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Potential of a national monitoring program for forests to assess change in high-latitude ecosystems

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ABSTRACT

Broad-scale monitoring in Alaska has become of increasing interest due to uncertainty about the potential impacts of changing climate on high-latitude ecosystems. The Forest Inventory and Analysis (FIA) program is a national monitoring program for all public and private forestlands in the US, but the program is not currently implemented in the boreal region of Alaska. We provide an overview of the strengths and weaknesses of the FIA system for monitoring the potential impact of climate change on Alaska's species, communities, and ecosystems. The primary strength of the system is a scientifically rigorous design-based statistical estimation method that produces estimates of forest attributes with known sampling error and quantifiable measurement error. The weaknesses of the system include low power for small area estimates, lack of spatial context and contiguity, and difficulty in inferring causality of factors when changes in monitored attributes are detected.

Climate change is expected to impact many components of boreal ecosystems, but for most indicators the direction and magnitude of change are difficult to predict because of complex interactions among system components. Status and trend information provided by FIA monitoring that could be helpful to conservation decisions includes abundance and rarity of vascular plants, invasive species, biomass and carbon content of vegetation, shifting vegetation species distribution, disturbance frequency, type, and impact, and wildlife habitat characteristics. Because of unique factors such as the low level of infrastructure, modifications to the FIA monitoring system used in the conterminous US have been proposed for Alaska. Remote sensing data would play a greater role in meeting monitoring objectives, and sampling intensity of field plots would be reduced. Coordination with other national, regional, and local monitoring efforts provides potential for increased understanding of change in boreal ecosystems at multiple scales.

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1. Introduction

Monitoring is the dubious science of conservation, frequently criticized as being unscientific, unfocused, and ineffective (Lovett et al., 2007). Yet monitoring programs play an important role in conserving biological diversity. Large-scale long-term monitoring programs are critical to detecting trends and changes in species prevalence (Nielsen et al., 2009). Monitoring of ecological indicators may provide early warning of problems (Dale and Beyeler, 2001). Adherence to international agreements such as the Kyoto protocol or the Convention on Biological Diversity may require standardized reporting of monitoring results (Vidal et al., 2008). Monitoring is considered an essential component of adaptive management, as it is a prerequisite for understanding whether management actions had the intended effect (Walters, 1986).

Recently, monitoring in northern latitudes – boreal and arctic ecosystems – has become of increasing interest because of changing climate. Predictions for temperature increases in the next century from most global circulation models are highest for northern latitudes (Christensen et al., 2007). In some regions warming trends are already apparent: in the boreal forest region of Alaska, USA, the average mean annual temperature increased 1.6 °C from 1949 to 1999 (Stafford et al., 2000). It is believed that these changes in climate are causing numerous direct and indirect impacts in arctic and boreal ecosystems, including thawing permafrost, altered fire regimes, broad shifts in composition and structure of vegetation, and changes in energy, chemical, and hydrological cycles (Euskirchen et al., 2009; Hinzman et al., 2005). While modeling can often be used to generate predictions of key indicators, because of the complexity of interactions and multiple feedbacks in ecosystem components, accurately predicting trends of even simple indicators is difficult. Thus monitoring in the northern latitudes is critical to early detection of trends and determining accuracy of model predictions.

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However, monitoring that is effective and efficient is difficult to achieve (Nichols and Williams, 2006). Failure to clearly state objectives and consider statistical power is common (Legg and Nagy, 2006). Agencies that implement monitoring often fall into the trap of data gathering without sufficient consideration of hypothesis testing and experimental design (Noss, 1990). Monitoring programs may lack clear links to decision making (Olsen et al., 1999). In many countries, different agencies collect different types of monitoring data, but integration is complicated when objectives and spatial and temporal design are varied (Henry et al., 2008). Logistical issues are often not adequately considered.

These problems are compounded in northern latitudes. Inclement weather and lack of roads greatly increases cost and limits accessibility to sample sites. Short growing seasons reduce time for vegetation surveys, both in the field and using remote sensing technologies. Remote sensing systems are frequently optimized for the temperate latitudes, reducing availability of data at high latitudes. Relatively low population levels and a lack of infrastructure increase logistical problems, and also lead to assumptions that monitoring is unnecessary. In the US, until the recent recognition of the impact of climate change on conservation issues, there was an assumption that monitoring programs did not need to be as extensive for the boreal and arctic regions because those lands were mostly undeveloped. Thus, in the US only reduced or minimal monitoring programs have been used in Alaska by the two primary federal programs that monitor terrestrial vegetation, the USDA Natural Resources Conservation Service's National Resources Inventory (NRI) program and the USDA Forest Service's Forest Inventory and Analysis (FIA) program (Spaeth et al., 2003; van Hees, 2009).

Although FIA, initially called Forest Survey, began conducting inventory on public and private US forests in 1928, timber remained a primary focus through the 1970s (LaBau et al., 2007). In Alaska, the focus on timber meant that inventory was concentrated on the maritime temperate rainforest in southeast Alaska (Fig. 1), as most of the boreal forest has growth rates that would be incapable of supporting sustained timber harvest. The exception to this was some limited inventories in the 1970s of the roughly 6% of the boreal forest that met timberland definitions, most of it located along river drainages. In the 1980s and 1990s, in response to increasing interest in environmental quality and conservation, FIA inventories in many parts of the US gradually shifted away from a timber emphasis toward a more comprehensive suite of forest monitoring indicators. In the 1990s, under the Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP), a separate forest health monitoring program was developed for the US (Olsen et al., 1999). However, Alaska was not included in the program, perhaps due to a combination of difficult logistics and the perception that forest health issues were more critical in more populated regions. Thus the historical context of US forest inventories has resulted in most US states having long-term monitoring data collected over multiple decades, while the 45 million ha of boreal forest has never had a baseline inventory.

In 1998, the Farm Bill substantially revised FIA. The revised program was merged with EMAP's forest health monitoring program and a process to develop a set of nationally consistent monitoring protocols was started. As of 2010, this revised FIA program has been implemented throughout the US, with the exception of the boreal forest region of Alaska. In Alaska, the current FIA monitoring program consists of the maritime temperate rainforest ecoregion and a small portion of the boreal forest on the western portion of the Kenai Peninsula (Fig. 1). Although currently excluded, a modi-

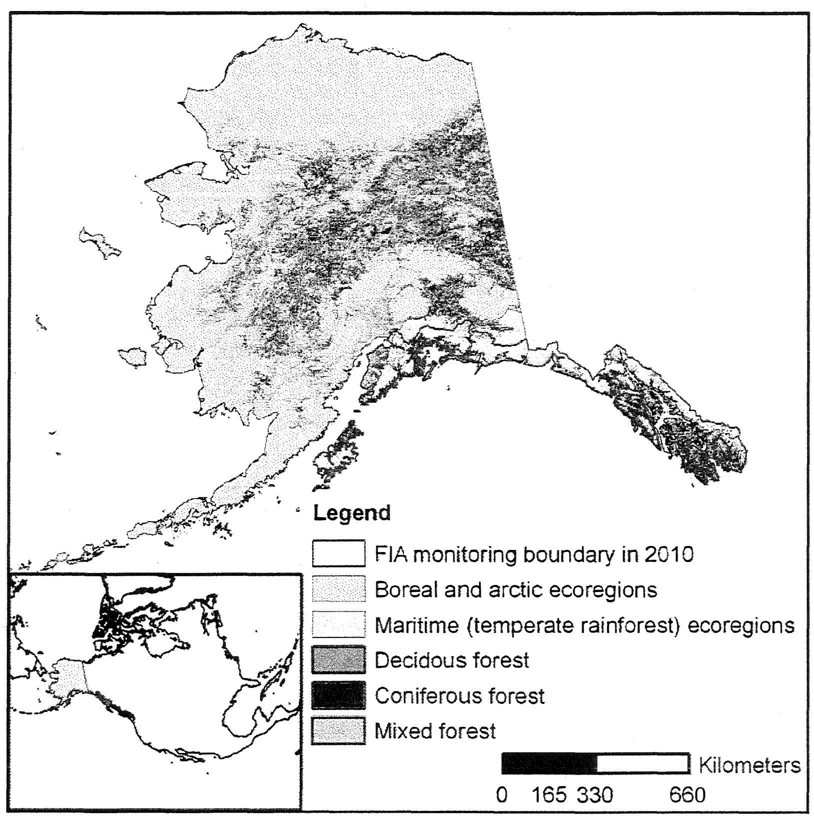

Fig. 1. Forests within the maritime (temperate rainforest) ecoprovinces are monitored by the FIA program, but boreal forests in Alaska are not currently monitored except on the Kenai Peninsula. Data sources: Spencer et al. (2002) and Homer et al. (2007).

fied monitoring program for the entire boreal region is one of the goals for the national program (USDA FS, 2007). Our objective in this paper is to review the potential contribution of this national monitoring program to conservation management decisions for the boreal forest region of Alaska. In particular, we discuss the strengths and weakness of the FIA program for monitoring the possible impacts of climate change on Alaska's forests. The following three sections present (1) the monitoring design of the national FIA program and proposed modifications for Alaska, (2) examples of diverse applications relevant to conservation management in northern latitudes, and (3) a discussion of the strengths and limitations of the program.

2. Sampling design

A statistically sound design for monitoring is needed for hypothesis testing. The national FIA design considers the population of interest to be all possible sample points (an infinite population) within a defined area such as a state or region; attributes of the sampling unit are measured on the ground with four fixed-area nested subplots centered on each point (Bechtold and Patterson, 2005). The national design is spatially and temporally balanced. Spatial balance is achieved by using a tessellation of hexagons superimposed across the population, with one sample point selected randomly within each 2400 ha hexagon (Fig. 2). Temporal balance is achieved by systematically assigning each hexagon to a panel and measuring one panel each year. In the western US, 10 panels are used to create a 10 year remeasurement interval, while 5–7 panels are used in the eastern US for a 5–7 year remeasurement interval.

Where FIA is currently implemented in southeast and southcentral Alaska, sampling is the same as for other western states: one sample plot per 2400 ha with a 10 year remeasurement interval and a balanced sample taken annually. Although the southeast Alaska region is largely unroaded and difficult to access, the use of both boats and helicopters does make implementation of a balanced annual sample feasible. When the FIA program was revised in 1998, the proposed system for the remainder of Alaska was a sampling intensity of approximately one plot per 10,000 ha and a 20 year remeasurement interval. While the current proposal for the boreal region calls for approximately one plot per 12,000 ha, the sampling design could be altered in the future since monitoring has not yet begun. One plot per 12,000 ha would result in more than 3600 forested plots for the boreal region, as some plots fall in partially forested areas.

Sampling methods with some degree of spatial regularity are the most efficient for many types of environmental populations (Stevens and Olsen, 2004). Spatial balance allows more efficient estimates of change resulting from disturbances such as wildfire or disease, which causes points in proximity to be more similar than points far apart. In the boreal region of Alaska, wildfire is common and, because suppression is limited, mean fire size is larger than fire size in temperate regions, making the spatially balanced design particularly advantageous (Fig. 3). The spatially balanced design used by FIA results in equal probability of selection for any point, but the probabilities of selection for points within the same hexagon are not independent.

Equal-probability sampling is inefficient when variance of an indicator varies between different subsets of a population, as is typical for most indicators in different vegetation types. Stratified sampling is often used as a more efficient alternative to equal-probability sampling for assessment at a single point in time. However, when extended to long-term monitoring, experiments with stratified sampling by FIA and other monitoring programs have of-

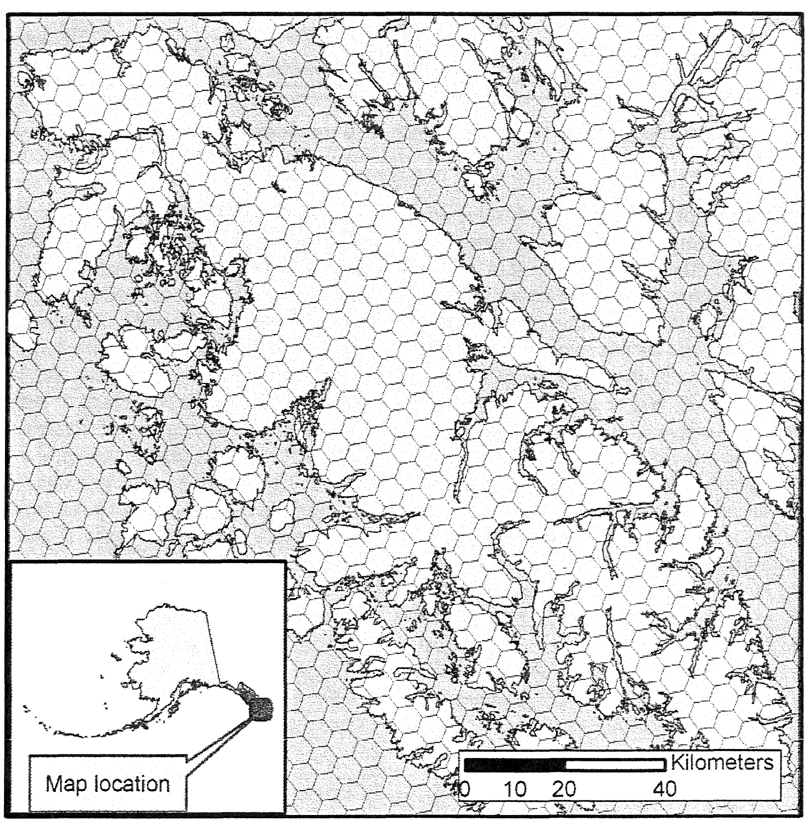

Fig. 2. Each FIA sampling unit is randomly located within a 2400 ha hex, as shown here for Prince of Wales Island in the Alexander Archipelago of southeast Alaska.

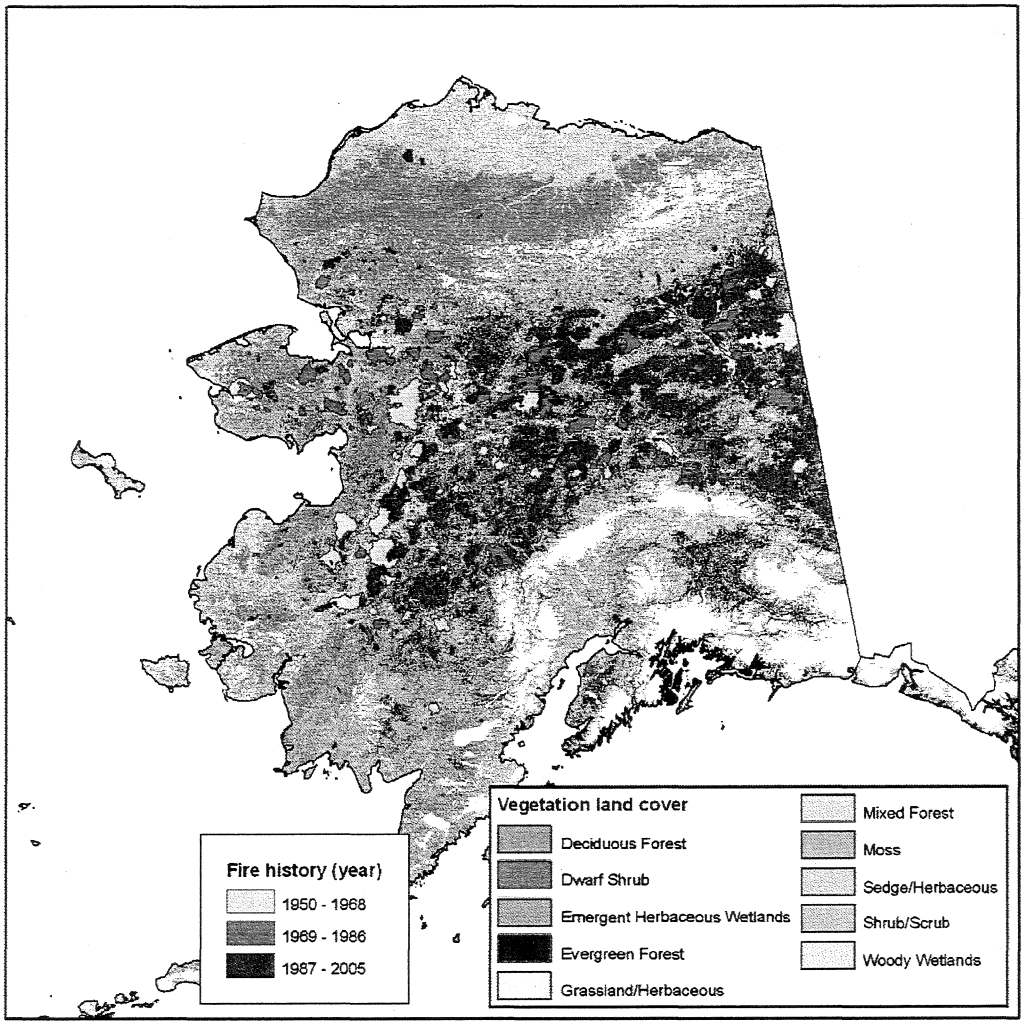

Fig. 3. Boundaries of fires 1950–2005; limited fire suppression in the boreal region of Alaska results in large fires and spatial autocorrelation of vegetation attributes. Vegetation data source: Homer et al. (2007).

ten failed, because of the difficulties of keeping track of sampling frequencies that vary by both time and space among numerous vegetation strata (LaBau et al., 2007; Overton and Stehman, 1996).

In the western US, the FIA inventory design is temporally balanced by measuring a systematically-selected one-tenth of field plots each year. Temporal balance allows the use of data from any single year, or combination of years, as a population sample. This is useful for the conterminous US, where increased area can compensate for the reductions in sample size realized from using the data from a single year. However, the boreal region of Alaska is not large enough to allow one-tenth of the proposed sample, or one plot per 120,000 ha, to be useful for most estimates. In addition, collecting data from sites across the region within a single field season creates logistical difficulties. Thus proposals for implementation of FIA monitoring in the boreal forest region do not include the temporal balancing used in the rest of the US. Instead, the boreal region would be divided into five areas. Under the low cost proposal for the region, each area could have an inventory completed within a 5 year interval, resulting in a complete inventory of the region approximately every 20–25 years. If available, additional funding could be used to reduce the interval between remeasurement.

While every land and water point in the population has a probability of being included in the sample, the FIA program only collects field information at points that fall into forest.[1] Limiting monitoring to forests is a consequence of FIA's mission and historical development as a program housed administratively within the Forest Service. A separate federal program, NRI, conducts assessments of non-federal rangelands, and the overlap of objectives has led to suggestions that the programs be merged (Olsen et al., 1999). For conservation-related decisions, the lack of detailed information on non-forest land is a drawback of current federal monitoring. Many species in Alaska require the combination of different types of habitat, which means that monitoring a particular subset of land type (forest, shrubland, tundra, grassland, wetland) is of limited benefit for many conservation purposes. However, the land cover and land use of every FIA sample point is assessed at each sample period in order to determine whether new areas qualify as forest and to quantify changes to and from forest land; some FIA regions have used this information in tandem with remotely sensed imagery to assess the abundance of different land cover types and their changes over time (Kline et al., 2007).

Monitoring that spans different land types is particularly critical when climate changes. Complex interactions among ecosystem

[1] The definition of forest used by FIA includes lands that were previously forest but which have had recent disturbances such as windthrow or harvest that temporarily remove tree cover.

components results in contradictory forces on the system, making prediction of the overall direction and magnitude of trend difficult. For example, increased growing season and warmer temperatures over the next century is predicted to generate increases in forest in northern Alaska (Euskirchen et al., 2009). However, thermokarsts, where the physical foundation of soil erodes from thawing permafrost, can collapse boreal forests, to be replaced over time by meadows, bogs, and lakes (Osterkamp et al., 2000). Thus even the direction of change in simple indicators, such as area of forest land, can be difficult to predict.

Natural disturbances further complicate direct impacts from temperature increase. Longer and warmer summers can increase fire frequency, which in turn affects permafrost and alters rates of dispersal and growth for boreal species (Wirth et al., 2008). Insects and diseases that impact forests are also likely to be affected by climate shifts (Bentz et al., 2010; Kliejunas et al., 2009). As extensive changes in species composition and vegetation structure seem likely, a modification of the FIA system to allow monitoring of more than forested areas would make the system more beneficial for managers in Alaska. Some federal landowners, such as the Chugach National Forest in south-central Alaska, have extended FIA plots and vegetation measurements onto non-forest lands using compatible sampling protocols, but comprehensive inventories throughout the US are lacking.

For any indicator, an estimate of accuracy is required for interpretation. For monitoring indicators over time, knowing the uncertainty of estimates is necessary to determine whether change has occurred and to allow for the construction of confidence intervals around the estimated rate of change. The FIA program uses standardized estimates of sampling error to understand the component of uncertainty resulting from using a sample to estimate population parameters (Bechtold and Patterson, 2005). A subset of sampling units is selected for measurement by a second independent field crew to provide information about measurement error. A quality assurance program includes specification of data collection methods and tolerances, training and certification programs for field crew, automated error-checking in the field and office, and peer review of methods and analysis.

The sampling intensity in the contiguous United States of one field plot per 2400 ha means that estimates for most indicators are often only sufficiently precise for practical management or policy decisions at an ecoregional, state, or national level. Some managers do increase the sample for their land (or rely on their own inventory systems), as do some states. Remote-sensing classifications are routinely used by FIA to improve the precision of estimates based on field-plot measurements using double-sampling for stratification or post-stratification with spatially-complete data (Bechtold and Patterson, 2005; MacLean, 1972). In southeast and

Table 1
Selected monitoring variables that could be used to assess impacts of climate change for Alaska boreal forests using Forest Inventory and Analysis plots. Climate-related driver abbreviations: P, precipitation; S, snow; T, temperature; GS, growing season; W, wind speed; CC, cloud cover; RH, relative humidity.

Type	Variables	Primary climate-related drivers	Example processes and mechanisms
General forest attributes			
	Land cover (e.g., forest, tundra, wetland)	P, S, T, GS, CC, RH	Permafrost thaw, biome shifts, treeline increase, lake/wetland water level changes
	Land development	Indirect	Displacement of villages from permafrost thaw, sea level rise
	Forest age	P, T, GS, CC, RH	Changes in species composition, disturbance frequency
	Forest density	P, T, GS, CC, RH	Changes in growing degree days, site quality, species composition
	Tree mortality	P, T, CC, RH	Changes in disturbance type and frequency, evapotranspiration
	Tree regeneration	P, S, T, GS, W, CC, RH	Changes in species composition, soil temperature, evapotranspiration
	Tree growth	P, T, GS, W, CC, RH	Changes in growing degree days, evapotranspiration, active layer depth
Vascular plants			
	Abundance – cover	P, S, T, GS, CC, RH	Changes in growing degree days, drought, herbivory
	Abundance – frequency	P, S, T, GS, CC, RH	Changes in disturbance type and frequency, evapotranspiration
	Abundance – distribution	P, S, T, GS, CC, RH	Spatial shifts in bioclimatic envelopes, changes in disturbance
	Diversity – species richness	P, S, T, GS, CC, RH	Changes in disturbance and dominant vegetation
	Community composition	P, S, T, GS, CC, RH	Spatial shifts in bioclimatic envelopes, changes in disturbance
Invasives	Abundance – frequency	P, T, RH	Indirect link to climate from changes in disturbance, herbivory, land cover
	Abundance – distribution	P, T, RH	Indirect link to climate from changes in disturbance, herbivory, land cover
Fire			
	Fire risk rating	P, S, T, W, CC, RH	Changes in fuel moisture, fuel quantities, fuel types
	Burn severity	P, S, T, W, CC, RH	Changes in fuel moisture, fuel quantities, fuel types
	Post-fire succession	P, T, GS	Change in surface albedo, active layer depth, soil temperature
Other disturbance			
	Windthrow	W	Changes in soil stability, storm events, root diseases
	Disease	T, P, RH	Increased drought stress for trees
	Insects	T, P, S	Reduced winter mortality, increased life cycle frequency
	Harvest	Indirect	Bioenergy use, fuel reduction, timber production
Habitat			
	Habitat location, abundance, quality	P, S, T	Shifts in phenology, vegetation structure and composition, water availability
	Habitat-species relationships	P, S, T	Changes in habitat use
Carbon accounting			
	Aboveground live tree mass	P, T, GS	Biome shifts, changes in species composition and disturbance frequency
	Snag mass	P, T, W, RH	Changes in mortality, decomposition, fall down rates
	Downed woody debris mass	P, T, W, RH	Changes in mortality, decomposition, fall down rates
	Soil carbon	P, T	Atmospheric exchange rates, decomposition, erosion, thaw, leaching
	Permafrost depth	P, T, GS, CC	Changes in albedo, snow cover, vegetation cover

south-central Alaska, for example, post-stratification uses the LandSat-based National Land Cover Database for Alaska (Stehman and Selkowitz, 2010), climate data from the Parameter Regressions on Independent Slopes Model (PRISM Climate Group, 2002), elevation, and ownership. Precision for commonly used indicators varies with both the sampling intensity and the size of the area for which estimates are needed.

Because of limited infrastructure, field costs are much higher in Alaska than in the conterminous US. Thus efficient monitoring solutions for the boreal forests may require shifting a larger portion of the budget to acquisition and processing of remote sensing data. Options for remote sensing vary in their ability to contribute to measurement of different indicators. Airborne laser scanning (lidar) data is useful for measuring vegetation height (Andersen et al., 2006), cover (Hopkinson and Chasmer, 2009), and biomass (Lefsky et al., 1999). Combining lidar with field data would be an efficient solution for an objective of monitoring vegetation biomass in interior Alaska, but multi-spectral platforms have greater promise (for example, see Clark et al., 2005 or Key et al., 2001) for identification of species and community types.

Successful monitoring programs typically have well-defined specific objectives (Mattfeldt et al., 2009). As the only regional-scale monitoring program for forests in the US, the FIA system has grown over time to include dozens of quantified indicators to meet the needs of diverse interests and management objectives. These indicators include measures of species composition and distribution, forest structure, presence of invasive species, rates of deforestation, mortality, growth, and regeneration of tree species, crown cover and condition, extent and impacts of disturbances such as disease, insect outbreaks, windthrow, and fire, biomass and carbon, quantity of down logs and snags, soil composition and structure, and air pollution (via lichen community composition). In the conterminous US, some of these forest health indicators are measured on a 1/16th subsample of plots (Woodall et al., 2010). In the boreal region of Alaska, travel cost to plots is a much higher proportion of total cost than in the conterminous US. Because of costs and the reduced sampling intensity proposed for the boreal region, the Alaska FIA office has field-tested simplified indicator protocols that would be used on all plots instead of a 1/16th subsample. In the next section, we present some examples of monitoring variables (summarized in Table 1) that could provide information about conservation decisions and climate change impacts.

3. Applications of FIA monitoring to conservation issues

3.1. Abundance and rarity of vascular plants

Changes in vascular plant species abundance are a reliable indicator of changes in habitat for a large suite of organisms, in addition to being an important component of biodiversity in their own right. FIA samples plant species and communities in proportion to their abundance on the landscape. Because species presence and community richness is a function of plot size, the use of a consistent plot design across large regions enables assessment of species' distribution and abundance. Although assessments of species' relative abundance and rarity are possible with FIA data, the dispersed, low density sample precludes having sufficient information to describe the distribution of rare species accurately (e.g., endangered plants). The combination of species data, information on site productivity, and disturbance history from FIA plots with geographic information on climate and geology allows for evaluation of factors affecting community composition (e.g., Ohmann and Spies, 1998), predictive mapping of species distributions (e.g., Rehfeldt et al., 2006), and assessing potential effects of climate change (e.g., Brady et al., 2010; Iverson and Prasad, 1998).

In addition to trees, which are measured on all forested FIA plots, the vegetation indicator protocol includes measurements of all vascular plants on nested quadrates and subplots by qualified botanists (Schulz et al., 2009). In states where the indicator has been implemented, measurements are usually limited to a 1/16th subsample of the plots to enable sampling during the portion of the field season when plant phenology is most conducive to good identification; FIA data collection in most states lasts for at least 6 months per year. In most western states, FIA crews also record the abundant species present (i.e., those with $\geqslant$3% cover) on all measured plots. However, we anticipate that full vascular plant enumeration may be possible in interior Alaska given the short field season and low species diversity of boreal forests (Chapin et al., 2006; Rees and Juday, 2002). The importance of mosses in boreal forests (Beringer et al., 2001; Shetler et al., 2008) has led to a desire to include an assessment of their abundance and composition, even though mosses are not generally sampled by FIA elsewhere. In other parts of the US, lichen diversity is monitored as part of the FIA program, primarily as an indicator of air pollution (e.g., Geiser et al., 2010), but it is not clear that available resources would allow the inclusion of this protocol in the boreal inventory.

3.2. Invasives

Invasive species (i.e., species introduced to ecosystems in which they are not native) can have large and long-lasting impacts on native biodiversity, including driving some species to extinction and moving ecosystems into alternative stable states (D'Antonio and Vitousek, 1992; Mooney and Hobbs, 2000). The FIA program is focused primarily on vegetation measurements, and is a valuable tool to assess the impact of invasive plants, as well as the effect of animals and pathogens on the plant community. Vegetation data from inventory plots has been used to assess the abundance and distribution of non-native plant species, the relative dominance by invasive plants in different communities, and associations between invasives and forest structure and management history (Gray, 2005). FIA monitoring has also been used to assess mortality caused by new pathogens, and to predict the potential spread of pathogens or insects in forests (Barrett et al., 2006; Crocker and Meneguzzo, 2009). The existing plot grid can be an excellent resource for conducting rapid assessments and special studies for damaging organisms.

In addition to protocols for measuring all vascular plant species on a subset of plots, or dominant species on all plots (see Section 3.1 above), most FIA inventories across the country record the abundance of a regionally-prioritized list of invasive plants (Rudis et al., 2004). Although the list of non-native plants that occur in forest environments in a region can number in the hundreds, many plants are only readily identifiable for a short portion of the commonly long field seasons, and training general field crews to accurately identify a large number of plants, many of which they may never see, is difficult (Gray, 2008). As a result, FIA invasive plant lists usually emphasize woody species and only the most potentially destructive and identifiable forbs and graminoids. Although invasive plants are still uncommon in Alaska, many are increasing near populated areas and the habitat potential along rivers and on recent burns is vast (Carlson and Shephard, 2007; Villano, 2008). FIA has developed a priority list of species for Alaska in cooperation with invasive plant experts in the region. Invasive animals and pathogens are also found in interior Alaska (McClory and Gotthardt, 2008); although many are outside the scope of a vegetation monitoring program, several insects that feed on trees and other vegetation could be monitored via their impact on plants.

3.3. Fire risk, fire effects, post-fire succession

Changing climate is likely to alter the fire regime in the boreal forest of Alaska. Changes in climate and fire regime combined are expected to impact the distribution and relative abundance of tundra, grassland, white spruce (*Picea glauca*), black spruce (*Picia mariana*), and deciduous forest (Rupp et al., 2002). In turn, ungulates such as moose and caribou can be affected as quality and quantity of forage shift, affecting the availability of subsistence resources for rural populations (Nelson et al., 2008; Sharma et al., 2009).

Three types of indicators based on FIA data can be used to help understand and predict the interaction of fire with vegetation and climate in the boreal forests of Alaska. Long term post-fire successional pathways in boreal forest types can be quantitatively estimated by combining forest inventory plots with fire history information (de Grandpré et al., 2000). Indicators of fire risk, fire frequency, and fire type, calculated from FIA vegetation data and weather information, are extensively used in the conterminous United States (e.g., Cruz et al., 2003; Woodall et al., 2005; Zhai et al., 2003). Indicators used to understand and predict short-term fire effects, such as the impact of fire on soils, vegetation, and invasive species, also use pre-fire FIA data and post-fire measurements (Huebner et al., 2009).

3.4. Disturbance frequency and impact

In addition to estimating fire risk and fire effects, FIA data is used to estimate the frequency and impact of other disturbances such as diseases, insects, and wind. The southern extent of white spruce is on the western Kenai Peninsula of Alaska, but that range limit may be moving northward. Large outbreaks of spruce beetles that occurred on the Kenai in recent decades are believed to be among the largest insect disturbances recorded for North America and caused extensive *P. glauca* mortality (Matsuoka et al., 2006). Researchers have attributed the scale and intensity of the outbreaks to climate change, through increased overwintering survival of the beetles and the reduction of maturation time from 2 years to 1 year (Berg et al., 2006; Werner et al., 2006). FIA data has been used to understand the impact of the spruce beetle outbreaks on regeneration and vegetation change (Boucher and Mead, 2006) and dead woody material (Schulz, 2003), and to predict risk factors for beetle outbreaks (Reynolds and Holsten, 1994).

Research predicting future tree species ranges for different climates commonly uses FIA data (e.g., Iverson and Prasad, 1998; Rehfeldt et al., 2006; Woodall et al., 2009) but generally does not address how migration might occur. While direct climate–plant interactions may cause range shifts, the beetle-spruce–climate interactions on the Kenai during the 1980s and 1990s suggest that disturbance events may also play a role in species range changes. Examples from the paleological literature also indicate that disturbances can play a substantial role in altering direct impacts of climate on species distribution (Green, 1982). Indicators based on FIA data have been used to understand ecoregional dynamics of other types of disturbance, including hurricanes (Zeng et al., 2009), windstorms (Nelson et al., 2009), diseases, and declines (Drohan et al., 2002).

3.5. Habitat distribution

Vegetation composition and structure are frequently used to characterize the abundance and quality of wildlife habitat. In forest habitats, the live plants are not the only attribute to consider; standing snags, down wood, and the presence of clearings or water can be critical determinants of habitat suitability. Wildlife-habitat relationships based on forest type and stand size class allow for simple assessments of the abundance and distribution of potential habitat (e.g., Brown, 1985). With better information, more sophisticated versions of wildlife-habitat relationship models have been created which incorporate additional habitat elements like the presence of snags, down wood, seed- and forage-producing species, or water (e.g., Johnson and O'Neill, 2001). Applying these relationships to plot data is likely to work well for many species with small home ranges.

For species with home ranges larger than the FIA plot footprint, or for which the context of different land cover types is important, models have been developed which combine FIA plot data with remote sensing and topographic and climate models to map detailed forest attributes across large regions (Ohmann and Gregory, 2002). These maps have been combined with detailed spatial models for species of interest to conduct regional biodiversity analyses of current and projected future landscapes (Spies et al., 2007). However, many habitat features critical for individual species are missing from standard inventories, including caves, talus, sandy riverbanks, proximity to water, and forage quality and production. The FIA plot grid can be a useful resource for creating new habitat models by sampling wildlife at FIA plots (Dunk et al., 2006). In other instances FIA plots are installed at sites used by rare species with the existing grid used as a null set to build models (Zielinski et al., 2006). These models can then rely on the stable FIA vegetation inventory to make current or future assessments of habitat availability. In addition, protocols have been devised to conduct direct monitoring of vertebrate and invertebrate species tied to the vegetation inventory grid (Manley et al., 2004, 2006; Bowser and Morton, 2009).

3.6. Carbon accounting

One of the newest indicators where FIA data is being used extensively is carbon (Fahey et al., 2010). For conservation purposes, carbon markets offer a potential revenue stream to natural area managers and land owners. Because carbon trading will likely change substantially in response to future legislation and international agreements, it is currently difficult to predict how carbon markets and treaty obligations will affect aggregate land owner decisions. FIA data is the primary source of information for estimates of national biomass and carbon stored in forests (Smith et al., 2009). The current lack of inventory data for interior Alaska means that these 'national' estimates are for the conterminous US only (e.g., Woodbury et al., 2007). Almost all developed countries use sample-based inventories similar to FIA for biomass and carbon accounting for the forest sector (Smith et al., 2008).

Possible land management decisions in the boreal forest that may be affected by carbon accounting include fire suppression, development of land, and tree planting and harvesting. FIA data can be combined with IPCC climate projections to predict how basic forest growth rates may change over time (Latta et al., 2010). However, while forest growth may increase in some areas due to longer growing seasons, overall the boreal region is suspected to be a significant possible source of greenhouse gases as climate warms, due to melting permafrost and consequent decay of organic materials (Zimov et al., 2006) and release of methane. Limited access to most of the region, and the consequent uncertainty about carbon storage in soils and permafrost, has resulted in discussions among Forest Service and US Geological Survey scientists about using a future FIA inventory of the boreal region to improve knowledge of carbon in soils and vegetation.

4. Strengths and limitations

The wide-spread application and long-term duration of the FIA program allows a fairly comprehensive understanding of the program's strengths and weakness. One limitation for making conservation decisions is that estimates for small land areas are imprecise. Many land managers find that there is insufficient precision for estimates made with FIA data for practical application, although they may still use the data in combination with other sources of information or use it for analysis of the larger multi-owner region surrounding their land. For example, national forests in Oregon, Washington, and California, which range in size between 344 and 712 thousand hectares, have chosen to double the number of field plots to gain sufficient precision for management decisions. Some states and other ownerships have also chosen to increase sampling intensity, either spatially or temporally.

A second limitation for making conservation decisions is that the field plot portion of the FIA program does not allow for looking at spatial context and contiguity, because it is a point sample. To address these limitations, FIA field data is routinely combined with remote sensing data, either to improve precision of estimates or to create map products. Integration with remote sensing data to improve precision of estimates is accomplished with post-stratification (Bechtold and Patterson, 2005). The remote sensing data used to improve precision varies, but most regions use LandSat products such as the National Land Cover Dataset (Homer et al., 2007). Examples of spatial applications that combine remote sensing data and FIA field data include mapping forest type (Ruefenacht et al., 2008), wildland fuels (Pierce et al., 2009), forest productivity (Latta et al., 2009), biomass (Blackard et al., 2008), wildlife habitat suitability (Spies et al., 2007), and forest composition and structure (Ohmann and Gregory, 2002).

While baseline installation of the inventory provides for many of the uses discussed so far, monitoring of trends may be the most valuable use of the FIA program for conservation purposes. All sampling locations currently being installed by the FIA program are permanent, with remeasurement at the same location scheduled every 10 years. Using permanent locations helps to greatly increase the statistical power to detect change. While the FIA program has been active since the late 1930s, it has often not been able to take full advantage of the use of permanent plots to detect change, as program managers have changed plot designs every 10–20 years (LaBau et al., 2007). The current field plot design has been stable since 1998 legislation revised the program, but basic methods such as the definition of 'forest' continue to be altered, impacting the ability to provide long-term trend information.

As for any monitoring program that is not part of a designed experiment, while changes in ecological attributes may be observed, assumptions about causality are problematic. Shifts in species compositions, altered mortality or regeneration rates, and changes in vegetation biomass can have many different causes from either natural or anthropogenic factors. In some cases, information collected about disturbance and management history helps to develop hypotheses about why change has occurred. Yet for many issues, results from broad-scale monitoring programs like FIA need to be tied to focused research studies to be able to draw inference regarding cause and effect.

Monitoring of yellow-cedar (*Chamaecyparis nootkatensis*) in southeast Alaska provides an example of the link between monitoring and research. Yellow-cedar has been widely reported as declining due to a warming climate (e.g., Associated Press, 2006), based on research studies that focused on numerous yellow-cedar snags observed in southeastern Alaska landscapes. Live yellow-cedar trees, however, could not be distinguished from other species in the aerial surveys used to map snags. In contrast to the previous reports of a decline, analysis from the most recent FIA data for the region shows no overall change for the species in live tree biomass or numbers within its range in Alaska between 1995–2003 and 2004–2008 and a live-to-dead tree ratio that increases with elevation (Hennon et al., in press). This result from the monitoring data in turn suggests where future research should focus, such as on survival and growth at higher elevations or on dendrochronological work to date the past mortality episodes and relate them to specific weather events. Combining monitoring and research in this manner helps to ensure the efficacy of any actions taken for conservation of yellow-cedar.

5. Conclusion

The boreal forest region of Alaska has many unique qualities. The preeminent natural disturbance regime, fire, has been largely unaffected by human activities (Chapin et al., 2003), and invasive species are notably less common than in the remainder of the United States (Tempel et al., 2004). Compared to other regions of the US, flora and fauna have had relatively less impact from 20th century development. The majority of the population in rural Alaska is Alaska Native, and subsistence activities remain an important part of the economy and culture (Huskey et al., 2004). Climate change is expected to greatly impact both human and natural systems within the state. The logistical difficulties in this region, the lack of infrastructure, and the paucity of previous monitoring data suggest that cooperation between various federal, local, and state agencies is particularly important for achieving comprehensive biodiversity monitoring to support conservation management.

Partnerships enhance the ability to do monitoring in a variety of ways (Lindenmayer and Likens, 2010). Combining limited resources can allow diversification of indicators or increased precision through more sampling units. If designed carefully, large-area monitoring programs and small-area experimental research can be combined to address specific conservation issues at multiple scales. Cooperative analysis and research among university and federal scientists takes advantage of varied areas of expertise. Recent examples of integrated multi-agency monitoring approaches have occurred on the Kenai National Wildlife Refuge (Morton et al., 2009) and the Delaware River Basin (Murdoch et al., 2008).

Many of the most pressing conservation questions in Alaska center on wildlife. While vegetation monitoring can provide information about habitat, which in turn influences occupancy, dispersal, and population dynamics of wildlife, other types of monitoring would be required to comprehensively address biodiversity (Psyllakis and Gillingham 2009). The FIA program should not be thought of as a replacement for monitoring programs by individual national parks or wildlife refuges in Alaska. Ideally, those monitoring programs would have direct ties to management actions and policies of the individual parks and refuges. However, the FIA program is unique in providing vegetation composition and structure information across broad multi-owner landscapes, and it can thus provide context for isolated parks and refuges. The robust statistical design, focus on quantifiable indicators with known sampling and measurement error, and integration of field and remote sensing data would make it an important foundational program for biodiversity monitoring in the boreal region of Alaska.

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