Chapter 4

Forest Monitoring Methods in the United States and Canada: An Overview

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Chapter Outline

4.1 INTRODUCTION

The forests of North America cover approximately 677.5×10^6 ha, one-third of the total land area of North America (UNFAO, 2005) and 17% of the global forest area, with Canada and the United States ranking the third and

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fourth, respectively, among countries with the largest forest areas. Besides being an immense resource in spatial terms, North American forests are so also in terms of ecological diversity and variety of benefits provided, including water, recreation, wildlife habitat, timber, and other forest products. As such, the manteinance of the health and productivity of these forests is essential, and their sustainability relies directly on their capacity to increase or maintain productivity while maintaining resistance to biotic and abiotic stressors (McLaughlin and Percy, 1999). As reported by Tkacz et al. (2008), the health and sustainability of North American forests have been monitored and assessed for decades from several perspectives—from the early concern about pests, diseases, and air pollution effects (e.g., the North American Sugar Maple Decline Project; Millers et al., 1991) to the more recent, broad perspectives in the context of Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests developed under the Santiago Agreement (Anon., 1995; NRCan, 2006; SEMARNAT, 2003; USDA, 2004). In this chapter, we provide an overview of the development in Forest Health Monitoring (FHM) in the United States and Canada. The former case provides a clear example of a fully cooperative program that has evolved in order to meet the changing national and local perspectives, with attention to data consistency, new methodologies, and proper reporting. With the latter case, special emphasis will be given to recent developments in FHM in the Athabasca Oil Sands Region (AOSR; Percy et al., 2012) as a case study that demonstrates the importance of adaptive FHM in response to new and specific environmental questions. Commonality among Canadian, United States, and European programs and recent initiatives including Mexico can be valid ground to foster development and cooperation in FHM.

4.2 FHM IN THE UNITED STATES

4.2.1 History and Implementation of FHM Program

The FHM program was initiated over two decades ago in response to increasing concerns about the status and trends in the health of the forests of the United States. While existing inventory and monitoring programs were providing information on timber (Forest Inventory and Analysis (FIA) program), forest pests (Forest Health Protection (FHP) pest detection surveys), and air pollution effects (National Acid Precipitation Assessment Program—NAPAP), none of these provided a holistic assessment of the major factors affecting the health and sustainability of forested ecosystems across all ownerships. Starting in 1990, partners from federal and state agencies in the United States established the FHM program with the goal of monitoring and evaluating the status, conditions, and trends in indicators of forest health (Riitters and Tkacz, 2004). The conceptual approach to FHM is analogous to a system of annual physical checkups for human health. The initial component called “Detection Monitoring” is a periodic check of a variety of health indicators that could detect changes from "normal" conditions, serving as a signal of a potential forest health problem. This is followed by Evaluation Monitoring (EM)—a more intense examination focused on the problem to identify causes and determine treatments for solution. The third component of FHM is Intensive Site Monitoring (ISM)—long-term research sites focused on determining forest health processes at a more detailed level. All of these components are supported by components called "Research on Monitoring Techniques", and "Analysis and Reporting."

Initial efforts of the FHM program focused on evaluations of existing monitoring networks (Hazard and Law, 1989), followed by reviews of candidate indicators (Riitters et al., 1991), testing sample designs and procedures (Alexander et al., 1991), development of Quality Assurance protocols (Palmer, 1992), and information management systems (Liff et al., 1994). The first field plots were established in 1990 in six of the states in north-eastern United States (Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island) with additional states incorporated into the network gradually over time (Alexander and Palmer, 1999). Starting in the late 1990s, the FHM plots were integrated with the national FIA program. The forest health indicators are now collected on a subset of the FIA plots labeled Phase 3 (Bechtold and Patterson, 2005; Woodall et al., 2011) to distinguish them from area estimation on Phase 1 plots and timber inventory on Phase 2 plots.

From its inception, the FHM program has been a truly collaborative effort involving federal and state agencies and universities (Riitters and Tkacz, 2004). Since the scope of the program includes all forested lands, regardless of ownership, partner federal and state agencies share in the financial support of program implementation. While the initial focus of the program was on air pollution-related impacts on forests, this was subsequently expanded to encompass a broad range of factors affecting long-term health and sustainability of forests as addressed in the Montreal Process Criteria and Indicators (MPCI; Montreal Process Working Group, 2007). In fact, the MPCI became the organizing framework for the annual FHM National Technical Reports starting in 2001 (Conkling et al., 2005).

4.2.1.1 Detection Monitoring

The purpose of Detection Monitoring is to establish baseline forest health conditions for analysis of future changes and trends and to trigger EM (see below) actions. Detection Monitoring is accomplished by utilizing a variety of survey methodologies. Remote sensing is used with greater frequency to detect changes in forest condition, cover, fragmentation, and land use at regional scale using space-based platforms. The U.S. Forest Service (FS) and the National Aeronautics and Space Administration are cooperating in the development of automated change detection systems based on the Moderate Resolution Imaging Spectroradiometer (MODIS; Hargrove et al., 2009) to alert forest health specialists to defoliation or mortality events as they occur. By comparing a self-standardizing version of the Normalized Difference Vegetation Index of land surface greenness on recent and historic scenes, areas of change are identified and mapped. Areas of possible forest damage can then be further assessed through traditional survey and evaluation techniques.

The FS and cooperating state forestry agencies conduct annual aerial surveys to detect visible tree mortality or damage to tree crowns from insects, diseases, and abiotic causes (McConnell et al., 2000). Specially trained aerial observers fly over forested areas in small, fixed, or rotary winged aircraft at heights of 300–600 m above ground level and look for higher than normal levels of damage caused by major forest insects, diseases, or abiotic agents (e.g., Ciesla et al., 2008). Observers use the Digital Aerial Sketch Mapping system which allows surveyors to track the exact location of the aircraft on moveable map displays, digitize polygons of affected areas, and attribute the polygons with codes for host species, damage type, likely causal agent, and severity (Shrader-Patton, 2003). These data are compiled in a national database (http://foresthealth.fs.usda.gov/portal) that facilitates consistent reporting of forest health conditions at the national, regional, state, or local levels (Tkacz et al., 2008).

Concerns over the spread of an invasive forest pathogen, *Phytophthora ramorum* (S. Werres, A.W.A.M. de Cock), the cause of sudden oak death in California (Rizzo et al., 2002), prompted FHM partners to develop a national, risk-based detection survey for the pathogen (Smith et al., 2002). Over 3,500 locations in a total of 39 states were surveyed between 2003 and 2006 (Oak et al., 2008). Over 12,500 samples of symptomatic tissues were analyzed for the presence of *P. ramorum*, and only two were found to be positive for the pathogen, both occurring in San Francisco, California. These results reduced the fears that the pathogen had spread beyond the infested nurseries and led to the development of a more sensitive survey methodology. Due to the formation of water-borne propagules, the distribution of *P. ramorum* can be determined by baiting streams with leaves of susceptible plants (Murphy et al., 2006). Stream baiting was incorporated into the national *P. ramorum* survey in 2007 (Oak, 2011) and has continued in 17 states through 2011 with positive streams being found in California, Oregon, Washington, Mississippi, Louisiana, Florida, Georgia, and North Carolina (Oak, 2011). Although *P. ramorum* continues to be found in streams associated with infested nurseries, it has not yet been found to be established in forest environments in the eastern United States.

As mentioned previously, the FHM program developed a suite of forest health indicators which are now part of the FIA integrated plot network and design. The country is divided into a hexagonal grid pattern with randomized plot locations in each 2,400 ha hexagon (Bechtold and Patterson, 2005; Figure 4.1).

Trend analysis is done once plots are remeasured every 5–10 years. A phased approach is used by the FIA program (Woodall et al., 2011). Phase

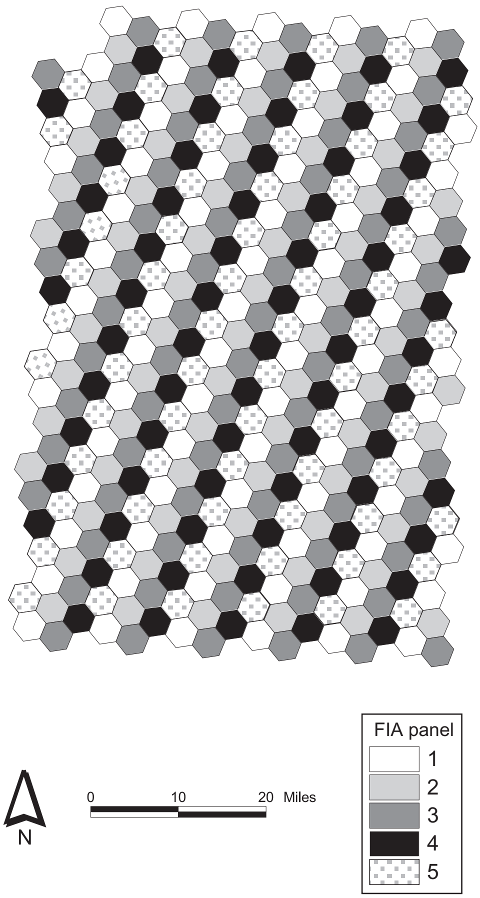

FIGURE 4.1 The FIA sample design is based on a tiling of hexagons. A Phase 2 inventory plot is located within each hexagon, and a Phase 3 forest health plot is located within one of every 16 hexagons. Plot measurements are scheduled according to a rotating panel design as indicating by the shading of hexagons. *Source: US Forest Service, 2005*.

1 broadly classifies land as forest or nonforest utilizing aerial photography. Phase 2 consists of ground plots for measurements of basic forest condition variables at an intensity of 1 plot per 2,428 ha (approximately, 125,000 plots nationwide). In Phase 3, 1/16 of the Phase 2 ground plots are visited for more detailed forest health indicator measurements at an intensity of 1 plot per 39,000 ha (approximately 8,000 plots nationwide). The standard FIA ground plot consists of four 7.4 m fixed-radius circular subplots (Figure 4.2) in a triangular arrangement. Within each subplot, a 2.0-m radius microplot is established for measurement of seedlings and saplings. Basic tree and forest condition measurements are taken on the subplots and microplots.

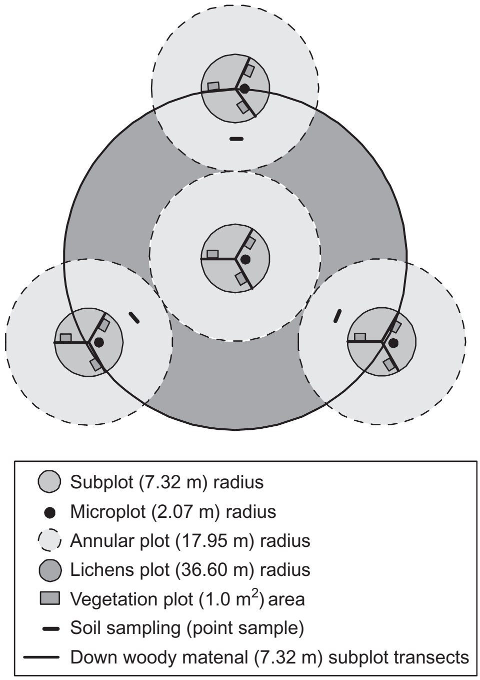

FIGURE 4.2 Field plot layout for FIA forest condition and forest health measurements. *Source: US Forest Service, 2005.*

The forest health indicators measured on the Phase 3 plots focus on measurements that provide quantitative data about specific ecosystem components (Woodall et al., 2011). Tree crown condition reflects overall tree health and may predict the ability of trees to survive and grow. The tree crown indicator (Schomaker et al., 2007) includes measurement of uncompacted live crown ratio, light exposure, canopy position, crown density, dieback, and foliage transparency on trees greater than 12.7 cm diameter at breast height (DBH). These variables can be analyzed separately or combined into estimates of crown volume and health indices.

Down woody material (DWM) is measured because it contributes to fire risk and is important for many wildlife species and for assessing carbon sequestration in forest ecosystems (Woodall and Monleon, 2008). Lichen communities are very sensitive to microclimatic conditions and ambient air quality (Geiser and Neitlich, 2007). The lichen indicator measures cover and composition of lichens on a 0.378-ha circular plot centered on the center of one subplot of the standard FIA ground plot (Jovan, 2008). Data from lichen communities are used to develop regional gradients of response to climate and air quality (Will-Wolf and Neitlich, 2010). Another indicator of air pollution effects developed by the FHM program is the ozone (O_3) bioindicator (Campbell et al., 2007; Smith et al., 2007). Ozone-sensitive plant species

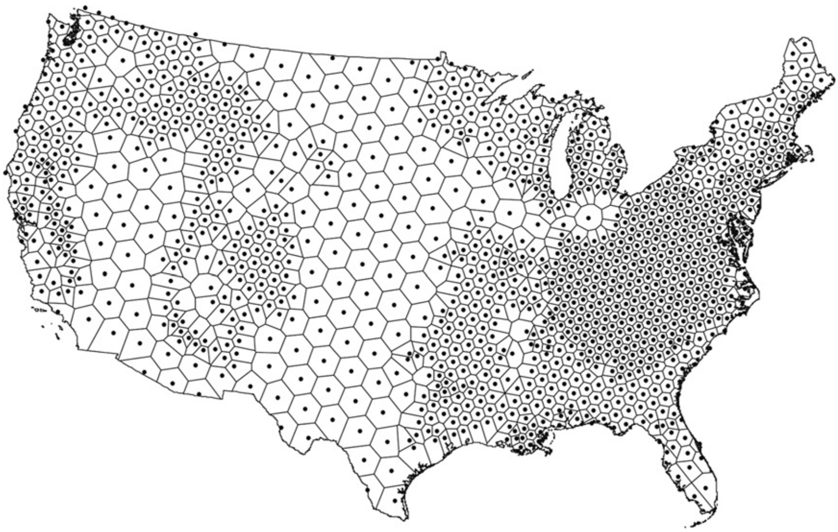

FIGURE 4.3 FIA ozone biomonitoring grid. The grid has four sampling intensities based on ozone-sensitive species and ambient ozone concentrations. *Source: US Forest Service, Forest Health Monitoring.*

are evaluated for symptoms of damage on ground plots on a biomonitoring grid (Figure 4.3) that intensifies sampling in areas with historically higher ambient O_3 exposure (Smith et al., 2007).

Ozone biomonitoring sites are located in forest openings in areas where O_3 exposures are relatively high and sensitive species are common. Plants are rated for foliar injury symptoms using an Ozone Injury Score during mid-to-late summer when O_3 injury is most evident. The intent is to identify areas where O_3 injury is high and relate those to changes in growth, mortality, or diversity.

The soil indicator evaluates soil physical and chemical properties to assess potential to influence the productivity, species composition, and hydrology of forest ecosystems (O'Neill et al., 2005; Woodall et al., 2011).

The vegetation diversity and structure indicator assesses the composition, abundance, and spatial arrangement of all vascular plants on the Phase 3 plots (Schulz et al., 2009; Woodall et al., 2011). Vegetation sampling is conducted in a multiple-scale nested approach utilizing three 1.0 m^2 quadrats per subplot (Schulz et al., 2009). Vegetation data can be used to monitor diversity, track the spread of invasive plants, and investigate impacts of soil chemical and physical changes, O_3 exposures, and climate change.

4.2.1.2 Evaluation Monitoring

The purpose of EM is to determine the extent, severity, and causes of undesirable changes in forest health (Forest Health Monitoring, 2009). An annual competitive process is used to select EM projects which delve into forest health issues identified through Detection Monitoring and other means. Projects are typically 1–3 years in duration and focus on providing more detailed assessments of inciting and contributing factors associated with insect and pathogen outbreaks, fires, air pollution, climatic, and other abiotic stressors. The FHM program recently summarized the results of 150 EM projects completed between 1998 and 2007 (Bechtold et al., 2012). A wide range of topics were evaluated by EM projects during this period: tree disease problems (34% of the projects), insect problems (27%), abiotic stresses (droughts, fires, and air pollution) and indicators (DWM and soil conditions) (25%), and other biotic stresses (invasive plants) and indicators (lichens, tree crowns, and tree declines) (14%). Several EM projects evaluated a dramatic increase in mortality of piñon pine (*Pinus edulis* Engelmann) and ponderosa pine (*P. ponderosa* Dougl. ex Laws.) in the southwestern United States between 2002 and 2003 caused by several species of bark beetles (*Ips* spp. and *Dendroctonus* spp.) following a prolonged drought (McMillin et al., 2008; Negrón et al., 2009; Shaw et al., 2005). The extremely warm drought of 2002 was also identified as a primary inciting factor in the sudden aspen (*Populus tremuloides* Michx.) decline syndrome evaluated by another EM project (Worrall et al., 2010). Increased mortality of aspen covered 220,000 ha, or nearly 17% of the aspen forest type in Colorado.

4.2.1.3 Intensive Site Monitoring

In some cases, the specific causes and/or effects of abnormal forest conditions cannot be established through the EM process. For those cases, FHM includes a component called ISM to support testing of specific cause–effect hypotheses through detailed measurements in a research setting. Ideally, such research is designed to be compatible with, and therefore potentially able to take advantage of, existing data and knowledge from long-term ecological research sites such as LTER sites and NEON (National Ecological Observatory Network) sites. For example, the NEON program is focused on the long-term impacts of climate change, land use change, and invasive species on natural resources and biodiversity, and may be a suitable context for ISM to address terrestrial forest health issues. Many of the LTER sites are oriented around watershed (catchment) issues and may provide a suitable context for aquatic or riparian forest health issues. Until recently, the FHM program was engaged in a pilot ISM project which had a slightly different focus in that it was designed to understand forest conditions in a holistic landscape-scale framework. The Delaware River Basin Pilot Project (Murdoch et al., 2008) combined monitoring and research efforts of several Federal programs to evaluate health and sustainability of forest and freshwater aquatic systems in the Delaware River Basin. The project considered forest health issues such as urbanization, carbon sequestration, air pollution, forest pests, and the interacting effects of those factors. Models were developed to associate data from ISM sites within the project area with extensive landscape-scale information from satellite, aerial, and ground monitoring systems. The pilot project showed that integrating ISM with extensive landscape-scale data was a practical way to address forest health and sustainability issues at multiple spatial scales (Murdoch et al., 2008). From a programmatic perspective, the pilot project emphasized the importance of interagency cooperation and a willingness to modify agency-specific procedures to address clearly identified issues of interagency importance (Murdoch et al., 2008).

4.2.2 Research on Monitoring Techniques

In long-term monitoring programs, there is always a tension between the requirement for consistency of procedures over time and the requirement to adjust the procedures in response to changing information needs. The FHM program has a good track record of combining the consensus of participants with a firm scientific basis when deciding to change monitoring procedures. The Research on Monitoring Techniques component of FHM is designed to provide program managers with scientific information needed to make these decisions. Research and development of the FHM program is currently focused on six major themes:

1. Development of forest health indicators
2. Quality Assurance/Quality Control (QA/QC) procedures
3. Development of techniques for special detection surveys
4. Urban monitoring pilots
5. Risk assessment methodology
6. Monitoring along ecotones.

Here, we provide some examples to illustrate the range of research activities supported by the FHM program.

Forest health indicators: The main focus of the development of forest health indicators has shifted from field plot measurements to applications of remotely sensed data. The research to develop spatially explicit early warning indicators from MODIS images (described earlier) is being combined with research on procedures to monitor land-cover spatial patterns derived from Landsat images (e.g., Riitters, 2011) and FIA inventory data (e.g., Riitters et al., 2012) to better identify the landscape context of forest disturbances and potential consequences for specific types of forest. This research also provides a natural linkage between FHM and ecological monitoring at multiple spatial scales as conducted by the NEON and LTER programs mentioned previously.

QA/QC: In this area, the integration of information and reporting systems through the FHP aerial survey program represents a major achievement of the FHM program. The research challenge was met by the Forest Health Technology Enterprise Team (FHTET) in cooperation with the Remote Sensing

Applications Center who together developed an efficient method for collecting and reporting data on forest insects, disease, and other disturbances utilizing remote sensing and aerial sketch mapping, as described in Section 4.2.1.1.

Techniques for special detection surveys: Research is also needed to develop protocols for special detection surveys, as demonstrated in the case of *P. ramorum* reported in Section 4.2.1.1.

Urban monitoring pilots: Trees in urban areas contribute to human health and environmental quality, but until recently, urban areas were excluded from FHM. The FHM program in cooperation with the FIA program and state agencies developed methods to monitor urban forest structure, function, and health at a large statewide scale, and conducted pilot studies in five states (Cumming et al., 2008). Results suggested that monitoring basic attributes like canopy cover, biomass, and leaf area of urban trees provides information that can be used to track ecosystem services and values such as carbon sequestration and air pollution removal.

Risk assessment: Information about risks to forest health has long been used at the national level to develop policy and to allocate resources to control risks and estimate future resources needed to mitigate impacts. One of the key successes of the FHM program has been the development of a multicriteria risk assessment framework that is aimed at providing consistent and timely risk data at the national level (Krist et al., 2010; see Section 4.2.4).

Ecotones: The project known as "Monitoring on the Margins" is aimed primarily at understanding forest range dynamics and forest gene conservation in relation to climate changes. Because of the current concern for several conifer species found only at high elevations in the western United States (e.g., Keane et al., 2011), the initial research focused on supplementing the ongoing research on that topic, and on understanding how FHM monitoring protocols might be used or modified in order to provide additional information to address the concerns for these species. With the increasing attention given to potential climate change impacts globally, FHM research has since broadened to include a systematic evaluation of the potential ranges (e.g., Hargrove and Hoffman, 2005) and risks to forest genes (e.g., Potter et al., 2010) of all important tree species across the country.

4.2.3 Reporting on Forest Health Conditions in the United States

FHM is of little value unless the observations are translated into information that can be used by the public, by forest managers, and by policy makers. The reporting component of FHM provides for the periodic reporting of forest health conditions in a consistent way over time and space. The original rationale for periodic reporting was to achieve the goal of Detection Monitoring, that is, to identify the type and location of apparently abnormal forest health conditions and trends. The earliest reports (e.g., Brooks et al., 1992) were conceptually similar to traditional forest inventory reports except the statistics described forest health characteristics instead of (or in addition to) traditional forest mensuration characteristics. As described by Riitters and Tkacz (2004), the FHM reporting framework later evolved to help satisfy the national reporting under the international Montréal Process Criteria and Indicators agreement. An example of reporting within that framework was the 2001 FHM National Technical Report (Conkling et al., 2005) which was organized specifically to address forest indicators identified by the Montréal Process, along with an integrated statistical analysis of forest indicator data. Since that time, many of the field plot measurements are now summarized as part of periodic reporting by the FIA program, which is responsible for making those measurements. Furthermore, national reporting pursuant to the Montréal Process has evolved into a framework that emphasizes forest sustainability rather than indicators (e.g., USDA Forest Service, 2011). Today, FHM produces periodic reports at the national level and contributes to periodic reports at the state and regional levels. At the national level, the annual FHM National Technical Report is designed to be a more flexible and dynamic framework than before. For example, the 2008 National Technical Report (Potter and Conkling, 2012) has three general objectives: (1) to present forest health status and trends from a national or a multistate regional perspective using a variety of sources, (2) to introduce new techniques for analyzing forest health data, and (3) to report results of recently completed EM projects funded through the FHM national program. The new framework allows for contributions from a wider range of participants. Contributions to the reports are accepted from throughout the FHM program. All EM projects funded by FHM are required to provide a project summary for the National Technical Report.

Now that FHM information is more widely available in electronic databases, it is easier to include in regional and state forest health reports. Regional reports typically appear online and not in a published format, which allows for rapid updates and thus more effective usage by regional forest managers. FHM data are increasingly used in the ongoing series of reports known as state Forest Health Highlights which are collaborative efforts led by state and federal forest health specialists (http://www.fs.fed.us/foresthealth/fhm/fhh/fhmusamap.shtml). The content of the reports varies according to the current health problems and priorities of individual states. An illustrative example is the 2010 Forest Health Highlights for the State of Oregon (Flowers et al., 2011). That report provided a detailed summary of the data collection effort in Oregon and used FHM and other data to provide maps, statistics, and status reports related to 11 insect species, three disease complexes, and damages from O_3 and bear (*Ursus americanus* Pallas) across the entire state.

4.2.4 Assessing Future Risks to Forests of the United States

Under the direction of the FHM program, the National Insect and Disease Risk Map (NIDRM) project has produced a spatially explicit national risk map at 1 km^2 spatial resolution depicting areas at risk to outbreaks of insects, diseases, and other mortality agents (Krist et al., 2007). The mapping is driven by 188 models which predict how individual tree species will react to various mortality agents, based on the interactions between predicted agent behavior and forest parameters drawn from the FHM and FIA programs. The 2006 NIDRM estimated that more than 23 million ha of forest land in the United States are at risk of experiencing mortality of 25% or more of the standing live basal area of trees greater than 2.5 cm DBH over the next 15 years. The majority of the risk can be attributed to 11 specific agents including: several species of bark beetles attacking western conifers, oak decline, southern pine beetle (*Dendroctonus frontalis* Zimmermann), root diseases, and gypsy moth (*Lymantria dispar* L.). The 2006 NIDRM has provided a valuable tool to help determine broad prevention strategies for the major insects and diseases affecting forests of the United States. The FHM program is currently updating and revising the NIDRM to incorporate the latest forest inventory data, improved risk models, and higher resolution satellite imagery. The next version of the NIDRM is expected to be completed during 2012 and will display risk at a 0.0625 km^2 resolution. Future enhancements will include incorporation of future climate change scenarios.

4.3 FOREST MONITORING IN CANADA: NATIONAL EARLY WARNING SYSTEM AND THE AOSR CASE STUDY

4.3.1 Early Attempts and Recent Systems

Early examples of national scale at forest monitoring in Canada were reported by McLaughlin and Percy (1999). The Acid Rain Early Warning System was initiated in 1984 and consisted of 150 rectangular plots (10×40 m) (with associated soil subplots) purposively selected and stratified by forest regions. Approximately, 11,700 trees with DBH $\geq$ 10 cm were present in the plots (Hall, 1995). Investigations were carried out according to Standard Operating Procedures (SOPs; e.g., D'Eon et al., 1994) and following different time frequency: foliar symptoms, broadleaves seeds, pests (foliar insect/disease, woody tissue insect/disease, and severity), tree condition (mortality, live crown height, crown damage, needle retention) were assessed with annual or seasonal frequency; regeneration, saplings, and ground vegetation were assessed biennially; soil and foliar nutrients as well as radial growth were collected every 5 years. After its termination, ARNEWS was replaced by other programs within, or with the cooperation of, the Canadian Forest Service (2011; http://cfs.nrcan.gc.ca), with emphasis on carbon monitoring, accounting, and reporting, a revised National Forest Inventory (NFI; e.g., Gillis, 2001; Gillis et al., 2005), regional initiatives (e.g., Hopkin et al., 2001), and paralleled by ecological monitoring initiatives, like EMAN (the Ecological Monitoring and Assessment Network; e.g., Vaughan et al., 2001). From 1994 to 2010, EMAN was established as a national network of organizations involved in ecological monitoring in Canada to better detect, describe, and report on ecosystem changes (Vaughan et al., 2001). The network is based on government and nongovernment organizations, academic institutions, aboriginal organizations, and community groups. For its component related to terrestrial ecosystem, EMAN adopted SOPs to monitor among other, soil, plant diversity, lichens, tree health and regeneration, and saplings (see http://www.ec.gc.ca/faunescience-wildlifescience/default.asp?lang=En&n=9C4F74C5-1, accessed on August 2012).

4.3.2 FHM in the AOSR of Alberta, Canada

4.3.2.1 Rationale

The Canadian Oil Sands represent the third largest oil reserve in the world, after Saudi Arabia and Venezuela. Among the three deposits in Alberta, the AOSR in north-eastern Alberta is the largest (Figure 4.4).

Oil production in the AOSR has been steadily increasing over the past decade, from 0.6 million barrels day^{-1} in 2000 to 1.6 million barrels day^{-1} in 2011. Production is expected to be 3.5 million barrels day^{-1} by 2025. While there has been a general pattern across North America of decreasing levels of sulfur (S), oxidized nitrogen species (NO_x), mercury (Hg) deposition, and O_3 since the 1980s, important exceptions exist. There is evidence for increasing NO_x deposition across western North America and stable or increasing ammonium (NH_4) (Hidy et al., 2011). The implications of air pollutants to North American ecosystems have recently been reviewed (Clair et al., 2011). In the AOSR, north-eastern Alberta, Canada, atmospheric emissions of S, N, trace metals, and organic compounds, and their possible effects on the terrestrial environment including soil acidification, eutrophication of water bodies, and boreal forest health are of concern.

In the AOSR regional air pollution dispersion model domain, combined industrial stack/nonindustrial emissions of sulfur dioxide (SO_2) were listed as 363.9 t per day (t d^{-1}). Emissions of NO_x from industrial stacks/mine fleets/nonindustrial sources were listed as 310 t d^{-1} (Teck-Silver Birch, 2011). Regional dispersion modeling by Davies (2012) shows that the main influence of the SO_2 sources was within a nominal 20 km radius where the deposition was greater than 5 kg S ha^{-1} year^{-1}. The influence of the sources decreased from 5 kg ha^{-1} year^{-1} at 20 km from production facilities to about 3 kg S ha^{-1} year^{-1} at 50 km. At a distance of 100 km, the deposition converged to the background value of about 2.2 kg S ha^{-1} year^{-1}. For NO_x, there is a similar trend of decreasing deposition with increasing distance from the main NO_x emission sources (fixed stacks and mines). The influence of the NO_x sources was within a 20-km radius where the deposition was greater than 4 kg N ha^{-1} year^{-1}. The influence of the sources decreased from 4 kg N ha^{-1} year^{-1} at 20 km to about 2 kg N ha^{-1} year^{-1} at 50 km. At a distance of 100 km, the deposition converged to the background value of about 1.8 kg N ha^{-1} year^{-1} (Davies, 2012).

FIGURE 4.4 Location of the Alberta Oil Sands. *Source: Canadian Association of Petroleum Producers, 2012.*

4.3.2.2 Forest Monitoring 1980–2004

The AOSR bitumen deposits lie beneath the Boreal Plains Ecozone consisting of upland jack pine (*Pinus banksiana* Lamb.), aspen (*P. tremuloides* Michx.), mixed forest, and wetlands (ca. 19%). Monitoring of air pollutant effects on forests in the AOSR has been underway to varying degrees since the first oil sands operation began in the 1970s (Addison, 1980; Addison et al., 1986). Since 1997, the Wood Buffalo Environmental Association (WBEA; www.wbea.org), a multistakeholder, not-for-profit association located in Fort McMurray, Alberta, has been working to quantify the relative contributions of each production method to air quality, atmospheric deposition to terrestrial receptors, and more recently, forest health within a 68,444-km^2 airshed.

In 2004, resampling of 13 forest plots compared vegetation and soil status to those reported from the previous 1998 sampling. Monitoring of foliar vigor and stand condition in 2004 revealed no emission-related effects on either needle retention or condition, and no anomalous damage/health issues in any of the 13 study sites (Jones and Associates, 2007). Analysis of foliar chemistry data showed that local industrial emissions were evident in increased concentrations of total S, inorganic S, iron (Fe), and nickel (Ni), all of which are known to be components of oil sands emissions. However, despite evidence of increasing elemental concentrations in foliage with increasing predicted deposition levels, there was no demonstrated evidence of a negative effect on forest productivity.

4.3.2.3 FHM 2008–2012

4.3.2.3.1 The Design

In the AOSR, monitoring of terrestrial effects is a regulatory requirement in many industry approvals to operate by the Government of Alberta. Effects from atmospheric industrial emissions are managed under cumulative management frameworks and regional land use plans. Retrospective analysis (Percy, 2002; Percy and Ferretti, 2004) of monitoring programs has demonstrated air pollution to be an important factor in forest ecosystems when, in the design: scales of stressors were considered; monitoring was coupled with process-oriented research; appropriate indicators and endpoint were measured; and, there was dedicated effort over one or more decades to fully document the cumulative role of air pollutants on long-lived organisms such as trees. Following scientific peer-review of the existing program in 2006/2007, terrestrial environmental effects monitoring (TEEM) adopted a new design in order to implement a more ecological, and less anthropocentric approach for determining cause–effect relationships between air pollutants and forest ecosystem health in the AOSR. Key elements of the new design are (1) the adoption of a forest health approach as defined by McLaughlin and Percy (1999) and adopted by the UNFF (2003); (2) a changed conceptual design from the original categorical (1998–2004) to a pattern/ecologically oriented design; (3) relaxation of the previously held stand area restriction; (4) establishment of a robust plot network with sufficient adaptive capacity (sampling with replacement) under rapid AOSR industrial development; (5) addition of ecologically analogous sites to minimize within and between plot variability; thus, maximizing the pollution signal and cost-effectiveness; and (6) the comeasurement of inputs (meteorology, pollutants), and responses (indicators, endpoint) in space and time (Table 4.1).

The new science-enhanced WBEA forest health network (FHN) is structured to evaluate responses at appropriate frequencies across gradients of forest resources that sustain them (McLaughlin and Percy, 1999) was in place. The plots are dispersed across five distinct zones of S and N deposition.

The WBEA FHN consists of 23 forested, interior-to-stand plots in Boreal Plains (21) and Boreal Shield (2) ecozones (Figure 4.5). The plots extend out 150 km to the north, west, and east from Fort McMurray, with two plots in Saskatchewan. Nine of the plots are equipped with towers holding passive monitors above the tree canopy and measuring monthly average concentrations of SO_2, NO_2, O_3, HNO_3, and NH_3. Eleven other nonforested sites contribute monthly passive data for the region (Percy et al., 2012).

The macro- or subplot layout in use was adapted from ARNEWS (D'Eon et al., 1994) and comprises a centrally located 10 m × 40 m rectangular main vegetation plot, with four 10 m × 40 m rectangular soil plots (each divided into four microplots) situated away from the vegetation plot. Complete details on plot layout, locations, SOP including the analytical procedures, and supporting scientific literature citations are included in the draft (final 2013) TEEM Forest Health Monitoring Manual (Foster et al., 2011).

By 2012, five forest health plots (namely, 104, 107, 201, 213, 316) were equipped with 30 m tall comeasurement towers. Three more towers will be added by 2014 to complete the grid. With no power available, and a need for continuous meteorological measurements to account for the influence of interannual climate differences, a second tower at each plot is fitted with a solar array (five panels) and ground-installed batteries (six) to provide year-round power. Continuously measured wind direction/speed, relative humidity, temperature, radiation (global or PAR) data from 10 to 2 m above canopy height, 2 m below canopy, and 2 m above ground are uploaded daily through cell modem/satellite connection to the WBEA database. Barometric pressure is measured at one height. Automated precipitation measurements are collected and uploaded, along with continuous CO_2 and O_3 at several of the plots. Below-ground soil moisture and temperature sensors operate seasonally at two depths and these data are also transmitted to the database. Plant root simulator (PRS^{TM}) probes (ion exchange membranes) constantly accumulating ions as they become available in solution are installed to determine the soluble ion concentrations at two soil depths (10 and 50 cm). Bulk and throughfall deposition is measured.

In 2011, the WBEA FHN of plots (two were burned during a 700,000-ha regional fire event May–June) was intensively sampled over a 6 weeks period as part of the routine cycle for above- and below-ground measurements (1998, 2004). Tree allometry was measured, and tree cores taken on off-plot trees beside the 0.04 ha permanent plots. Foliar samples were collected for chemical analysis from the upper-third crown of the off-plot, numbered trees. Canopy cover, frequency of occurrence, and composition by canopy cover was evaluated in microplots for the ground cover and forb species. Soils were sampled at various depths in four subplots located away from the vegetation plot. Tree condition on each plot was assessed by forest health specialists with Alberta Environment and Sustainable Resource Development. Insect/disease incidence and severity is scored because of the potential for air pollutant–

TABLE 4.1 Receptor Response Indicators and Supporting Science Measurements Used in the Wood Buffalo Environmental Association Forest Health Monitoring Program

Vegetation	Soil	Lichens	Source–receptor	Meteorology
Plant community assessment	pH	Epiphytic lichen community composition	Fixed, mobile, fugitive, and natural source type chemical fingerprints	Temperature, wind speed/direction, relative humidity, and radiation at four levels
Needle retention	Exchangeable cations and cation exchange capacity	Total N and S	S, N, Pb, Hg stable isotopes in emissions, and lichen/tree/soil receptors	Precipitation frequency and amount
Foliar analysis Total C, N, and S Total Ca, Mg, K, and Na Inorganic SO_4–S Inorganic SO_4–S/organic S ratio Total Fe, Al, and Mn Micronutrients Cu, Zn, B, and Mo Potential metal contaminants Ni, and V	Total C, N, and S	Potential metal contaminants	Ambient air quality monitoring with continuous and time-integrated techniques	Soil temperature and soil moisture content
Bark deposition	Available SO_4–S, NH_4–N, NO_3–N, and PO_4–P			
Cuticular wax structure and chemistry	Calculated C:N and base cation: Al ratios, % base saturation			
	Litter decomposition			
	Ectomycorrhizal associations			

Modified from Percy et al. (2012).

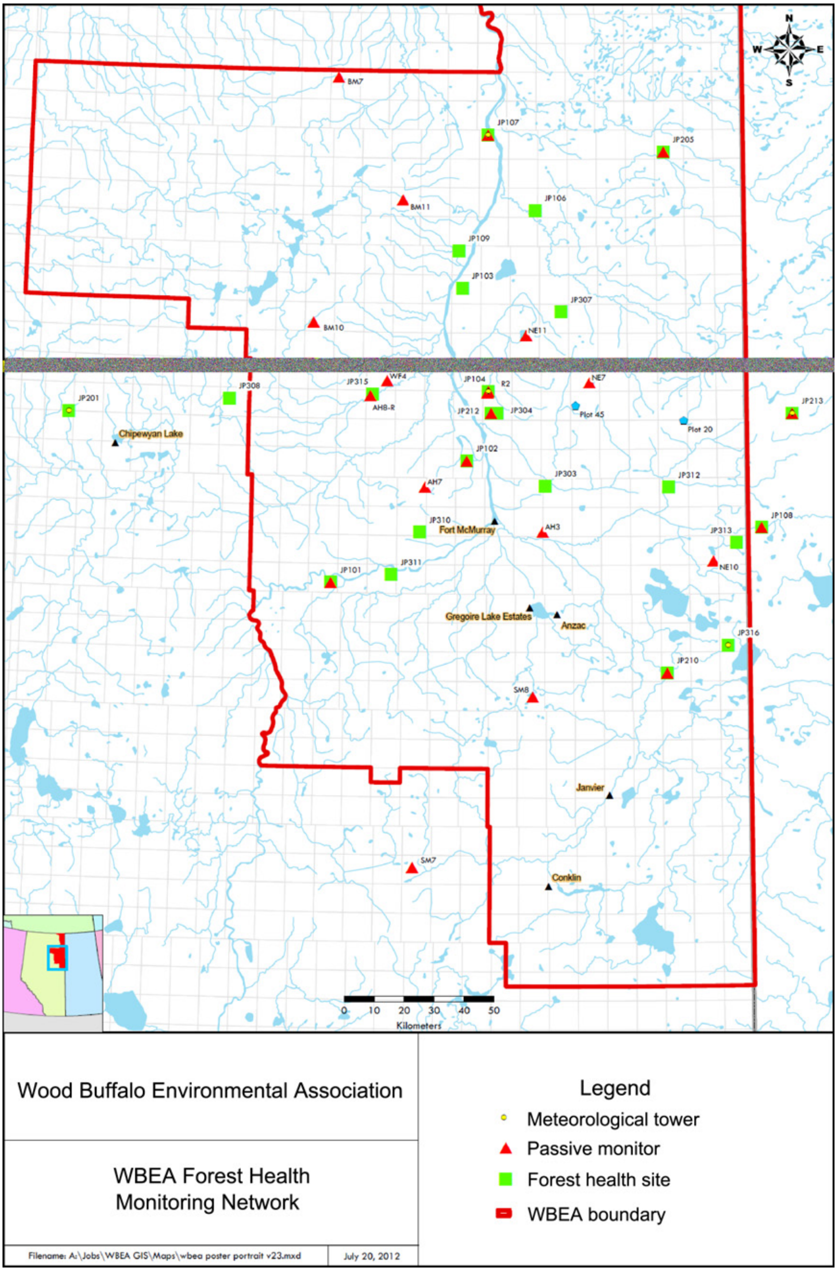

FIGURE 4.5 The WBEA forest health monitoring network of interior plots and passive monitoring locations. *Source: Wood Buffalo Environmental Association.*

insect interactions. Annual assessments will be made beginning 2012 on all WBEA FHN plots.

WBEA FHN in stand interior plots is being coupled where possible with jack pine edge plots to provide early warning of indication change. In 2012, 25 edge plots were established near new ecologically analogous interior plots. Many of these sites will have minitowers installed into the fen in front of the edge trees. The minitower will be equipped with continuous, solar-powered meteorological measurements, and passive samplers. Indicators will be measured in the early warning edge plots on a 3-year cycle (beginning 2013). Each second suite of measurements (i.e., 2016) will coincide with the intensive, 6-year cycle for interior plots. It is anticipated that the early warning indicators will provide a window of opportunity for detection well in advance of eventual quantification within stands.

4.3.2.3.2 Source to Sink Monitoring to Support Forest Health Measurements

In 2008, WBEA–TEEM adopted the source-to-sink approach, monitoring by measuring at key components along the emissions, chemical transformation, deposition, effects, and endpoint pathway (Percy et al., 2012). Conditional time averaged gradient (COTAG) measurements taken 2 m above fen surfaces near an ecologically analogous WBEA FHN stand provide site-specific deposition velocities for S and N compounds that can be used to validate/adjust inputs for regional dispersion modeling. Ion exchange resins (Fenn et al., 2009) collect bulk deposition in the open and beneath jack pine canopies in order to estimate regional SO_4 and NO_3 loadings near source, and at remote WBEA FHN plots. Stable isotope signatures measured in stack particulate, jack pine foliage and soils trace the transfer of S and N to forest receptors. “Real-world” characterization of emissions of large stacks and 400 t mine fleet heavy haulers has been used to chemically fingerprint (S, N, PAH, trace elements, organics) emission source types. Atmospheric deposition to terrestrial receptors is being measured and mapped using S and N concentrations in two epiphytic lichen species growing at 359 sampling sites within the AOSR. Patterns for S and N in the lichens have been identified (Berryman et al., 2010). Further analysis has been completed using state of the art preparation and analytical techniques for 42 trace elements, coupled with analysis for lead and mercury isotopes to distinguish between natural/anthropogenic, local/long range inputs.

The geospatial array of 2008 lichen elemental concentrations has been used as an input to AOSR regional dispersion modeling to verify accuracy (over-, underprediction) patterns in modeled deposition with distance from main fixed and mobile emission sources. Source apportionment techniques and receptor modeling have then been used to attribute over 87% of variability in lichen elemental concentrations to source type (i.e., oil sands processing, mining, forest fires, urban, fugitive dust). The reader is referred to Percy (2012) for the results of this source to sink suite of 2008–2012 measurements and modeling.

4.4 CONCLUSION

Different FHM initiatives have been undertaken in Canada and United States since the 1980s. The timing is in line with similar initiatives launched in Europe (see Chapter 2). In the United States, the FHM has evolved into a system tied to the FIA and organized into a series of components ranging from large-scale monitoring plots to intensive sites and including remote sensing from satellites and aircrafts. A hallmark of the FHM program has been the development and implementation of nationally consistent measurement protocols for a suite of forest health indicators along with QA and QC. In recent years, the program has shifted to a more issue-driven approach for analysis and reporting on significant forest health issues. This has provided timely assessments of key forest health problems as they develop and provides land managers with critical information to inform land management decisions. Although in the past the FHM program has always provided monitoring and assessment of all forested lands in partnership with state and federal agencies, the challenge now is engage new partners and better leverage scarce resources in support of long-term monitoring of forest health.

In Canada, after the termination of the ARNEWS programme in 2000, forest monitoring is mostly carried out by means of the NFI, ecological monitoring programmes (EMAN), and regional initiatives such as the WBEA program in the AOSR an example of regional, issue-specific forest monitoring. The goal of the WBEA FHN is to elucidate the role of industrial air emissions in AOSR on forest ecosystem health. A multidisciplinary, integrated program has now been deployed to the landscape using a forest health approach. Coupled with the WBEA air quality monitoring network, the new WBEA FHN design will be essential for tracking and evaluating the effectiveness of governmental policies/actions on airshed management, a key component of any Air Quality Management System (AQMS; Bachmann, 2007). Integrated into the full science-enhanced TEEM program, the WBEA FHN will be essential in meeting the Government of Alberta's regulatory and management requirements under Regional Land Use Planning, and Cumulative Effects Management. It will also provide stakeholders with more accurate, timely, and scientifically credible information upon which to base regional air quality and emissions management decisions.

Despite their different focus (international, national, regional), it is worth noting that commonality exists among the various programs (ICP Forests, U.S. FHM, and WBEA FHN) in terms of aims, possible stakeholders, and structure. When considering that cooperation in the field of developing forest health indicators is also currently occurring between U.S. FHM and Mexico (see e.g., the workshop held in Guadalajara, Mexico, April 26–May 1, 2009 http://www.fs.fed.us/foresthealth/fhm/misc/2009-tkacz-mexico-fhm.pdf), existing similarities may provide a valid ground for future cooperation that can be of mutual value.

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