Eyes in the Sky: A Comparative Spatial Analysis of Aerial and Satellite Surveillance of East Coast Canadian Oil Pollution

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Abstract

Canada's coastal and offshore ship-source oil pollution monitoring effort chiefly relies on information gathered by two important programs: National Aerial Surveillance Program (NASP) and the Integrated Satellite Tracking of Oil Pollution (ISTOP). The primary goal of this study was to perform a unique comparative and retrospective GIS-based analysis of the spatial pattern of oil pollution for Canada's East Coast for data obtained under three different regimes: (1) visually unaided aerial surveillance (NASP, October 2003 to February 2005); (2) SLAR-assisted aerial surveillance (NASP, May 2007 to May 2008); and (3) RADARSAT-based image processing (ISTOP, April and May, 2006 and continuously from August 2006 to September, 2008). Oiling rates (corrected for search effort) were calculated for 50-km x 50-km grid cells distributed throughout the Territorial Waters and Exclusive Economic Zone (EEZ).

The monitoring programs proved to be spatially complimentary: the NASP surveillance revealed areas of high oil pollution in the vicinity of coastal ports and in areas along the continental shelf break, the inner coast of the Gulf of St. Lawrence, and the area of the Cabot Strait; information from the ISTOP program extended the detection of oil pollution throughout the continental shelf area, revealing relatively high oiling rates off the entire Atlantic coast of Nova Scotia. This study provides insights into Environment Canada's surveillance programs, offers a technique for combining information from different surveillance regimes, reveals current oil pollution "hotspots", and suggests surveillance gaps which could be incorporated within future adaptive management frameworks.

1 Introduction

Detection of ship-source oil pollution is challenging for a number of reasons, including the fact that the marine area is large, and that the probability of detecting oil discharges is low and highly variable. In Canada since 1968, aircraft-borne pollution surveillance has been a central tool used for detecting ship-source oil pollution. Initiated as surveillance over the Ontario region of the Great Lakes as part of the Great Lakes Water Quality Agreement, aerial pollution surveillance was expanded to encompass all Canadian EEZ waters using three dedicated aircraft following the *Nestucca* and *Exxon* Valdez oil discharges in 1988 and 1989 (Transport Canada, 2004), and developed into a national program (National Aerial Surveillance Program or NASP). Pollution surveillance was conducted by unaided visual observation prior to 2006, which is relatively inexpensive (i.e., no remote sensing equipment used) but oil pollution detection was hampered by light availability and other ambient conditions affecting visibility. Highly trained NASP personnel estimate that the range for accurate oil spill detection extends up to approximately 2 nm on either side of the aircraft, under optimal conditions (Transport Canada, 2004). In spite of limitations, unaided visual detection has been and continues to be an important means for confirming oil pollution incidents.

At the federal level, recent legislative changes to the Migratory Bird Convention Act and the Canadian Environmental Protection Act (CEPA) reflect increasing efforts within Canada to manage ship-source oil pollution (Wiese and Elmslie, 2006). These changes include: the incorporation of a clearer definition of legal authority that spans the entire EEZ (extending to the 200 nautical mile mark off the coast of Canada); increased maximum fines (up to $1 million); and a general mobilization of resources to support these legislative changes (i.e., increased surveillance, for example, Wilhelm et al., 2007). In 2006, Transport Canada substantially increased NASP capacity with the purchase of a longer range aircraft for the Pacific region, and the installation of an array of state-of-the-art remote sensing equipment in all aircraft used for oil pollution surveillance in all three maritime regions (Pacific, Atlantic and Arctic; Transport Canada, 2009). Included in this array of instruments is the side-looking airborne radar (SLAR), which greatly enhances the ability of NASP personnel to detect oil discharges by not only extending the detection swath up to 25 nautical miles on either side of the aircraft, but also by allowing for surveillance during periods of low visibility.

As a companion program to assist in the detection of offshore oil pollution, the Integrated Satellite Tracking of Oil Pollution (ISTOP) has been administrated by Environment Canada since 2003. The program utilizes imagery gathered by RADARSAT Synthetic Aperture Radar (SAR) satellite sensors to identify unusual surface features (‘anomalies’) potentially caused by slicks on the ocean surface through expert image analysis. Under appropriate sea conditions, ISTOP-detected anomalies can be identified, documented, and flagged for investigation by the aerial reconnaissance team of NASP.

The primary goal of this study was to perform a comparative and retrospective GIS-based analysis of the spatial pattern of oil pollution for Canada’s East Coast for data obtained under three different regimes: (1) visually unaided aerial surveillance (NASP, October 2003 to February 2005); (2) SLAR-assisted aerial surveillance (NASP, May 2007 to May 2008); and (3) RADARSAT-based image processing (ISTOP, April and May, 2006 and continuously from August 2006 to September, 2008). Oiling rates (corrected for search effort as measured by visitation rate) were calculated for each of these regimes using 50-km x 50-km grid cells distributed throughout the Exclusive Economic Zone (EEZ). A secondary goal was to compare the resulting patterns revealed by the NASP and ISTOP programs to determine the degree of spatial complementarity in measured oil spill intensities, and assess the potential for enhancing the effectiveness of Canadian oil pollution monitoring in general. It is anticipated that the results of this study will help guide pollution monitoring and allow for an assessment of the potential risk to marine organisms in the region.

2 Methods

2.1 National Aerial Surveillance Program (NASP)

2.1.1 Aircraft and Procedures

The area of interest for this study focused on the Gulf of St. Lawrence, surrounding waters of Nova Scotia and the southwest coast of Newfoundland. In maritime Canada, aerial pollution surveillance is primarily conducted using the De Havilland Dash 8 based out of Dieppe, New Brunswick (Transport Canada, 2004). During maritime patrols the aircraft's crew normally consists of two pilots, and two senior technologists (one who acts as the surveillance system operator and the other as an observer). For overnight trips, an aircraft maintenance engineer also accompanies the crew. Occasionally, other observers accompany the mission (Armstrong and Derouin, 2004). Standard operational procedures (see Transport Canada, 2004) call for surveillance to be conducted when winds are < 30 knots, the cloud base is at least 1000 feet, and the horizontal visibility is at least 3 nautical miles (nm). Assuming these conditions are met, visual observation is conducted from 1000 to 1500 feet and remote-sensing monitoring from 5000 to 10,000 feet. Once oil discharges are detected, flight crews are tasked with the assessment of the likely source and documentation of relevant evidence for legal proceedings. In the case of mystery discharges, legal action is not always possible, but the extent and disposition of the pollution, as well as proximity to items of interest, is still documented. Regardless of actionability, however, all pollution cases are subjected to the same procedures and all evidence is captured and maintained in the event of possible future use. Furthermore, if oil is detected near areas of concern, appropriate response agencies are notified.

It should be noted that aerial surveillance, concentrated in Newfoundland offshore waters, is also conducted by Provincial Airlines (PAL). We did not have access to flight track information for this surveillance program.

2.1.2 Unaided Visual (Pre-SLAR) Surveillance

Information was available for 112 pre-SLAR flights flown between October, 2003 and early February, 2005 when detection of oil discharges was reliant on visual detection by trained human observers. Transport Canada (2004) identified two key limitations of direct (naked-eye) pollution surveillance: restriction to daytime operations and a narrow swath of 2-nm on either side of the aircraft for detecting oil. Pollution reports were provided in the form of Microsoft Word documents. Because aircraft position is archived temporarily by the CCGAir system (Armstrong and Derouin, 2004), we were unable to acquire digital flight path records. Therefore, flight paths were generated by manually georectifying digital flight maps that appeared as images appended to the Word documents. This allowed us to produce ESRI-proprietary format shapefiles, which could be analyzed within ArcGIS 9.3 (Environmental Systems Research Institute, 2008).

2.1.3 Side-looking Airborne Radar (SLAR) Surveillance

Between May, 2007 and May, 2008 information was available for 221 SLAR flights equipped with the MSS6000 maritime surveillance system. This system includes a SLAR, which is a fixed-antenna radar capable of sending pulses to either side of the aircraft that can be used to detect ocean surface feature anomalies possibly caused by oil slicks on the water surface, as well as other devices useful for discriminating different types of oil (e.g., an IR/UV line scanner). Not only does SLAR surveillance permit night-time operations (or operations in conditions of limited visibility), but it allows for a greatly extended detection range of 25-nm on either side of the aircraft (Armstrong, 2004). SLAR-era pollution reports were made available in the form of

Microsoft Excel spreadsheets which were parsed by a research assistant and imported into a database. Some flight paths for the SLAR-era surveys were obtained using an archival web-based interface ("Skytrax") owned by Transport Canada, and exported to ESRI shapefiles. Pollution report records, for both surveillance methods, included information about flight number, flight date, spill date and time, position (latitude and longitude), as well as the estimated volume of the spill.

2.2 Integrated Satellite Tracking of Pollution (ISTOP) Program

The ISTOP program relies on RADARSAT-1 ScanSAR N (narrow beam mode, nominal resolution of 50-m), and is capable of detecting anomalies greater than 50-m in size (but more likely ≥ 200-m). Images are subjected to expert analysis and, with favourable sea state conditions, may lead to the identification of slick-like anomalies on the surface of the ocean. Many features in the ocean scene resemble oil pollution (e.g., natural films, ship wakes, new or 'grease' ice) and can lead to false positive detections of oil, which is why contextual information and shape is important (e.g., sea state, synoptic weather conditions, or a nearby ship or platform). To account for the analyst's degree of confidence in classifying an anomaly as an oil 'slick', a 'confidence code' is assigned at the time the image is analyzed. Categories '1A', '1B' and '2' indicate: possible oil with a target clearly associated, possible oil with a target within 50-km, and possible oil but without an identifiable source, respectively. Category '3' anomalies constitute probable oil, but with a subjectively determined level of confidence of less than 75%. For the purposes of this analysis, only categories 1A, 1B and 2 were utilized, and for the period April, 2004 to March, 2011 we had ground-truthed validation for 26 anomalies.

We had access to 3060 RADARSAT-1 image outlines describing the location and extent of each image from June 2003 until the end of September, 2008. It was not necessary to use the raw imagery for this analysis; rather, image outlines were collected as GIS layers in order to quantify search effort. The 3060 GIS polygons were obtained from the Canadian Ice Service and Radarsat International (now MDA – Geospatial Services). Additionally, a separate, digitized (GIS polygon) layer was obtained consisting of anomalies observed over the same time period.

2.3 GIS-Based Data Processing

Each flight path (with a buffer area surrounding it of either 2-nm or 25-nm depending on whether it was pre- and post-SLAR surveillance) and RADARSAT image was intersected with a 50-km grid file of the study area so that the total area surveilled and number of flight paths/images within each grid could be calculated. The same procedure was applied for the oil discharge events (NASP data) and anomalies (ISTOP data) to calculate the number of oil events/anomalies per grid.

2.4 Calculation of Oil Loading and Encounter Rate

To account for variation in search effort, we adopted a similar approach to Serra-Sogas et al. (2008) and calculated a standardized oil loading measure:

$$\text{Oil Loading}_i = \text{Number of oiling events}_i \,/\, \text{number of surveys}_i \tag{1}$$

for each 50-km x 50-km grid cell, *i* (738 in total).

ESRI software (Environmental Systems Research Institute, 2008) and Hawth's Analysis Tools version 3.27 (Beyer, 2004) was used to tabulate both the number of oil discharge events, as well as the number of flight paths or images that occurred in each grid cell. Encounter rate was defined as the number oil discharges encountered per surveillance flight.

3 Results

3.1 Analysis of Survey Effort

Pre- (Fig. 1a) and post-SLAR (Fig. 1b) surveys were generally concentrated along near-shore regions (e.g., the Northumberland Strait region of the Gulf of St. Lawrence or the Eastern shore of Nova Scotia) and along main shipping routes (such as that between the St. Lawrence estuary and the Cabot Strait). The latter was consistent with NASP policy, which deliberately concentrates search effort in commercial shipping lanes (Transport Canada, 2004). There was a greater concentration of SLAR-era flights in the Gulf of St. Lawrence and Cabot Strait (Fig. 1b), and a wider spatial coverage in such offshore regions as Sable Island. To a limited extent, some NASP surveillance fell outside of our study area and over the south-west coast region of Newfoundland, but this region is normally patrolled by a different aircraft (contracted from Provincial Airlines Limited). The average distance traveled during single surveillance flights was 1577.4 km ± 32.9 km SE (median = 1590.4 km).

In addition to differences in the number of flights flown, the wider detection window of the SLAR-enabled aircraft meant that regions benefited from many more overlapping patrol swaths. We define a ‘patrol’ as that portion of an individual flight that occurs within a given survey region. On average, approximately 16 times as much area was surveyed by aircraft equipped with SLAR technology compared to aircraft without.

The ISTOP program revealed a markedly different pattern in the allocation of surveillance effort (Fig. 1c), with the bulk of the images concentrated in waters off the south and south-east shore of Newfoundland.

3.2 Spatial Patterns in Oil Loading and Encounter Rates

Patterns in oil loading depended heavily on the monitoring regime employed. Consideration of Figure 2 reveals that during the pre-SLAR period, oil loading was primarily confined to near shore areas, particularly in the vicinity of busy coastal ports (Fig. 2a). Following the introduction of the SLAR equipment, however, detections occurred throughout the Gulf of St. Lawrence and further offshore (Fig. 2b). The ISTOP program suggested that oil loading (derived from image anomalies) was variable but widespread throughout the continental shelf area off the coasts of Nova Scotia and Newfoundland (Fig. 2c). There were also more cells with relatively high oil loading beyond the continental shelf break.

In terms of encounter rate, eighty-four small-scale oil discharges were detected out of 333 surveillance flights, resulting in an estimated 0.25 discharges per flight. This is somewhat lower than the encounter rate for the west coast of British Columbia (271 out of 786 surveillance flights, or 0.34 discharges per flight; see Serra-Sogas et al., 2008). Overall, detection rates for SLAR-enabled flights (66 / 221, or 0.30 oil discharges / flight) were nearly twice as high as that of unaided flights (18 / 112, or 0.16 oil discharges / flight). Detection rate (per image) for ISTOP anomalies was 0.045 (139 / 3060 images).

Ground-truthed information for 26 anomalies are presented in Table 1. For category ‘1A’ anomalies, 29% (2/7) were subsequently confirmed to be oil, while 8.3% (1/12) and 25% (1/7) of category ‘1B’ and ‘2’ were confirmed to be oil, respectively. The percent positive agreement between these classes of anomalies and subsequent confirmation as oil pollution was an average of 15.4% (weighted by sample size).

As a final step, we integrated the results of each of these programs by calculating a weighted average of the oil loading scores for each grid cell, applying weightings on the basis of the oil spill identification accuracy of each of the surveillance regimes (Fig. 2d). We equally weighted pre-SLAR and post-SLAR aerial surveillance, but down-weighted the ISTOP loading to reflect the greater uncertainty about the status of its anomalies. This resulted in relative weightings of 0.465, 0.465, and 0.07 for pre-SLAR, post-SLAR and ISTOP, respectively. The combined surface nicely summarized the previous insights into Atlantic oil pollution, revealing that oil pollution is highest in the vicinity of coastal ports, but also in areas along the continental shelf break, the inner coast of the Gulf of St. Lawrence, and the area of the Cabot Strait. Information from the ISTOP program appeared to extend the detection of oil pollution throughout the continental shelf area, filling in some of the gaps in surveillance coverage.

4 Discussion

An initial goal of this study was to determine the level of agreement between oil pollution and surface feature anomalies detected under the NASP and ISTOP programs, respectively, but it quickly became apparent that in addition to differences in the surveillance method, each monitoring regime focused on different geographic regions. Each regime appeared to provide different information about oil pollution, gathered under different conditions, and may even have exposed different point sources and types of spills.

Evidence from this study can be used to test two hypotheses: SLAR technology significantly enhances the ability of NASP aircraft to detect oil pollution, and that ISTOP, by relying on satellite imagery, can efficiently gather information over larger areas than airborne monitoring due to its wide and synoptic view of the offshore zone. In the case of the first hypothesis, we showed that SLAR greatly improved the effectiveness of the NASP: SLAR-based survey patrols sampled about 16 times as much area and detected nearly twice as many oil discharges per flight as naked-eye surveys (0.30 vs.0.16 oil events/flight).

With regards to the second hypothesis, ISTOP monitoring detected additional potential oiling events throughout the maritime continental shelf. These differences can be partially attributed to the fact that the ISTOP and NASP programs are conducted at different spatial and temporal scales. In maritime Canada, NASP monitoring is concentrated within the Gulf of St. Lawrence and maritime coastal zone, and conducted during daylight hours. NASP monitoring is highly effective at detecting even the smallest quantities of oil (< 1 Litre), particularly in the vicinities of ports and coastal zones. In contrast, the radar imagery used by ISTOP covers a much larger area, extends well offshore, and also imagery acquired at night.

An important limitation of a purely imagery-based detection approach is a limited capacity for ground truthing and a tendency towards false positive detections. In this study we presented a weighted combination of the results of the two monitoring programs under the assumption of a 15% accuracy for ISTOP anomalies (Fig. 2d), but this could be easily modified if subsequent information were available to justify a different choice of weighting.

Clearly, aerial and satellite surveillance is a key component in the overall programme for managing oil pollution, and has the potential to deter would-be polluters. But there are other partners in oil pollution mitigation, including: port-side inspections, facilities for petroleum disposal, and the imposition of heavy fines for violations (Marine Transport Committee, 2003; Wiese and Ryan, 2003). Marine oil pollution is a complex issue, which we expect to be result from the interaction between operator behaviour, vessel type and fear of enforcement and prosecution. For this reason, the spatial distribution of oil pollution will be equally dynamic and in need of continuous analysis and evaluation. Under changing conditions (both spatially and temporally), we expect oil pollution management will be most effective when it can incorporate current oil pollution information within an adaptive framework.

5 Acknowledgements

We acknowledge the financial support of the Environmental Damages Fund of Environment Canada, the Science Horizons Youth Internship Program of Environment Canada, and the Marjorie Young Bell Faculty Fund of Mount Allison University. We thank H. O'Neill, L. Armstrong for reviewing and commenting on earlier drafts of the manuscript. We also thank: A. Miller for GIS data management and analysis while a Science Horizons intern; K. Derouin, S. Leger, M. McGregor and Y. Sivret for assisting with NASP flight data; J. Hurley and R. DeAbreu for assisting with ISTOP data; and N. Serra-Sogas for statistical advice.

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Table 1. Ground truth results for 26 ISTOP anomalies detected between April, 2004 and March, 2011.

Category	Number Validated	Confirmed Oil = Yes	Confirmed Oil = No	Agreement (%)
1A	7	2	5	29
1B	12	1	11	8.3
2	7	1	6	25

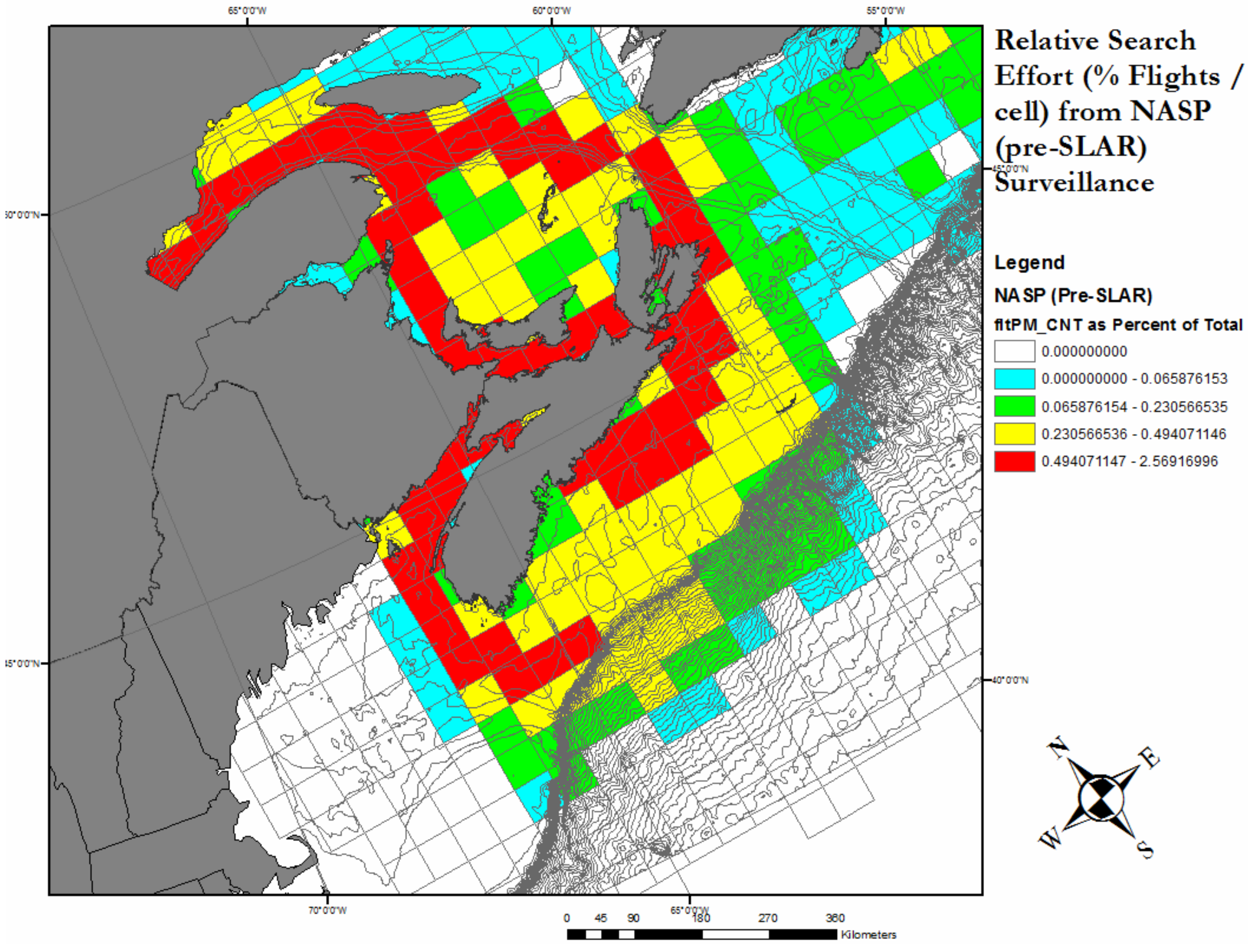

Figure 1a **Regional comparison of surveillance effort (percentage of the total number of surveillance events in all grid cells, for each cell) for the NASP program, unaided visual surveillance (pre-SLAR)**

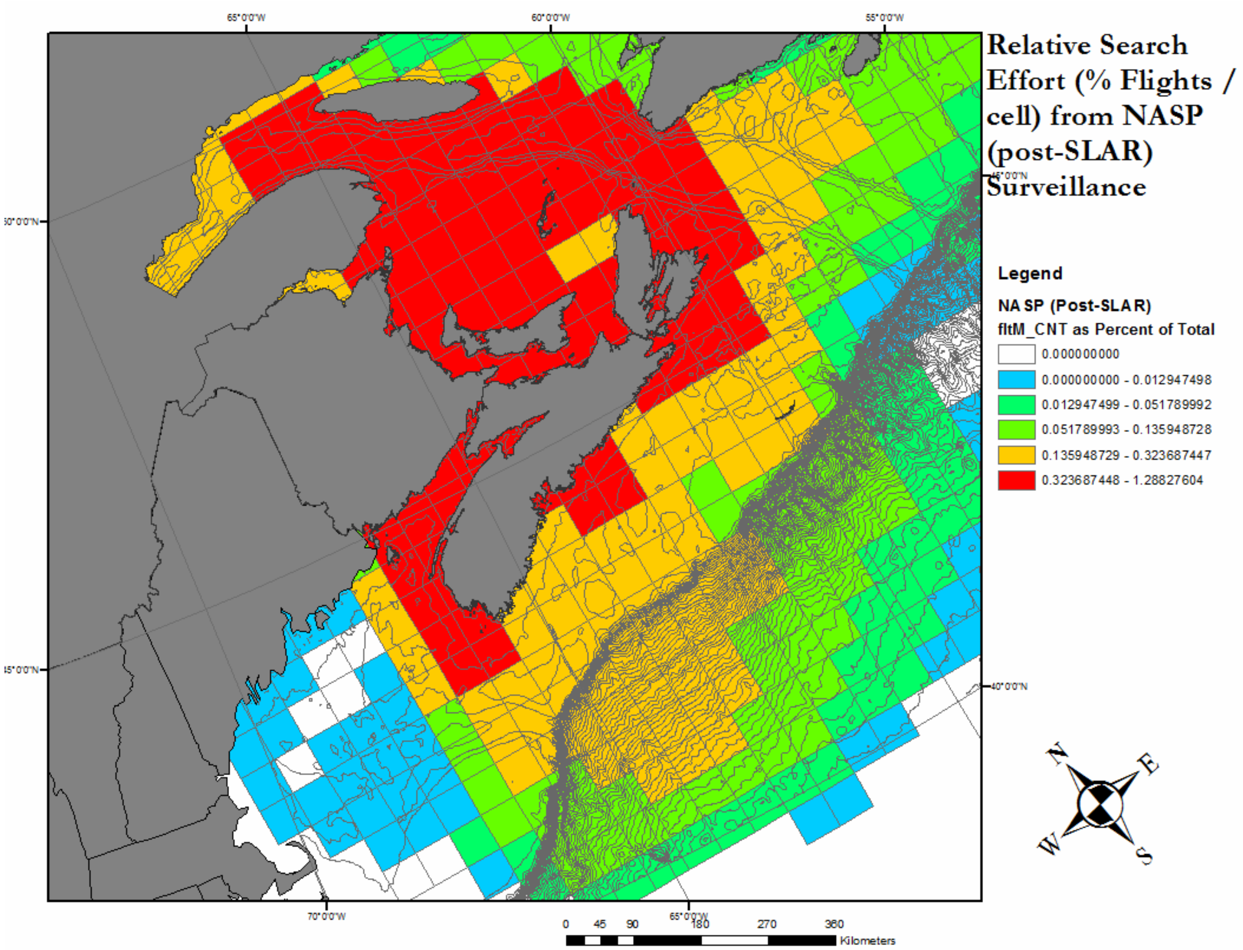

Figure 1b **Regional comparison of surveillance effort (percentage of the total number of surveillance events in all grid cells, for each cell) for the NASP program, SLAR-aided surveillance**

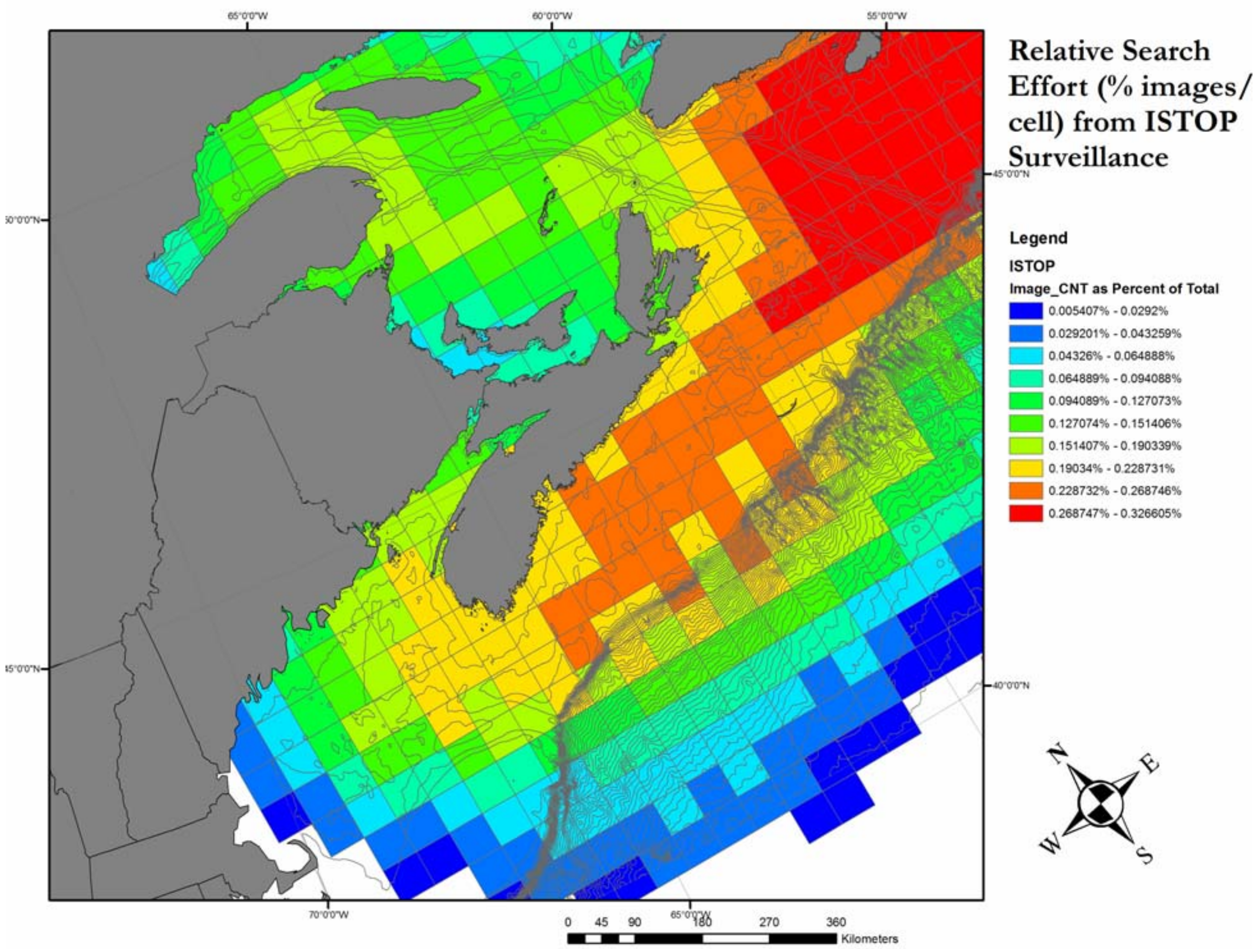

Figure 1c **Regional comparison of surveillance effort (percentage of the total number of surveillance events in all grid cells, for each cell) for ISTOP surveillance (based on Radarsat-1 imagery)**

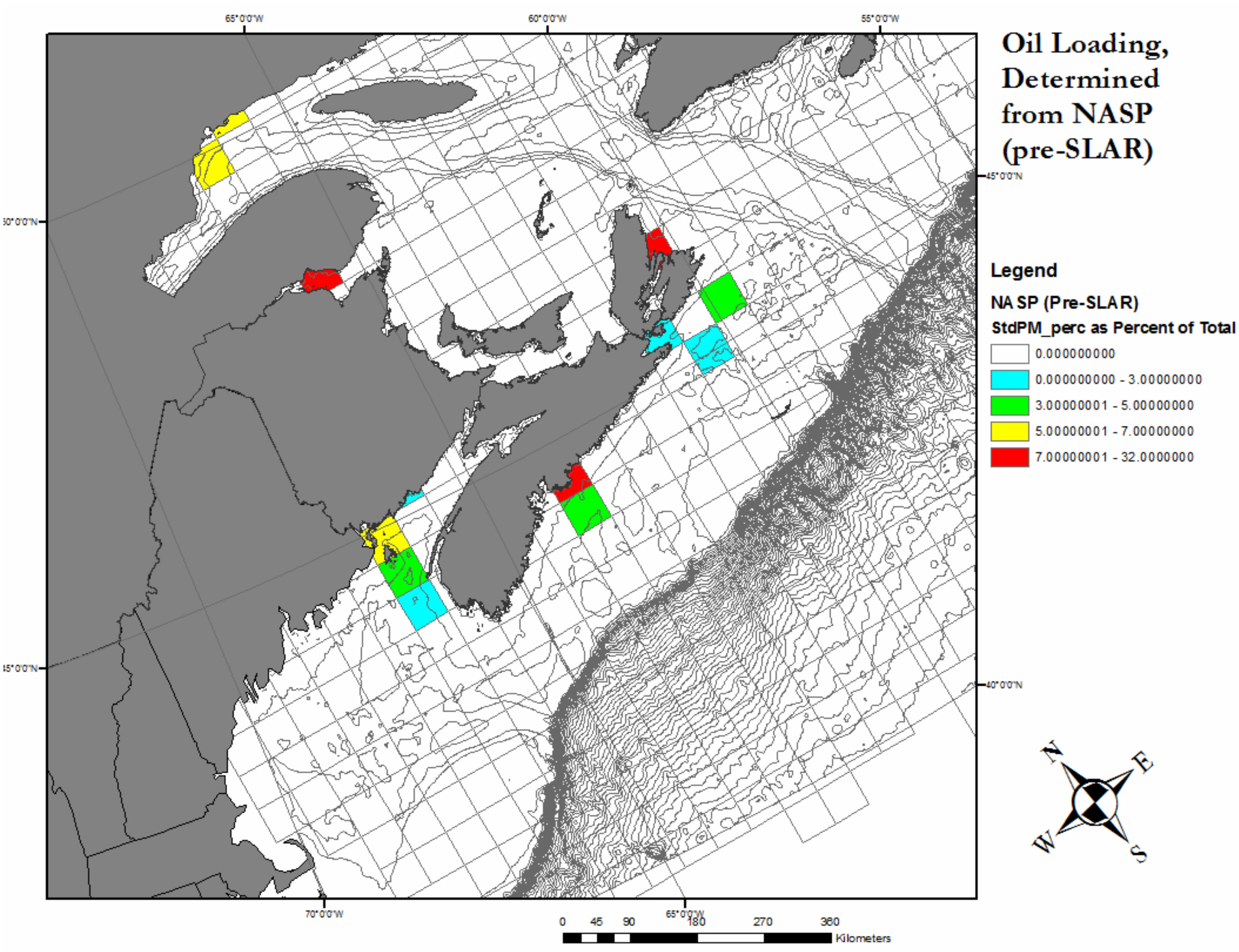

Figure 2a Regional comparison of oil pollution loading as determined by the NASP program, unaided visual surveillance (pre-SLAR)

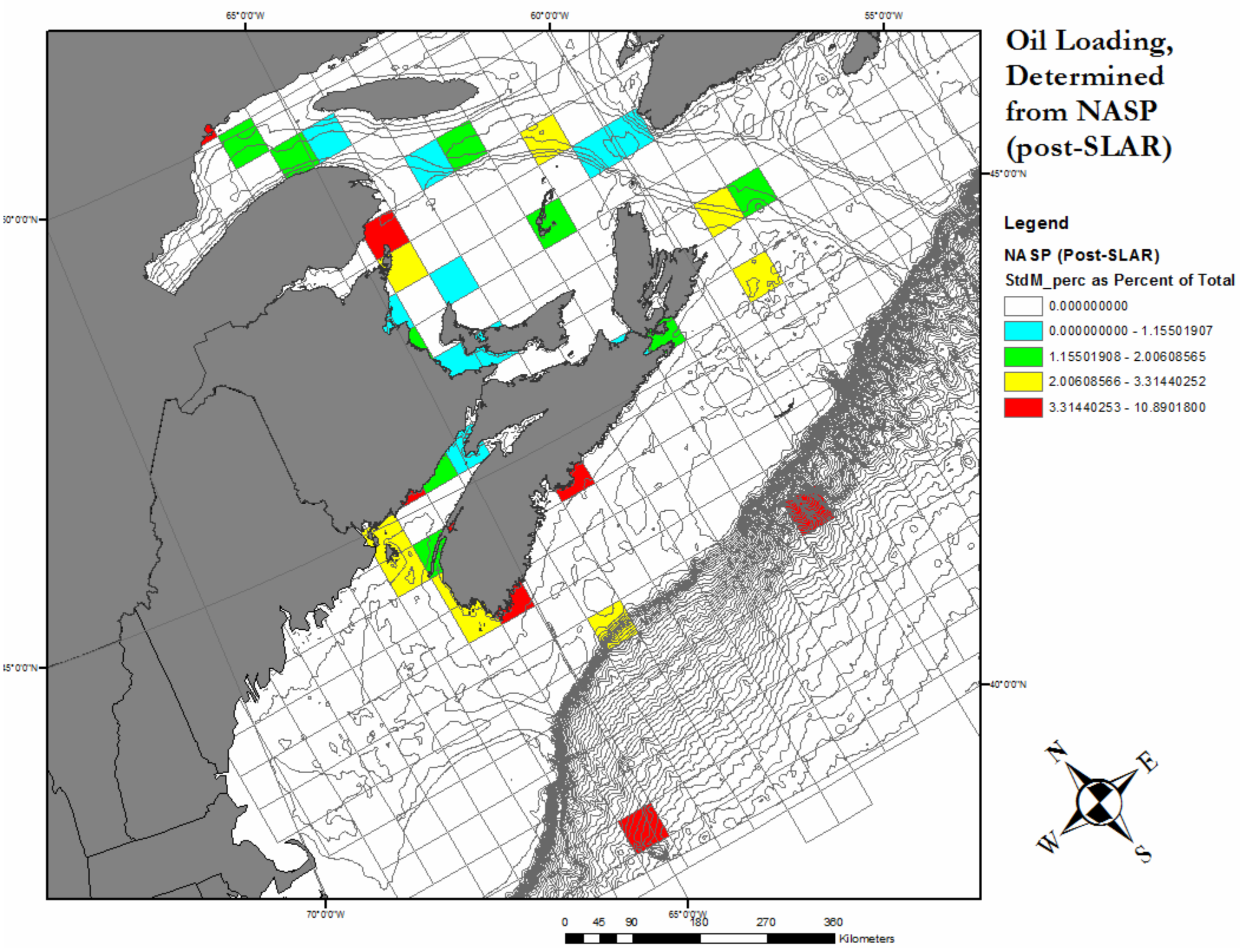

Figure 2b Regional comparison of oil pollution loading as determined by the NASP program, SLAR-aided surveillance

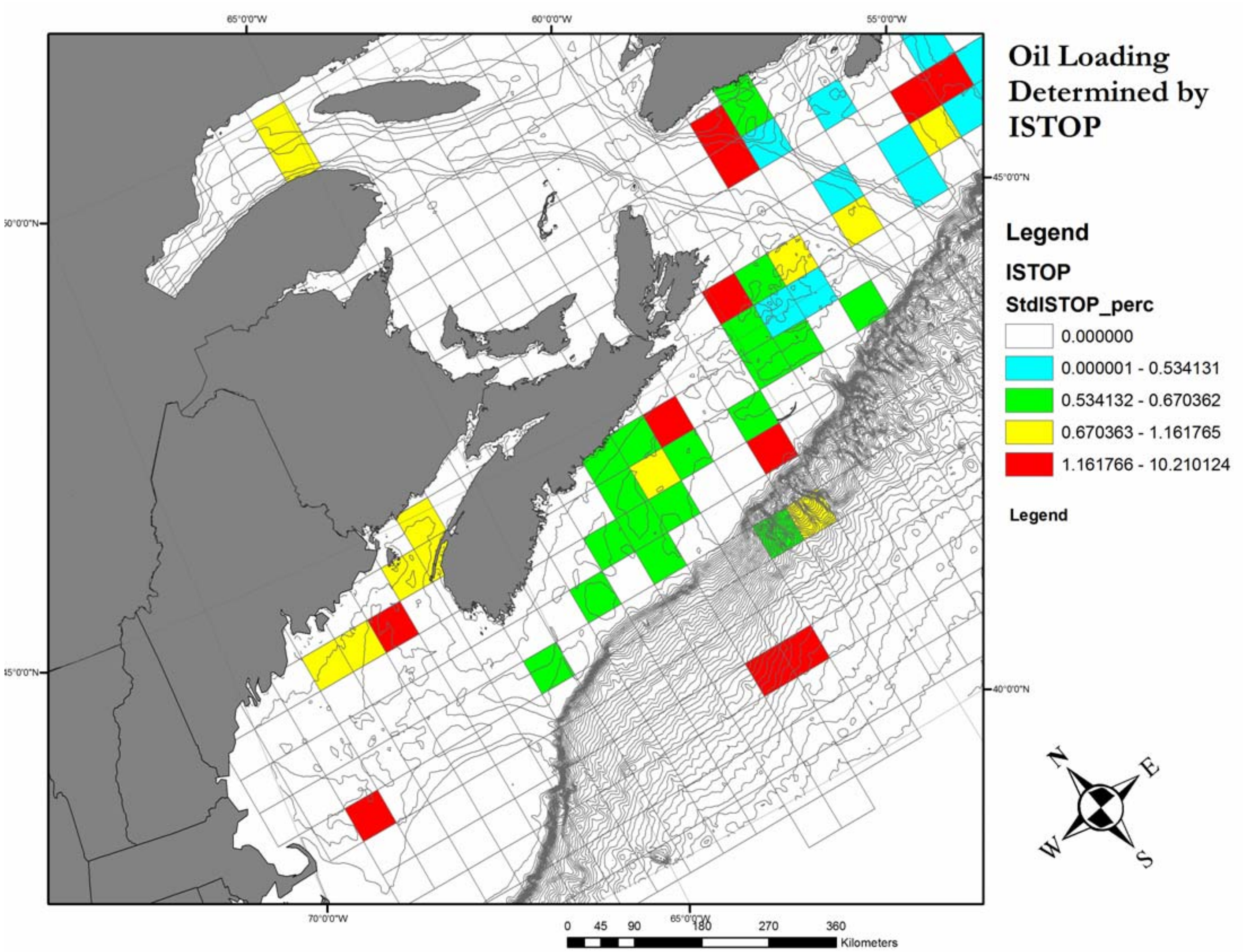

Figure 2c Regional comparison of oil pollution loading as determined by ISTOP surveillance (based on Radarsat-1 imagery)

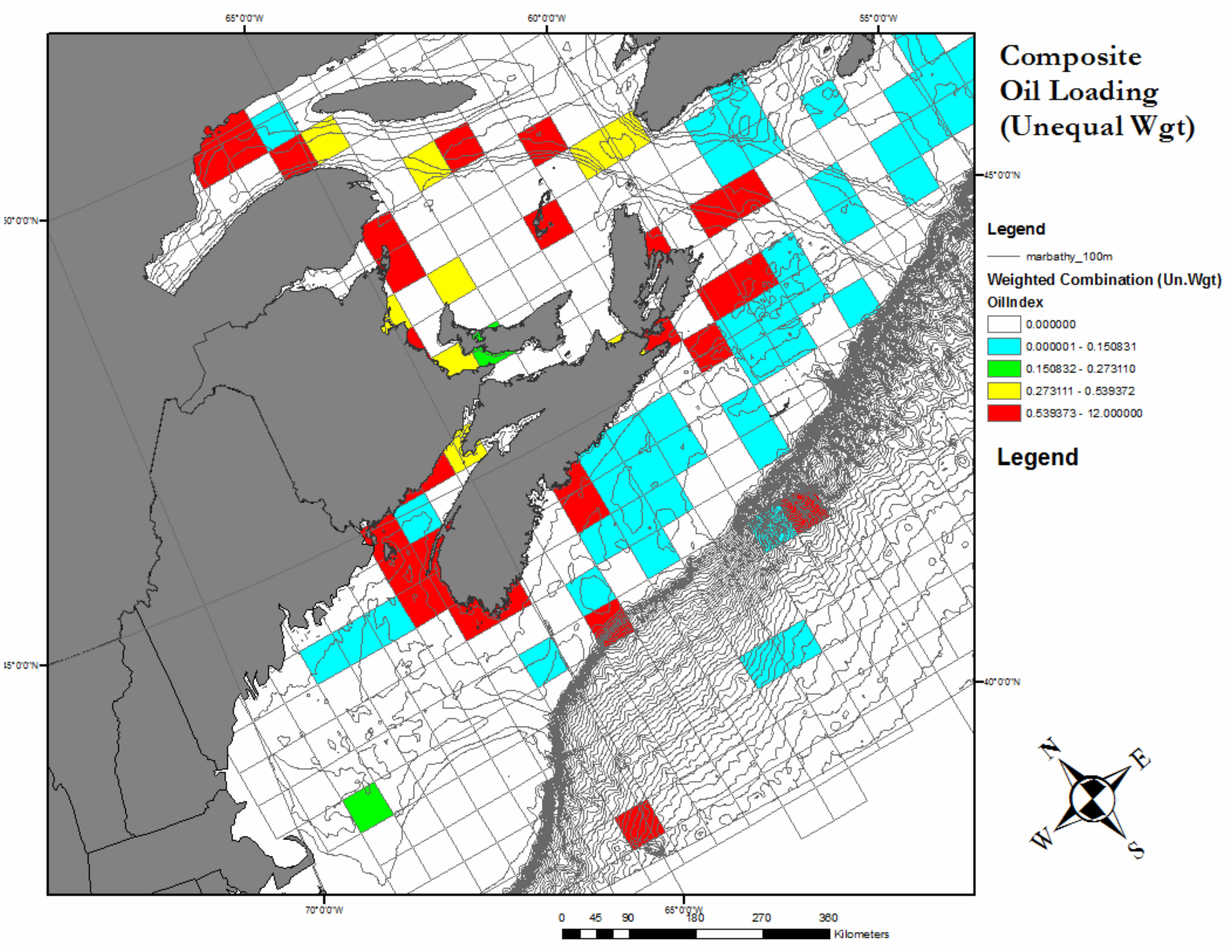

Figure 2d Regional comparison of oil pollution loading as determined by the composite derived from the unequally-weighted average of figures 2a, 2b and 2c