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MercNet: a national monitoring network to assess responses to changing mercury emissions in the United States

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Abstract A partnership of federal and state agencies, tribes, industry, and scientists from academic research and environmental organizations is establishing a national, policy-relevant mercury monitoring network, called MercNet, to address key questions concerning changes in anthropogenic mercury emissions and deposition, associated linkages to ecosystem effects, and recovery from mercury contamination. This network would quantify mercury in the atmosphere, land, water, and biota in terrestrial, freshwater, and coastal ecosystems to provide a national scientific capability for evaluating the benefits and effectiveness of emission controls. Program development began with two workshops, convened to establish network goals, to select key indicators for monitoring, to propose a geographic network of monitoring sites, and to design a monitoring plan. MercNet relies strongly on multi-institutional partnerships to secure the capabilities and comprehensive data that are needed to develop, calibrate, and refine predictive mercury models and to guide effective management. Ongoing collaborative efforts include the: (1) development of regional multi-media databases on mercury in the Laurentian Great Lakes, northeastern United States, and eastern Canada; (2) syntheses and reporting of these data for the scientific and policy communities; and (3) evaluation of potential monitoring sites. The MercNet

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approach could be applied to the development of other monitoring programs, such as emerging efforts to monitor and assess global mercury emission controls.

Keywords Mercury · MercNet · Ecological effects · Mercury regulation · Monitoring

Introduction

The mercury problem and the need for monitoring

Mercury (Hg) is a pervasive toxic metal of significant public health and ecological concern. The consumption of contaminated fish is the primary pathway of exposure for methylmercury (MeHg), the most bioaccumulative form of Hg in humans and wildlife (Mergler et al. 2007; Scheuhammer et al. 2007). Moreover, a growing body of recent research highlights the importance of terrestrial exposure pathways and impacts of MeHg on terrestrial food webs (Evers et al. 2005; Cristol et al. 2008; Wada et al. 2010). MeHg concentrations in fish and other biota commonly exceed dietary thresholds considered potentially harmful to humans and piscivorous wildlife throughout much of the United States and beyond. MeHg contamination has adversely affected the benefits derived from fishery resources in many of the nation's inland and coastal waters. In 2008, fish consumption advisories for (methyl) mercury existed in all 50 states and in many tribal lands, including several states with blanket advisories (U.S. EPA 2009a; Fig. 1). The consumption of fish with elevated MeHg can cause deleterious health effects in humans ranging from neuro-developmental and behavioral deficits in children to increased risk of cardiac disease (e.g., myocardial infarction) in adults (Mergler et al. 2007). Elevated concentrations of Hg in wildlife, including piscivorous fish, birds, and mammals, are linked to multiple adverse effects including decreased reproductive success, altered immune systems, behavioral and hormonal changes, physiological and neuro-chemical impairments, and damage to cells and tissues (Braune et al. 2006; Scheuhammer et al. 2007; Evers et al. 2008a; Frederick and Jayasena 2010; Sandheinrich and Wiener 2011). Human and wildlife exposure to MeHg through consumption of contaminated fish or other biota may be enhanced through nearby emissions sources or the sensitivity of landscapes to atmospheric Hg deposition (Wiener et al. 2003; Evers et al. 2007), underscoring the importance of local and regional Hg emissions to deposition impacts. In addition, Hg contamination of aquatic ecosystems distant from direct releases of Hg into the environment also demonstrates the importance of long-range Hg transport and deposition (Fitzgerald et al. 1998; Burgess and Meyer 2008).

Existing and anticipated regulations target the control of Hg emissions from major source categories. The expected outcome is a decrease in MeHg exposures across the U.S. The anticipated control of Hg emissions from coal-fired power plants, the largest current source of anthropogenic Hg in the U.S., and the cross-media, multi-scale effects of atmospheric Hg have led scientists to propose a cohesive national framework to monitor and assess ecosystem responses to changes in atmospheric Hg (Mason et al. 2005; Harris et al. 2007; Evers et al. 2008b). Existing Hg monitoring capabilities are not sufficient to provide accurate, comprehensive and quantitative assessments of long-term changes in Hg deposition, its transformation to MeHg, and bioaccumulation and biomagnification in food webs in diverse ecosystems across the U.S. In some areas, spatial and temporal gaps in existing Hg monitoring data may hamper the assessment of responses to future emission controls.

The capability of state, federal, and international agencies to adequately demonstrate the benefits and effectiveness of actions to decrease the risk of Hg exposure to humans and wildlife will require a robust, multi-media environmental monitoring and assessment program. Such a program would not only inform policy and management decisions about whether further controls in Hg emissions are warranted to decrease risks, but also quantify the effects of emission control policies.

Despite recent progress in developing capacity to monitor Hg in the atmosphere (NADP 2009), a coordinated multi-media Hg monitoring program that can systematically and quantitatively relate changes in Hg concentrations in biota and food webs to atmospheric Hg emissions and deposition does not exist. Systematically monitoring Hg in the atmosphere without a commensurate linked program to track atmospherically deposited Hg through the complex series of pathways and processes within an ecosystem will greatly reduce confidence in understanding source-receptor relationships (Wiener et al. 2006; Driscoll et al. 2007a). A holistic, multi-media monitoring program would provide policy makers and natural resource managers with a quantitative assessment of the effectiveness of emission control programs.

U.S. Hg emissions and regulation

In the U.S., an array of federal and state regulations governs the release of anthropogenic Hg to the atmosphere from major source categories; the proportion of source types can vary greatly among states (Fig. 2). During the past 15 years, anthropogenic Hg emissions in the U.S. have declined substantially. The total anthropogenic Hg emitted annually in the U.S. in 2005 was 101 tons (U.S. EPA 2005a, b; Table 1). This represents a decrease from 246

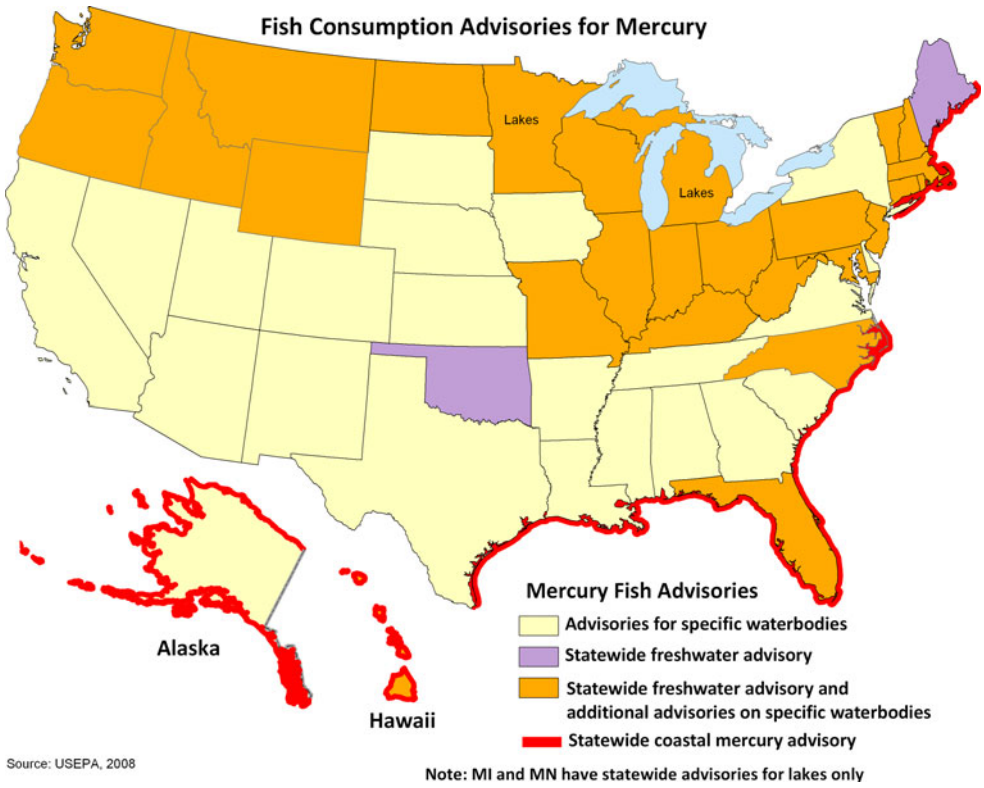

Fig. 1 Map showing fish-consumption advisories for Hg in the U.S. from the 2008 National Listing of Fish Advisories

tons emitted in 1990 (U.S. EPA 2000) and has been attributed largely to controls installed on municipal waste combustors and medical waste incinerators (Butler et al. 2008). Point sources are distributed across the U.S., and the magnitude of anthropogenic emissions varies widely (Fig. 3). Much of the anthropogenic Hg emitted in the U.S. originates from fossil-fuel combustion. Coal-fired power plants (utility coal boilers) across the U.S. emitted 52.3 tons of Hg to the atmosphere in 2005 and are the largest single source of anthropogenic Hg emissions, followed by other boilers, cement manufacturers, and electric arc furnaces (Table 1). Despite the noteworthy control of Hg since 1990, Hg emissions from coal-fired power plants have remained largely unchanged (Table 1). However, current Hg emissions from coal-fired power plants are likely lower than 2005 estimates due to the installation of Hg controls to comply with state-specific rules and co-benefit Hg reductions from the control of particulate matter and sulfur dioxide under state and federal actions (U.S. Federal Register 2011).

In 2005, targeting Hg emissions from coal-fired power plants, the U.S. Environmental Protection Agency (EPA) issued the Clean Air Mercury Rule (CAMR), which established performance standards limiting Hg emissions from new and existing facilities (Milford and Pienciak 2009). The rule created a market-based cap-and-trade program to decrease nationwide power plant Hg emissions. The use of trading to regulate Hg emissions raised scientific concerns about the potential for generating localized areas with unacceptably high levels of Hg deposition from clustered emission sources located in Hg sensitive regions or areas experiencing elevated local emissions in the U.S. from static or increased Hg emissions (U.S. EPA 2006; Evers et al. 2007).

In 2008, the U.S. Court of Appeals for the D.C. Circuit judicially voided (vacated) CAMR (Milford and Pienciak 2009). Following the court's vacatur, 17 states adopted regulations controlling Hg emissions from power plants, most of which have been implemented (U.S. EPA 2011). Several states also established emissions monitoring requirements for Hg (NACAA 2011). In 2011, the U.S. EPA proposed Hg and air toxic standards to reduce Hg, acid gases, and other toxic pollutants from power plants (U.S. Federal Register 2011). EPA's proposal sets emissions standards for Hg and other toxic air pollutants, reflecting levels achieved by the best-performing sources currently in operation.

In addition to controlling Hg from coal-fired power plants, EPA recently proposed or has finalized regulations to decrease Hg emissions from other major source categories. These include (1) national emissions standards for hazardous air pollutants for gold ore processing and production

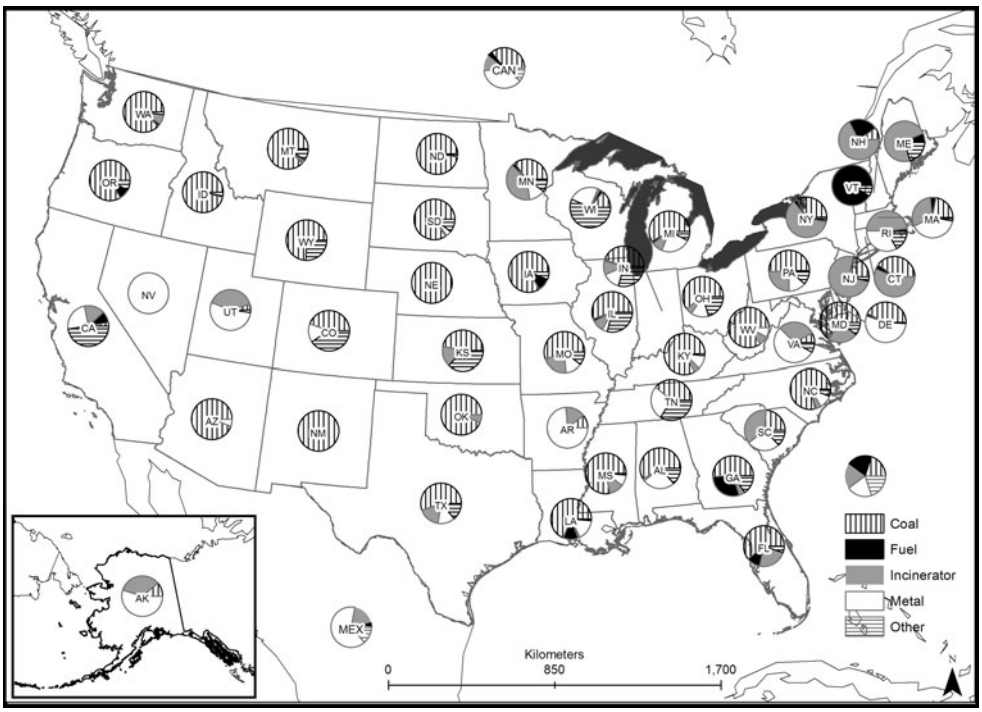

Fig. 2 Estimated distributions of four specific source types of anthropogenic Hg emissions for the United States (by state), Canada, and Mexico. Estimates are based on an analysis of emissions data from the U.S. EPA (2002 National Emissions Inventory), Environment Canada (primarily the 2002 National Pollutant Release Inventory), and the Commission for Environmental Cooperation, who supported the development of a 1999 Mexican Hg emissions inventory. These categories are the same as categories used in Fig. 3 to indicate the location and magnitude of Hg emission sources. The "Other" category includes minor emission sources

Table 1 Mercury emissions by source category for 1990 and 2005, and net emissions changes over this interval

Source category	Emissions (tons/year)		Net changes between 1990 and 2005 (tons/year)
	1990	2005	
Utility coal boilers	58.8	52.3	−6.5 (−11.1%)
Hospital/medical/infectious waste incineration	51	0.3	−50.7 (−99.4%)
Municipal waste combustors	57.2	2.4	−54.8 (−95.8%)
Industrial/commercial/institutional boilers and process heaters	14.4	10.3	− 4.1 (−28.5%)
Mercury cell chlor-alkali plants	10.0	0.3	−9.7 (−97.0%)
Electric arc furnaces	7.5	7.3	−.2 (−2.7%)
Commercial/industrial solid waste incineration (CISWI)[a]	Not available	0.3	
Hazardous waste incineration[b]	6.6	3.2	−3.4 (−51.5%)
Portland cement non-hazardous waste[b]	5.0	7.5	2.5 (50.0%)
Gold mining	4.4	2.5	−1.9 (−43.2%)
Sewage sludge incineration	2.0	1.1	−.9 (−45.0%)
Mobile sources	Not available	1.1	
Other categories[c]	29.5	12.4	−17.1 (−58.0%)
Total (all categories)	246.4	101.0	−145.4 (−59.0%)

[a] CISWI estimates in Table 1 do not include cement kilns

[b] Hazardous waste incineration category includes Portland cement hazardous waste kilns. 1990 estimates for Portland cement and hazardous waste incineration do not use the same methodology and are underestimated in 1990 based on current data

[c] Includes other Hg emitting source categories: chemical manufacturing, metal fabrication operations, agriculture mineral processing, cremation, dental amalgam, engine test cells, electrical equip manuf, fluorescent light breakage/recycling, ferroalloys, manufacturing, iron and steel production, landfills, nonferrous metals, oil and gas production, refineries, petroleum product distribution, plywood, pulp/paper, residential heating, and waste disposal

Table is based on data in the 1990 National Emissions Inventory (NEI) for Hazardous Air Pollutants and the 2005 National-scale Air Toxics Assessment (NATA) emissions inventory, provided by Anne Pope U.S. EPA/OAQPS 3/24/11

facilities; (2) rule to control Hg emissions from Portland cement manufacturing facilities; (3) proposed emission limitations for sewage and sludge incinerators; and (4) proposed revision to performance standards for emissions from chlor-alkali facilities. Emission limitations for industrial and commercial boilers are under reconsideration.

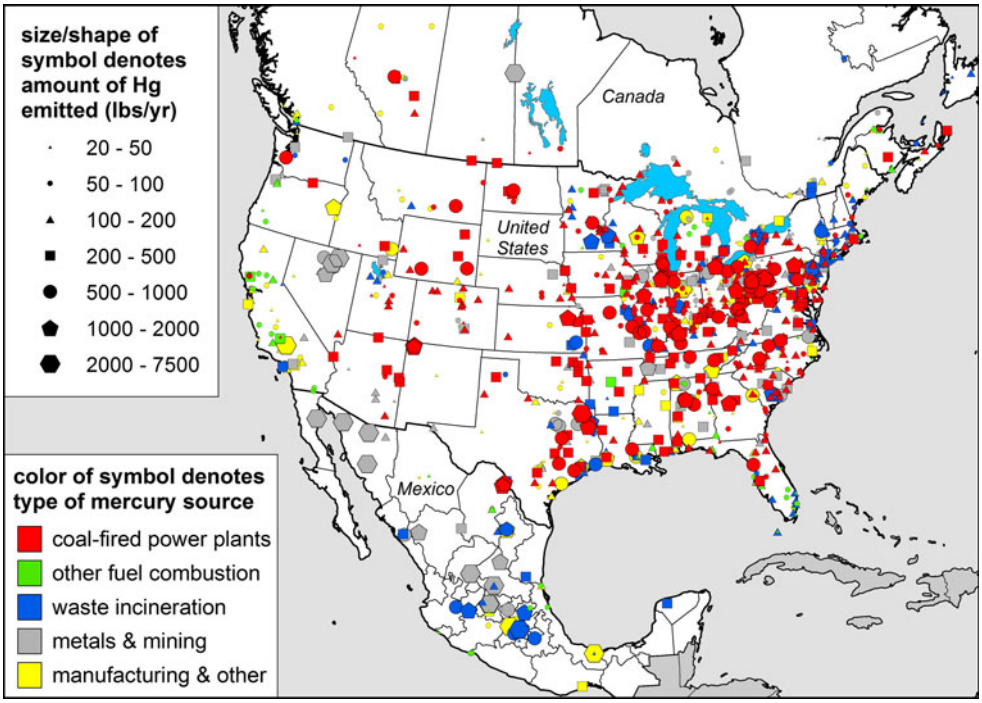

Fig. 3 Distribution of total Hg annual emissions for point sources in the United States, Canada, and Mexico. Emissions based on the same dataset and source categories described in Fig. 2. Total number of point sources in inventory is 15,892, which equals 155 tons/year. Point sources not mapped are those under 20 lbs/year ($n = 3{,}508$ point sources which equals 1.75 tons/year). Note, amount of Hg emitted does not include area sources. In the U.S., the largest contributors to area sources are mobile sources, oil combustion, lamp manufacturing, recycling and breakage, dental amalgam production, and cremation. The largest contributors to Canadian area sources are other fuel combustion, incineration, and cremation. Point source emissions in Alaska and Hawaii are minor (under 20 lbs/year) and not depicted here

MercNet: a national Hg monitoring network

Planning workshops

Two planning workshops for a national Hg monitoring network were held in 2003 and 2008. Important concepts are explained in two key publications. Mason et al. (2005) and Harris et al. (2007) presented a technical framework and a detailed plan for a national-scale network to track the sources, consequences, and trends of Hg in the environment following decreases in atmospheric Hg emissions. The network concept was a product of the first workshop co-sponsored by the U.S. EPA and the Society of Environmental Toxicology and Chemistry (SETAC) in 2003 involving more than 30 Hg experts from the U.S., Canada and Europe with experience in measurements of Hg in the atmosphere, terrestrial and aquatic ecosystems, fish and wildlife. Workshop participants developed groups of indicators that could be used to identify and interpret spatio-temporal patterns in Hg concentrations and fluxes in the atmosphere, land, water, and biota to assess ecosystem responses to changes in Hg deposition over policy-relevant timescales (Table 2). Ancillary data essential for defensible interpretation of Hg trends and dynamics were also identified. Workshop participants envisioned a national Hg monitoring network of 10–20 intensively-studied sites to establish causal relations between Hg pollution and ecosystem change, to measure environmental Hg trends, and to provide data for developing and refining predictive models. Surrounding each intensive monitoring site would be a group of about 10–20 less-intensively studied "cluster" sites intended to provide a general understanding of the ranges of ecosystem responses within the region (e.g., within 200 km).

In May 2008, 50 scientists and policy analysts from federal agencies, including the U.S. EPA, U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), U.S. Fish and Wildlife Service (USFWS), and the National Park Service (NPS), along with representatives from Environment Canada, state environmental agencies, tribes, the academic scientific community, industry, and non-governmental organizations convened a second workshop (U.S. EPA 2009b) to develop an implementation strategy for a national Hg monitoring and assessment network (MercNet). Specific goals for the workshop were threefold:

1. To share data and information on existing Hg monitoring programs (e.g., atmosphere, water, watershed,

Table 2 Types of indicators to be quantified at cluster or intensive sites for MercNet

Indicator[a]	Site	Frequency
Air & watershed		
Atmospheric Hg speciation; wet & dry deposition flux	IN	Continuously
THg wet deposition & flux[b]	CL	Weekly
Hg^0 evasion & flux[b]	IN	Monthly
THg & MeHg yield from watershed in surface-water and groundwater	IN	Monthly
Sediment & water		
THg stratigraphy & accumulation in dated sediment[c]	IN	Every 3–5 years
THg & MeHg in surficial (0–2 cm) sediment	IN + CL	Every 6 months
THg & MeHg in surface water	IN + CL	Every 6 months
THg & MeHg in water column (depth profiles)	IN	Every 6 months
Aquatic biota		
THg & MeHg in seston (mostly algae)	IN	Monthly
THg & MeHg in bulk zooplankton or selected benthic invertebrates	IN	Monthly
THg in whole, yearling fish	IN + CL	Annually
THg in axial muscle of adult piscivorous fish	IN + CL	Annually
THg in wildlife[d]	IN + CL	Annually

Site: *IN* intensive sites only, *IN + CL* intensive & cluster sites

THg total mercury, *MeHg* methylmercury, Hg^0 elemental mercury

[a] Revised from chapters in Harris et al. 2007

[b] Event-based wet deposition collection at intensive sites, weekly integrated sampling at cluster sites. At intensive sites, flux estimates would include wet, dry, gaseous, & particulate deposition; throughfall & litterfall; & snowpack sampling, as appropriate. Hg^0 concentration & evasion fluxes would be for both aquatic and terrestrial environments

[c] Intensive sites & a subset of cluster sites would be sampled to determine historic Hg trends

[d] Birds & mammals; both short-term & integrative sampling

sediments, biota) in North America to advance interagency collaboration;

2. To distill and translate recommendations from Harris et al. (2007) to develop more specific monitoring guidance on Hg indicators and ancillary parameters; and
3. To identify Hg monitoring data gaps across the U.S., options for filling those gaps, and potential network monitoring locations.

The workshop focused on design and implementation of MercNet covering terrestrial and aquatic ecosystems in the United States, including watersheds, freshwater and coastal systems. Linkages to ecosystem monitoring in Canada and Mexico were discussed. Some of the key tasks were to identify: the goals and objectives of MercNet, the major design elements needed to meet network goals and objectives, existing monitoring capabilities, existing sites that meet monitoring objectives, and near-term steps to address gaps.

Workshop participants reviewed and refined goals, objectives, and proposed network design strategies. There was recognition of the need to link monitoring activities to the information needs of policymakers, resource managers, and researchers for managing risks and predicting environmental outcomes of Hg emission changes.

Goal and objectives

The defined goal of MercNet is to establish an integrated, national network to systematically monitor, assess, and report on policy-relevant indicators of atmospheric Hg concentrations and deposition, and Hg levels in land, water, and biota in terrestrial, freshwater, and coastal ecosystems in response to changing Hg emissions over time. The six principal objectives of MercNet are aligned with the information needs of policymakers, resource managers, and researchers charged with managing risks and predicting environmental outcomes of Hg emission changes, as follows:

1. Establish baseline Hg concentrations in multiple ecosystem compartments that document environmental conditions before implementation of new Hg emission controls so that future changes may be attributable to these controls. This objective requires building on historical datasets and existing information on spatio-temporal patterns in baseline conditions.

2. Track spatial patterns and long-term trends in Hg concentrations throughout aquatic and terrestrial ecosystems before, during, and after Hg emission controls are implemented. This objective requires developing a comprehensive geographic and statistical approach that accounts for spatial variability and a long-term, consistent set of measurements to assess temporal responses.
3. Provide data to assess linkages among atmospheric Hg emissions and deposition, and MeHg concentrations in biota and their changes over time. This objective requires quantifying relations between Hg emission sources and aquatic receptors, accounting for lags in ecological response to Hg inputs (Munthe et al. 2007) and evaluating the ecotoxicological effects of Hg on organisms and populations.
4. Provide Hg and ancillary data to validate existing atmospheric and ecological models, and advance the development of models to assess source-receptor relations. This objective requires integrating monitoring and modeling activities to ensure that models account for the full range of factors affecting Hg transport, availability and bioaccumulation, and rates of methylation.
5. Assess potential ecological harm and linkages to air emission sources for important ecological areas (e.g., National Parks, National Wildlife Refuges) and wildlife of conservation concern, such as rare, threatened, and endangered species. This objective requires quantifying cause-and-effect relations among Hg emissions, deposition, and exposure of fish and wildlife.
6. Connect MercNet to other environmental monitoring programs to share expertise, enhance monitoring capacity, and maximize the effectiveness of the program.

Monitoring design elements

Workshop participants also agreed on five major monitoring design elements:

1. MercNet should include 10–20 nationally-distributed intensively monitored sites, or *intensive sites*, to establish cause and effect relationships between Hg loading and ecosystem response and to provide data for developing and refining predictive models.
2. A group of 10–20 less intensively studied sites, called *cluster sites,* in the vicinity of each intensive site (within 200 km), should be monitored to provide a general understanding of the range of ecosystem responses within the region.
3. Monitoring at each site should continue for 10–40 years, a time frame needed to quantify the expected broad range of responses expected among different ecosystems (Harris et al. 2007). Note that 10 years is probably inadequate to evaluate the response to decreases in loading given the lags in ecosystem processing of Hg, although some areas have shown markedly rapid response to decreases in Hg emissions (e.g., Evers et al. 2007). The 40 year monitoring period is probably more realistic to assess response to subtle and long-term changes in Hg deposition, particularly given the complexities of Hg response to other disturbances such as atmospheric deposition, climate change, introduced species and land-use change.
4. The network should build on existing surveillance and monitoring efforts, where possible (e.g., NADP, LTER, NEON), to maximize information, benefits, coordination, and efficiency, and to reduce cost.
5. Monitoring at intensive and cluster sites would focus on environmental indicators expected to respond to changes in Hg emissions and MeHg exposure over relevant time scales. Recommended measurements include concentrations of speciated atmospheric Hg (gaseous elemental, reactive gaseous, and particulate atmospheric Hg fractions), and total and methylated forms of Hg, wet and dry deposition, soils, forest litter, sediments, surface and ground water, snow, yearling fish, adult predatory fish, and Hg sensitive wildlife species (Table 2). These measurements minimize the confounding impacts of short-term variability while integrating the signal to ascertain environmental change.

The design of MercNet reflects that Hg cycling is complex and occurs within the context of other environmental drivers, such as (1) wet/drought cycles, (2) warming, (3) changing hydrologic regimes in lakes and rivers (partly due to wet/dry cycles; partly due to other influences), (4) acidic deposition, (5) land-use changes, and (6) various other ecosystem changes. These disturbances have the potential to influence MeHg production, transport, and bioaccumulation. Although a goal of MercNet is to locate monitoring at sites where "…response[s] should not be confounded by other natural or anthropogenic disturbances," (Table 3) in reality, there are factors that are uncontrollable. Sound scientific assessment is based on a strong understanding of ecosystems that comprise the network and that understanding is essential to explain trends as a function of Hg emissions and other ecosystem changes.

MercNet database

Because of the widely dispersed array of multi-media Hg measurements and data available across the U.S., MercNet

Table 3 MercNet siting criteria and considerations

Evaluation questions	Criteria	Definition
Does the site have an operational infrastructure & available long-term data to establish baselines?	• Site has available long-term Hg data (atmospheric or ecosystem data), supporting information on site characteristics, & ancillary measurements • Site has existing facilities & infrastructure to support the monitoring program	Resources are available to sustain operations, such as funding, shelter, power supply, site operators, transparent land ownership, site accessibility. Site is co-located with other long-term monitoring programs, such as NADP & CASTNet.
Will changes in Hg levels be observed and interpretable at the site?	• Site is considered to be sensitive and responsive to Hg inputs • Site is located near emission sources and may receive elevated Hg inputs • Site expected to exhibit a clearly defined response to changes in Hg emissions and deposition	Hg sensitivity is the relative efficiency of an ecosystem to transform an inorganic Hg load into bioaccumulated MeHg. Mercury-sensitive ecosystems will be more responsive to loading changes (magnitude & timing of response). The network will need rapid and slow methylating sites to quantify a range of responses across ecosystem types. Site response should not be confounded by other natural or anthropogenic disturbances
Does the site have potential for evaluating models?	• Information from monitoring at the site will be useful for developing, testing, and refining atmospheric & ecosystem models • Hg or ancillary data are available	For atmospheric model evaluation, sites should include simple terrain with few confounding variables (e.g., vehicle traffic), existing meteorological simulations, & well-characterized regional emission sources with a range of concentrations & plume episodes. Ecosystem model evaluation requires relatively uniform sites with well-characterized land cover, meteorology, hydrology, soils, and biology, & a relatively long time series of Hg measurements. Measurements needed include evasion, throughfall, litterfall, methylation, & soil adsorption.
Does the site contribute to an overall network covering a range of site types?	• Sites should collectively have a range of expected response times to changes in deposition, include an array of ecosystem types, and a nationwide geographic distribution • Site influenced primarily by global sources of Hg emissions	Sites cover a variety of ecosystem types (e.g., forest, lake, wetland, urban, coastal) and ecoregions. Sites include rapid response types (e.g., perched seepage lakes) & slow-response sites with substantial ground water input. One or more sites should be distant from domestic Hg sources, receiving atmospheric Hg inputs primarily from non-U.S. sources.
To what extent is the site located in Hg-sensitive wildlife habitat?	• Strong scientific information on exposure and effects on wildlife species • Site has endangered, threatened, or candidate species at risk of MeHg exposure	Sites capture temporal & spatial changes in MeHg exposure and potential effects in wide-ranging and limited range species relative to changes in Hg loadings to an ecosystem.

presents an opportunity to improve coordination across sampling programs, agencies, and networks to: (1) extend time-series measurements of Hg; (2) standardize quality assurance, including measurement methods and data management procedures to improve data integration; and (3) enable more spatially comprehensive interpretation, as Hg control programs are implemented. As part of the 2008 workshop, a team of scientists from federal and state agencies, academia, and research organizations compiled and analyzed more than 200,000 observations of Hg levels in air, water, sediment and soil, vegetation, fish, and wildlife based on environmental monitoring databases compiled by the U.S. EPA, NOAA, USGS, U.S. FWS, NPS, state agencies, and the Biodiversity Research Institute (BRI) (U.S. EPA 2009b). The MercNet database contains locations and meta-data about multi-media Hg measurement sites. It provides a useful tool for identifying and characterizing existing Hg monitoring activities across the U.S., for examining the spatial extent of Hg monitoring, for informing gap analysis, and for identifying potential, long-term network sites. BRI continues to manage and integrate Hg data into the MercNet database, which now exceeds 500,000 Hg observations (BRI 2010).

Monitoring sites

The locations of Hg monitoring sites will be linked to defined monitoring objectives as needed to document Hg

trends in multiple ecosystem compartments and/or establish causal linkages between changes in Hg deposition and bioaccumulation of MeHg in ecosystems. Important siting criteria and considerations are presented in Table 3.

To identify locations with a strong potential for contributing to MercNet, the multi-media indicators identified in Harris et al. (2007) and siting considerations (Table 3) were applied to existing monitoring sites derived from the MercNet database, primary scientific literature, and expert input. Review of the database reaffirmed the need for a long-term, consistent monitoring effort. Most of the Hg samples collected in the U.S. have been one-time collections conducted to characterize the extent of Hg contamination, rather than continuous long-term monitoring efforts. A review of fish Hg concentrations in the MercNet database indicate that only six sites in the United States have data for 10 or more total years (MercNet unpubl. data; Fig. 4). This limitation may constrain options for expanding monitoring to support long-term temporal trend objectives. Such data gaps in the temporal record would hamper the assessment of cause-and-effect linkages between Hg emissions and ecosystem effects.

Successes, challenges, and opportunities

New Hg monitoring

A few consistent, comparable and national scale long-term monitoring datasets do exist. These include the Mercury Deposition Network (MDN) and Atmospheric Mercury Network (AMNet), which were established as part of the National Atmospheric Deposition Program (NADP) to determine spatial patterns and long-term trends in concentrations of Hg species in the atmosphere and precipitation, and wet and dry Hg deposition. The MDN joined the NADP in 1996, and currently includes 115 sites in the United States and Canada. All MDN samples are analyzed for total Hg, and some for MeHg. The AMNet joined NADP in 2009. This network quantifies concentrations of atmospheric Hg forms that contribute to dry and total Hg deposition. At the 21 AMNet sites, automated continuous measuring systems obtain information on concentrations of atmospheric Hg species, and are co-located with MDN wet deposition collectors. Data on terrain, land cover, and meteorology useful for estimating dry deposition are collected, if locally available. For MDN and AMNet, samples are collected using standardized measurement methods,

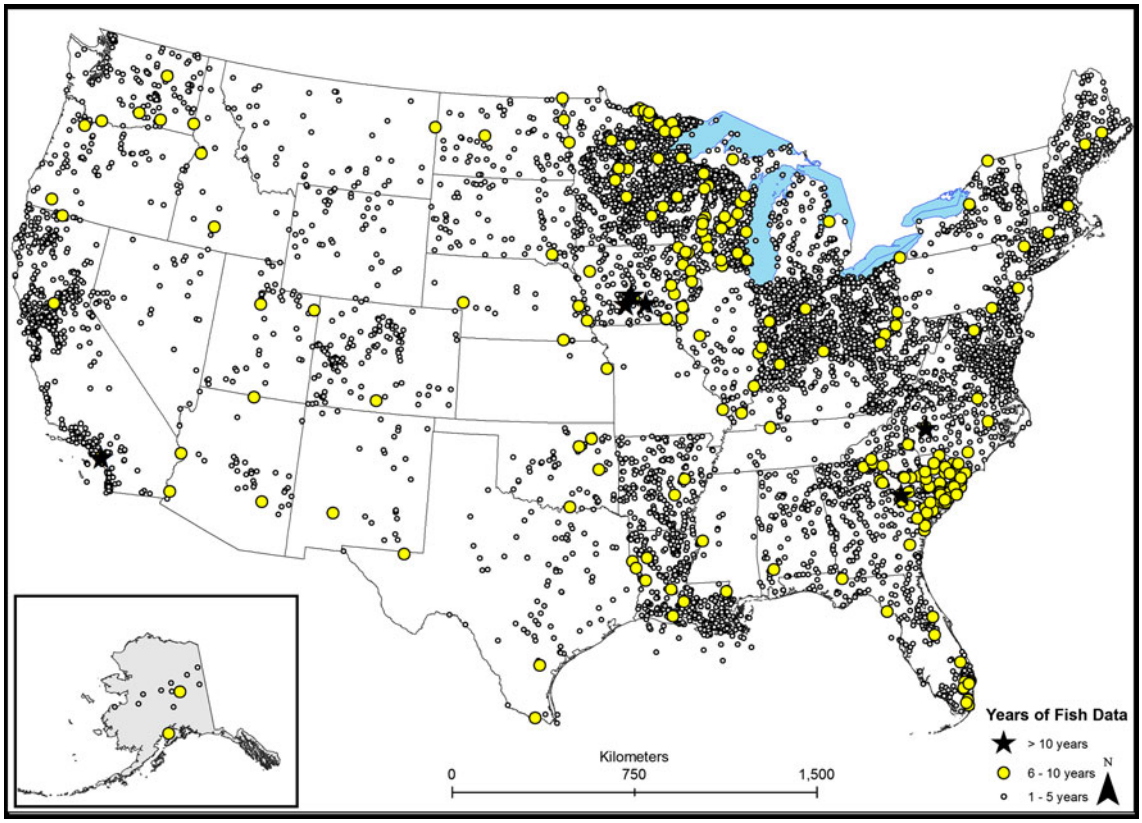

Fig. 4 Distribution of Hg data for fish fillets or axial muscle across the United States in relation to the duration or number of years of fish sampling and analysis at each site. The data are derived from the MercNet monitoring database (1967–2005)

and quality assured data are archived on the NADP website.

Sixty nine potential intensive network sites were initially identified. This list was reduced to 21 candidate sites for further characterization and consideration. These 21 sites represent key ecosystem, climatic and deposition characteristics, and meet a range of network monitoring objectives and site selection criteria; however, the full range of measurements needed to meet stated network objectives have not been made at the vast majority of these sites. The list of potential intensive sites includes candidate sites that range widely in geographic extent from fairly localized areas with established monitoring to multi-state regions (U.S. EPA 2009b; Fig. 5).

Regional Hg synthesis projects

Recent syntheses of monitoring data and scientific research have enhanced our understanding of the extent of Hg pollution and contributed to the groundwork for MercNet. Such syntheses are particularly useful because much of our data on Hg in the environment is from state, provincial and federal surveys. These surveys were intended to characterize Hg contamination and to provide information on consumption advisories and exposure risk. Moreover, as Hg contamination is a complex multi-media problem, understanding is often limited by a narrow disciplinary focus.

Two regionally-focused, bi-national projects facilitated the sharing and synthesis of multi-media Hg monitoring data. The first of these focused on the northeastern U.S. and eastern Canada and involved meetings that were conducted from 2000 to 2003, with funding from the U.S. Department of Agriculture through the Northern States Research Cooperative. Approximately 70 scientists compiled regional Hg data including information on air, atmospheric deposition and Hg concentrations in sediments, surface waters, aquatic biota and wildlife, resulting in a database of more than 60,000 observations. Much of these data were from government surveys that had never been interpreted through linkages with supporting observations. Following data compilation, scientists worked in groups to analyze and interpret the regional Hg data which resulted in presentations at the biennial Northeastern Ecosystem Research Cooperative meeting and 21 articles on Hg pollution in eastern North America, published as a special issue of *Ecotoxicology* (Evers and Clair 2005). This initial synthesis effort was followed by a higher order synthesis to integrate Hg data across environmental media, yielding two general reports (Evers 2005; Driscoll et al. 2007b) and two peer-reviewed journal articles (Driscoll et al. 2007a, Evers et al. 2007) that have advanced regional understanding of atmospheric Hg deposition, transport, and transformations and wildlife MeHg exposure.

The second bi-national synthesis focused on the Great Lakes region. This effort began in 2008 and the first phase will be complete in 2011. The Great Lakes Hg synthesis, funded by the U.S. EPA through the Great Lakes Atmospheric Deposition program, involves more than 155 scientists and managers. Similar to the eastern North America

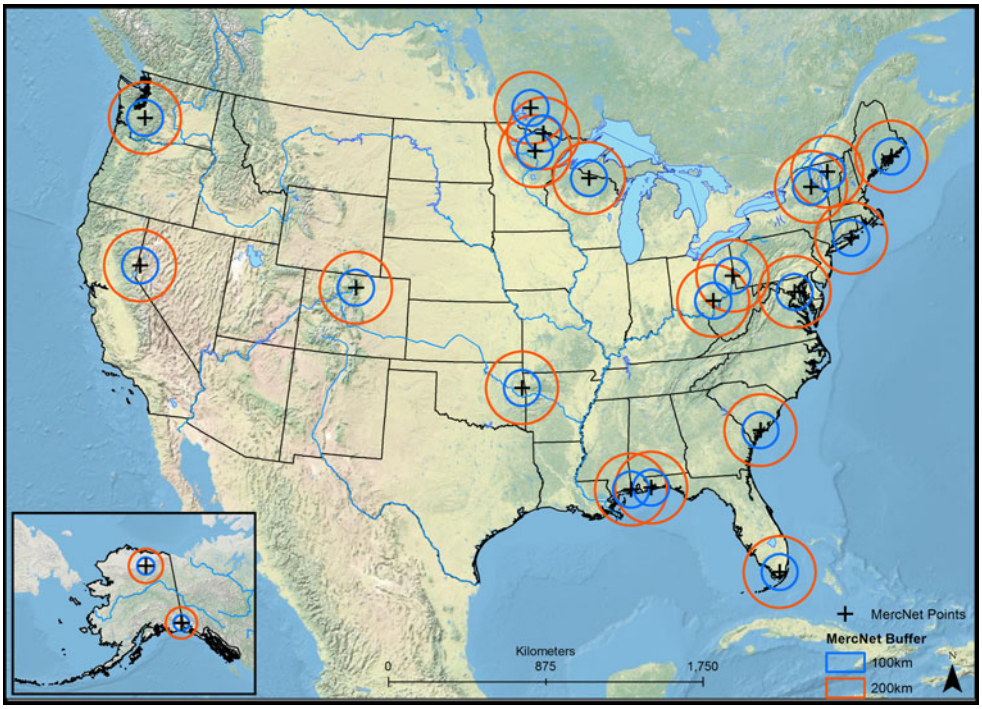

Fig. 5 Conceptual map of a national Hg monitoring network (MercNet). This map illustrates how monitoring sites might be distributed across the United States to achieve comprehensive regional and national coverage. The sites illustrated on the map are preliminary and do not represent a final set of sites to be included in a national Hg monitoring program. The concentric circles illustrate the proximity of cluster sites to intensive sites. The selection of sites reflects the need for ongoing and long-term Hg measurements, areas of high Hg contamination, proximity to national emission sources, ecosystem sensitivity to Hg deposition and potential reference sites

initiative, data have been complied and subsequently interpreted by workgroups focusing on ecosystem components (atmospheric deposition, sediments, water, lower food web, fish, and wildlife). Outputs include two project workshops, 22 papers scheduled for publication in this special issue of *Ecotoxicology* (Evers et al. 2011), and 13 papers in a concurrent special issue of *Environmental Pollution* (Wiener et al. 2011). A higher order synthesis of the Hg data in these papers is planned to result in journal articles, as was conducted for eastern North America.

These regional synthesis projects have provided a more holistic view of Hg pollution, and have strengthened the scientific foundation for identifying data gaps, customizing regional site selection criteria, and guiding Hg policy, including the need for additional emission controls and linkages of Hg contamination to other environmental disturbances—all are essential regional elements that can contribute to an integrated national Hg monitoring program. Such regional syntheses have also been effective platforms for communication among scientists, natural resource managers, policy makers, and the news media.

Global Hg monitoring

Internationally, the United States is participating in negotiations with more than 140 other countries to establish a global, legally binding instrument to control Hg pollution by 2013 (UNEP 2010). Related to these discussions, scientists from around the world are collaborating to establish a Global Mercury Observation System (GMOS) to assess spatial and temporal changes in atmospheric Hg concentrations and Hg wet deposition, and to provide data to evaluate regional and global-scale atmospheric models. Such a global network, based partly on data compiled by Pirrone et al. (2009), could support an international agreement, providing a scientific foundation for global Hg policy development, implementation, and assessment as outlined by the United Nations Environment Programme (UNEP 2010). GMOS is envisioned to include ground-based monitoring stations, shipboard measurements over the Pacific and Atlantic Oceans, European Seas, and aircraft measurements from the ground to the lower stratosphere (European Commission 2010). While current plans for GMOS do not include Hg monitoring in watersheds or biota, new additions to the UNEP Hg Air Transport and Fate Research Partnership Area (UNEP 2011) encompass objectives that would include ecosystem monitoring. As scientists consider different monitoring options for a global Hg network, linkages to existing national and regional Hg monitoring efforts in North America and elsewhere, where substantial investments and progress have already been made, would facilitate development.

Near-term steps and future challenges

MercNet is an important part of a conceptual framework for understanding and managing the effects of atmospheric Hg deposition on ecosystems and natural resources (Fig. 6). This framework involves integrated monitoring of Hg emissions, air, and atmospheric deposition, as well as other abiotic and biotic components (Table 2). These monitoring activities would be summarized through periodic status and trends assessments to link emission control actions to changes in atmospheric Hg deposition and biological responses.

A number of supporting activities could greatly enhance the success of MercNet. These include regional data syntheses and corresponding publication efforts, similar to those in the Northeast and Great Lakes regions. These could be multi-regional and eventually national in scope. Other critical activities include process-level research that would provide the detailed quantitative understanding of the mechanisms behind Hg processes in the environment; development, testing, and application of atmospheric transport and watershed Hg models; as well as the testing of hypotheses emanating from the analysis and interpretation of monitoring data. MercNet and the associated status and trends assessment, synthesis work and modeling would support environmental policy decisions and help guide future decisions on the need for additional emission controls. Equally important, MercNet would support accountability by providing environmental information that can be used to directly assess and quantify the benefits and effectiveness of emission control programs.

Support exists for MercNet at the national, state and local levels. Legislation was introduced in Congress in 2007 (S. 843, H.R.1533), 2009 (S. 2913) and 2011 (S.1183) to support a national Hg monitoring program. The proposed legislation provides for the establishment of a multi-agency national Hg monitoring program. In 2010, the Environmental Council of States (ECOS), Quicksilver Caucus adopted a resolution supporting actions to develop a comprehensive, long-term Hg monitoring program to evaluate trends in Hg levels in the environment and biota and inform the development of future Hg control policies (ECOS 2010). A similar resolution was agreed upon in 2010 by the Great Lakes Commission to promote comprehensive Hg monitoring, research and control efforts. The New England Governors and Eastern Canadian Premiers also support extensive Hg monitoring to improve scientific understanding of Hg sources, fate and impacts as part of their Mercury Action Plan (Smith and Trip 2005).

Monitoring and planning workshops and regional syntheses projects have involved diverse groups of participants, including scientists from academia and government, and representatives from industry, state and federal natural

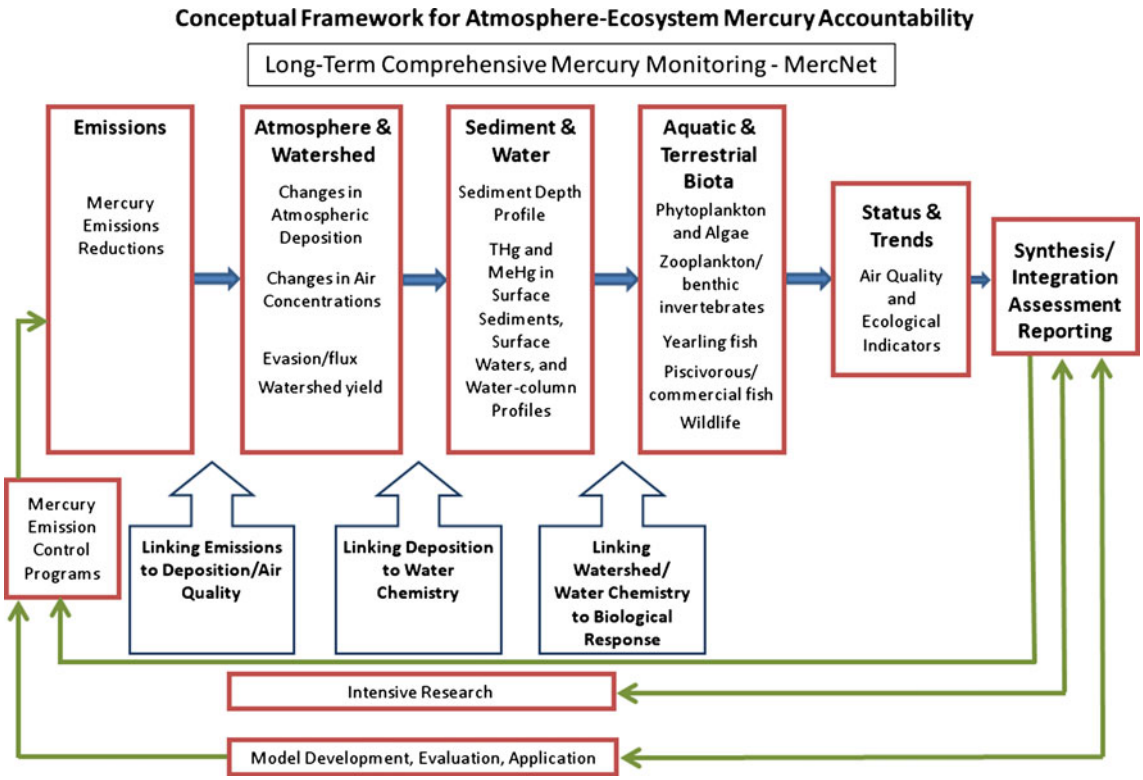

Fig. 6 Conceptual framework for a Hg monitoring program and linkages with synthesis, research and modeling to evaluate and guide emission control programs

resource agencies, tribes, and NGOs. Future activities in this initiative should be expanded to engage public health scientists and social scientists. As MercNet would be a long-term effort, it is essential that program and funding be leveraged through federal, state and industrial institutions to sustain a cost-effective, comprehensive program. The development of MercNet to date, described in this paper, demonstrates that strategic partnerships are crucial to success.

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