8	45,771	56.0
Goosefish	7,377,131	7,259,875	98.4	2,129,989	28.9
Silver hake	7,526,280	7,522,877	99.9	3,531,069	46.9
Red hake	549,641	547,200	99.6	154,666	28.1

TABLE 8.—Summary of the Vessel Monitoring System (VMS) data subsets compared with the subset of Vessel Trip Reports (VTR) landings (kg), by species and gear type (bottom otter trawl = OTF, Atlantic sea scallop dredge = DRS, sink gill net = GNS, and benthic longline = LLB) in 2005; NA = not applicable.

		VTR			VMS			
Species	Gear type	Number of vessels	Number of trips	Landings (kg)	Number of vessels	Number of trips	Landings (kg)	Percent of VTR landings
Atlantic cod	OTF	381	9,005	3,201,456	229	4,415	2,491,742	77.8
	DRS	8	11	1,209	7	10	100	8.3
	GNS	157	6,711	1,574,496	21	697	164,299	10.4
	LLB	89	1,373	205,952	45	638	98,546	47.8
Haddock	OTF	342	6,471	5,246,396	217	3,670	5,036,560	96.0
	DRS	3	4	15	2	3	14	93.9
	GNS	125	3,054	59,757	15	292	4,494	7.5
	LLB	80	1257	849,769	44	650	659,669	77.6
Yellowtail flounder	OTF	352	7,138	3,815,235	218	3,175	3,473,828	91.1
	DRS	30	45	2,059	28	42	1,883	91.5
	GNS	77	1,180	104,756	5	30	259	0.2
	LLB	5	19	28	3	16	23	83.6
Winter flounder	OTF	413	9,225	3,407,204	229	3,458	2,786,325	81.8
	DRS	37	65	13,237	36	64	12,772	96.5
	GNS	118	2,530	36,739	12	189	1,069	2.9
	LLB	11	84	549	6	66	473	86.1
Windowpane flounder	OTF	158	1,057	80,999	78	227	45,762	56.5
	DRS	0	0	0	0	0	0	NA
	GNS	9	77	523	0	0	0	0.0
	LLB	4	9	10	3	8	9	91.3
Goosefish	OTF	493	9,197	1,857,280	260	3,603	1,359,021	73.2
	DRS	317	2,722	335,072	266	1,498	321,271	95.9
	GNS	246	8,736	5,065,683	34	801	448,437	8.9
	LLB	36	212	1,841	30	182	1,260	68.4
Silver hake	OTF	193	2,689	7,391,321	96	1197	3,489,085	47.2
	DRS	2	2	365	2	2	365	100.0
	GNS	41	255	20,219	1	8	4,400	21.8
	LLB	7	30	110,972	5	20	37,219	33.5
Red hake	OTF	143	1,838	482,879	69	757	152,655	31.6
	DRS	1	1	125	1	1	125	100.0
	GNS	24	239	64,020	2	25	1,810	2.8
	LLB	4	10	176	2	6	76	43.3

the southern New England stock. The VMS-based allocation attributed fewer landings to the minor stocks of windowpane, silver hake, and red hake. There is no obvious predominant stock of goosefish, though in 2005, the VMS-based method resulted in greater landings attributed to the northern stock relative to the VTR-based allocation.

TABLE 9.—Summary of the agreement levels between statistical areas recorded on Vessel Trip Reports (VTR) and the statistical areas fished as determined using Vessel Monitoring System (VMS) positional data from matched fishing trips in 2005. Trip subcategories are based on the VMS-determined number of statistical areas fished.

Trip category	Number of trips	Agreement level	Number of trips	Percent of total category trips
Single area	5,630	Complete	5,267	93.6
		None	334	5.9
		Partial	29	0.5
Multi-area	4,279	Complete	265	6.2
		None	206	4.8
		Partial	3,808	89.0

Discussion

The underreporting of statistical areas on VTR logbooks is a problem that affects a large percentage of the multi-area trips examined. The VTR underreporting rates from this study agree closely with past studies that have used both NEFOP and haul-by-haul self-reported data (Palmer et al. 2007). While the impacts of this underreporting are relatively small in regards to overall stock allocation percentages, the relative impacts on less-abundant stocks such as southern New England–Mid-Atlantic yellowtail flounder can be significant. This is in agreement with the findings of other studies that have examined this issue using more restrictive data sets (A. Applegate and T. Nies, personal communication) as well as those that have considered the implications across several years (Palmer and Wigley 2007). These discrepancies have

TABLE 10.—Frequency of fixed (sink gill net, benthic longline) and mobile (bottom otter trawl, Atlantic sea scallop dredge) gear types used on trips fishing on multiple stocks based on Vessel Monitoring System (VMS) positional data from 2005.

Species	Number of total trips	Number of multiple stock area trips	Percent of total trips	Gear category	Number of trips	Percent of multiple stock area trips
Atlantic cod	5,760	600	10.4	Fixed	6	1.0
				Mobile	594	99.0
Haddock	4,615	562	12.2	Fixed	4	0.7
				Mobile	558	99.3
Yellowtail flounder	3,263	352	10.8	Fixed	0	0.0
				Mobile	352	100.0
Winter flounder	3,777	604	16.0	Fixed	1	0.2
				Mobile	603	99.8
Windowpane flounder	236	24	10.2	Fixed	0	0.0
				Mobile	24	100.0
Goosefish	6,084	511	8.4	Fixed	0	0.0
				Mobile	511	100.0
Silver hake	1,227	28	2.3	Fixed	0	0.0
				Mobile	28	100.0
Red hake	789	8	1.0	Fixed	0	0.0
				Mobile	8	100.0

implications on the estimation of fishery removals and the assessment of these stocks. While the impacts are minimal for the majority of stocks examined, the extent of the impacts on those few stocks that are significantly affected (e.g., southern New England yellowtail flounder) suggests that this is a problem deserving of attention.

Many of the stock assessments of these eight species use finer stratification of commercial landings (e.g., quarter and market category) to estimate the number of fish landed at age for use in age-based assessment models (NEFSC 2008). This paper does not consider the impacts of statistical area reporting patterns on these finer-scale stratifications of commercial landings. The accuracy of finer-scale allocations would be sensitive to the number of multi-area trips included in each strata. It is possible that the effects of statistical area misreporting on stock allocations are reduced due to offsetting errors (i.e., a trip that misallocates 1,100 kg to the Georges Bank Atlantic cod stock would be largely offset by a trip that misallocates 1,200 kg to the Gulf of Maine cod stock). However, the spatial accuracy of VTR reports is critical not only for the assessment of fish species but also of protected species such as sea turtles (e.g., Murray 2004, 2005, 2006; Orphanides and Bisack 2006) and marine mammals (Belden et al. 2006). When these data are used at finer spatial scales, the accuracy of VTR reports becomes increasingly important.

It is important to consider that the results of this study apply only to the trips monitored by VMS. By 2006, trips responsible for more than 70% of the species landings examined were monitored by VMS (Palmer and Wigley 2007). The VMS coverage of some fisheries such as the northeastern U.S. multispecies complex is nearing a census as all vessels are required to have a VMS unit installed when fishing under the Days-At-Sea (DAS) program (NEFMC 2006). The increased coverage improves the utility of VMS data as a validation tool for managers and as a data set of spatial fishing patterns for analysts. The number of vessels responsible for the landings of the eight species examined has remained constant at slightly less than 1,200; however, the number of these vessels monitored by VMS has increased from 38.5% in 2005 to 76.7% in 2006 (Palmer and Wigley 2007).

The VMS-based allocations are sensitive to the accuracy of average VMS vessel speeds in differentiating fishing activity from nonfishing activity as well as the validity of assuming constant CPUE. This study defines fishing activity using narrower speed ranges than have been used in past studies, which should lead to lower estimates of fishing effort. The speed range used for the mobile gears agree closely with the speeds obtained from high-frequency polling of vessels GPS units, suggesting that these ranges are reasonable. However, this study relied on average vessel speeds, not instantaneous vessel speeds, which are more analogous to the speeds estimated from high-frequency GPS polling. The averaging process blurs activity from observation to observation and results in speeds slower than actual speeds (Deng et al. 2005; Palmer 2008). These impacts were not considered in this study and represent an area of uncertainty.

The speed ranges adequately classify fishing activity (>98% success for mobile gear) but tend to overestimate the amount of fishing by incorrectly classifying nonfishing effort as fishing (69.3% misclassification of

TABLE 11.—Results of the Vessel Monitoring System (VMS) based stock area allocation compared with the stock area allocation based on the Vessel Trip Reports (VTR) reported statistical area for 2005. Relative difference is determined as percent difference/VTR stock allocation percentage; allocations greater than or equal to 5.0% relative differences are italicized. Stock area abbreviations defined in Table 1. Allocations may not sum to 100 due to rounding.

Species	Total species landings (kg)	Stock larea	VTR landings allocation (kg)	VMS landings allocation (kg)	Δ landings allocation abs(kg)	Σ Δ_i/total species landings (%)	VTR stock allocation (%)
Atlantic cod	2,754,687	GBK	1,920,110	1,879,800	40,310	2.9	69.7
		GOM	834,577	874,887	40,310		30.3
Haddock	5,700,737	GBK	5,319,329	5,285,374	33,955	1.2	93.3
		GOM	381,408	415,363	33,955		6.7
Yellowtail flounder	3,475,993	GBK	3,115,140	3,164,191	49,051	2.8	89.6
		GOM	286,276	281,958	4,318		8.2
		SNE	74,577	29,844	44,733		2.1
Winter flounder	2,800,638	GBK	1,976,251	1,985,963	9,712	1.4	70.6
		GOM	132,155	112,737	19,418		4.7
		SNE	692,232	701,939	9,707		24.7
Windowpane flounder	45,772	NOR	43,740	44,337	597	2.6	95.6
		SOU	2,032	1,435	597		4.4
Goosefish	2,129,989	NOR	1,188,433	1,223,924	35,491	3.3	55.8
		SOU	941,556	906,065	35,491		44.2
Silver hake	3,531,070	NOR	400,744	380,084	20,660	1.2	11.3
		SOU	3,130,326	3,150,986	20,660		88.7
Red hake	154,666	NOR	39,360	37,097	2,263	2.9	25.4
		SOU	115,306	117,569	2,263		74.6

nonfishing Atlantic sea scallop activity). The overestimation was apparent in the comparisons of statistical areas fished between VMS and NEFOP data (Table 5). Future work should focus on the use of more advanced statistical procedures such as mixture distribution models (e.g., Marin et al. 2005) to decompose the mixed distributions of vessels speed. The fine-scale observations taken from cooperative research vessels could be used to identify likely parameterization of the underlying probability density functions.

Vessel monitoring system data indicate where it is likely that fishing effort is occurring but provide no information on catch composition. A critical assumption of the VMS-based allocation is that the proportion of species caught across multiple stock areas on a fishing trip is only a function of the time spent fishing in each stock area. In the Gulf of Mexico penaeid shrimp fishery, this assumption has generally held true (Cole et al. 2006); however, it may not be appropriate in a multispecies groundfish fishery where the species habitat preference is variable and the target species changes from haul to haul. While the relationship between VMS and NEFOP allocations was significant (suggesting that the method is robust to nonconstant CPUE), there was a considerable amount of variability (Figure 5). The use of groundfish habitat models (e.g., Rooper et al. 2005) could improve the catch allocation used in this paper. The large degree of variability in this relationship is not independent of overestimating the time spent in an area by the VMS method; disproportionate overestimation of time spent fishing in a particular stock area will have a direct effect on the VMS-based allocation.

The various uncertainties and shortcomings of the VMS allocation method point out that this is not a replacement for a VTR-based allocation. Additionally, the low vessel coverage of historical VMS data (Figure 2) limits its use as a tool to correct historical misreporting. The results do show that VMS data can be used as a tool to monitor the accuracy and completeness of VTRs, and guide efforts to improve VTR compliance. The number of vessels which are potentially underreporting statistical areas on a frequent basis is small (<250 vessels) relative to the total number of vessels submitting VTRs (>2,500). Improvements are needed in the compliance of VTR reporting regulations, particularly among those vessels likely to be fishing on multiple fish stocks. Given the manageable size of the problem and availability of tools to monitor these data, the quality of self-reported data should be monitored and improved through targeted outreach and education activities.

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TABLE 11.—Extended.

Species	VMS stock allocation (%)	Difference (%)	Relative difference (%)
Atlantic cod	68.2	1.5	2.2
	31.8	−1.5	*−5.0*
Haddock	92.7	0.6	0.6
	7.3	−0.6	*−9.0*
Yellowtail flounder	91.0	−1.4	−1.6
	8.1	0.1	1.2
	0.9	1.3	*61.9*
Winter flounder	70.9	−0.3	−0.4
	4.0	0.7	*14.9*
	25.1	−0.3	−1.2
Windowpane flounder	96.9	−1.3	−1.4
	3.1	1.3	*29.5*
Goosefish	57.5	−1.7	−3.0
	42.5	1.7	3.8
Silver hake	10.8	0.6	*5.3*
	89.2	−0.6	−0.7
Red hake	24.0	1.5	*5.9*
	76.0	−1.5	−2.0

Legault. Reference to trade names does not imply endorsement by the U.S. Government.

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